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SPECIAL PUBLICATIONS BRL-SP-91

BRL

ELECTROTHERMAL-CHEMICAL MODELING AND DIAGNOSTICS WORKSHOP, VOLUME 1

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OCTOBER 1991

U.S. ARMY LABORATORY COMMAND

BALLISTIC RESEARCH LABORATORY
ABERDEEN PROVING GROUND, MARYLAND

NOTICES

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13. ABSTRACT *(Maximum 200 words)*
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.

14. SUBJECT TERMS
electrothermal-chemical; ETC; electrothermal gun; electric guns; interior ballistics

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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:

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.

Diagnostic Measurements Desired by ETC Modeling

Measurement	Response from Experimenters	Organization Addressing
*1. Characteristics of turbulence - time averaging or direct simulation required? - time scale of turbulence vs. time scale of acoustic wave	1. Possible experiments: laser sheet diag., void fractions, particulate scattering, flash x-ray diag. (On board diag.) Some work at Imperial College in boundary layer may be useful SNL can do	1. PSU (laser sheet diag.)
*2. Phase relationships - phase equilibrium or multiphase, nonequilibrium required?	2. Detailed acceleration profiles may shed some light	2.
3. Propellant surface area available - as function of plasma properties	3.	3.
4. Pyrolysis rates of propellants - as function of energy flux to surface	4.	4. PSU
5. Taylor cavity front - velocity, trajectory	5. NC State can do	5. Planned: SNL, BRL Some data available: LANL (center plasma), PSU (end plasma)
6. Temperature x Space x Time in mixing chamber	6. NC State can do	6.
7. Rates of droplet formation - at low temperature - at constant velocity	7. Early work at SNL	7.
8. Plasma velocity from capillary into chamber	8.	8. NC State, SNL
9. Pressure in plasma capillary	9. NC State can do	9. Planned: SNL Some data available: BRL
10. Species composition of plasma at chamber entrance	10. SNLL, NC State can do	10.

Diagnostic Measurements Desired by ETC Modeling

Measurement	Response from Experimenters	Organization Addressing
11. Mass and energy flux from plasma capillary into chamber	11.	11.
12. Interaction between plasma and propellant in terms of energy release - removing cavity formation - difference between free plasma and injected plasma	12.	12.
13. Pressure wave structure - axial - radial	13.	13. All
14. Projectile motion - early - base pressure	14. BRL, LANL, SNL can do	14. BRL, LANL
15. Heat flux into tube in order to benchmarch turbulence measurements	15. SNL, NC State can do	15. BRL
16. Chamber geometry effects	16.	16.
17. 3D effects	17. "Look" in different directions	17.
18. Muzzle effluent (after propellant chosen)	18.	18.

Current ETC Diagnostic Activities in the U.S.

Organization	Program Funding	Current Activities
1. ARDEC	Army	1. Combustion screening of alternate ETC propellants
2. BRL	Army	2. Diagnostics of pressurization in working fluid chamber, closed bomb/gun mode, IB pressure-time, in-bore velocity, gasification of alternate ETC propellants, flash x-ray diagnostics, electrical measurements (PFN)
3. FMC	DNA, IR & D	3. Gun firings, projectile motion (early time), pressure-time, electrical measurements (PFN)
4. GDLS	IR & D, Navy	4. Gun firings, projectile motion, pressure-time, electrical measurements (PFN)
5. Los Alamos National Lab	In-house	5. Diagnostics of in-situ generated plasmas in inert working fluid, projectile velocity, flash x-ray diagnostics, electrical measurements (PFN)
6. NC State University	SDIO	6. Plasma diagnostics, materials testing, electrical measurements (PFN)
7. Olin Corporation	IR & D	7. Ballistic diagnostics of solid propellant ETC, closed bomb
8. Penn State/FMC	FMC, IR & D	8. Real time flash x-ray & x-ray cinematography, plasma working fluid mixing, heat flux effects on combustion rate of working fluid
9. Penn State/SAIC	DNA via SAIC	9. Carbon dioxide laser pyrolysis effects on burning, x-ray study of gas jet penetration into liquid, laser loading effects on sheet & droplet burning
10. SAIC/FMC	DNA	10. X-ray diagnostics of plasma working fluid mixing, projectile motion, pressure, electrical measurements (PFN)
11. Sandia (Livermore)	Army, In-house	11. Plasma working fluid mixing imaging, laser generated plasma effect on surfaces, shock tubes
12. Sandia (Albuquerque)	Army, In-house	12. Increased mass output plasmas, diagnostics & synthesis of energetic plasma liners, electrical measurements (PFN)

Current ETC Modeling Activities in the U.S.

Organization	Program Funding	Current Activities
1. ARDEC	Army	1. 0D
2. BRL	Army	2. 0D, 1D, End-to-end, Plasma
3. FMC	DNA, IR & D	3. 0D, 1D, 2D (Finite Difference), End-to-end
4. GDLS	IR & D	4. 0D, 2D (Finite Element)
5. Los Alamos National Lab	IR & D, Olin	5. 2D, End-to-end
6. NC State University	Army, IR & D	6. 2D (submodules), Plasma
7. Olin Corporation	IR & D	7. 0D, 1D, 2D
8. Penn State University	IR & D	8. 2D (2 phase, multiple sites, detailed droplet shedding)
9. SAIC, Atlanta	Army, DNA	9. 0D, End-to-end, Plasma
10. SAIC, Ft. Washington	Army	10. 2D (Upwind/Implicit), 3D
11. SAIC, San Diego	DNA	11. 2D (FCT), 3D
12. S-Cubed, Maxwell Labs	DNA	12. 0D, 1D, 2D
13. Sandia National Labs	Army, DoD/DOE MOU	13. Plasma (1D radial), 2D (submodules)

Use of Diagnostic Measurements Desired by ETC Modeling (Plasmas)

Measurement	Response	Organization Addressing
1. Plasma tube pressure vs. time	1. Important measurement, can do in view of Sandia success	1. Sandia doing now; NC State could in future
2. Species vs. time for plasma effluent	2. Could be important for the hysteresis problem, but hysteresis is not now the pacing issue	2. NC State could do species vs. time; also Sandia (Livermore)
3. Plasma velocity	3. Important, can do	3. Sandia doing (Albuquerque)
4. Temperature distribution in capillary	4. Not essential now	4. N/A
5. Vapor shield effects	5. May be important in the future in a general sense on energy transfer	5. N/A
6. Effects of gun chamber events on plasma tube pressures	6. Very important	6. None at moment; Sandia, BRL or NC State could attack
7. Ablation depth of plasma liners, uniformity, pyrolysis rates	7. Could wait without major ill effects on models	7. Sandia doing now
8. Application of laser generated plasma to ETC diagnostics	8. Need base line information before potential utility can be assessed	8. Sandia doing now

Use of Diagnostic Measurements Desired by ETC Modeling (Chamber Events; Plasma-Working Fluid)

Measurement	Response	Organization Addressing
1. Degree of burning rate augmentation by plasma or intense radiation source	1. Now doing; (1)With solid propellant /with proposed alternate ETC propellants; (2)Also with laser circulating plasma radiant energy	1. (1) BRL (2) Penn State
2. Burning rate law changes with plasma	2. Will do once data is available	2. BRL & Penn State
3. Burning rate effects of plasmas on liquids, gels & solids	3. Need data, will soon be doing	3. BRL & ARDEC
4. Burning rate - mass generation effects in two - component systems	4. Need; efforts starting at BRL & ongoing at PSU	4. BRL & Penn State
5. Reaction front in bulk homogeneous energetic liquid vs. two phase	5. Important; no ongoing efforts directly addressing issue, but PSU & BRL work could be re-directed in this direction	5. N/A
6. Thermo-chemical code validation via closed bomb experiments for high water content propellants	6. General consensus is that it's not important at this time	6. No work ongoing
7. Data to support plasma augmented combustion model	7. Experimentalists felt data to be necessary; modelers felt less strongly about need for data	7. Work ongoing at BRL; related efforts at Penn State & Sandia
8. Effects of plasma mass output on mixing	8. Thought to be important	8. Sandia doing (Albuquerque)

Use of Diagnostic Measurements Desired by ETC Modeling (Chamber Events; Plasma-Working Fluid)

Measurement	Response	Organization Addressing
9. Analysis of closed bomb experimental data via fluid dynamic models	9. Could be important; can be done (GTD)	9. BRL will share closed bomb data with Neils Winsor, GTD
10. "Benchmarch experiments" for model testing - axial plasma - end-on plasma - in-situ plasma	10. Thought to be a good idea. Need for an all gas benchmarch added as suggested by SAIC. Experimentalists at BRL, FMC, GDLS, LANL, Sandia & etc. could all supply carefully obtained data sets for model validations	10. But, rules need to be worked out for study & standards for information to be provided

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National Electric Gun Reviews And Implications for the Army's ETC Gun Technology Program

William Oberle
US Army Ballistic Research Laboratory

William Morelli
Electric Armaments Program Office

Presented at
JANNAF Workshop
ETC Modeling & Diagnostics
9 - 11 JULY 1991

Objective

Summarize the findings from recent Congressional/ DoD electric gun reviews and the resulting impact on the Army's electrothermal - chemical technology program.

Outline

- Background
- IAT Technology Review (technology)
- Army Science Board (programatics)
- Other
  - HAC S&I Review
  - DDR & E EG Review
  - ADPA Electric Launch Symposium
- Joint Electric Armaments Committee (JEAC)
- Summary

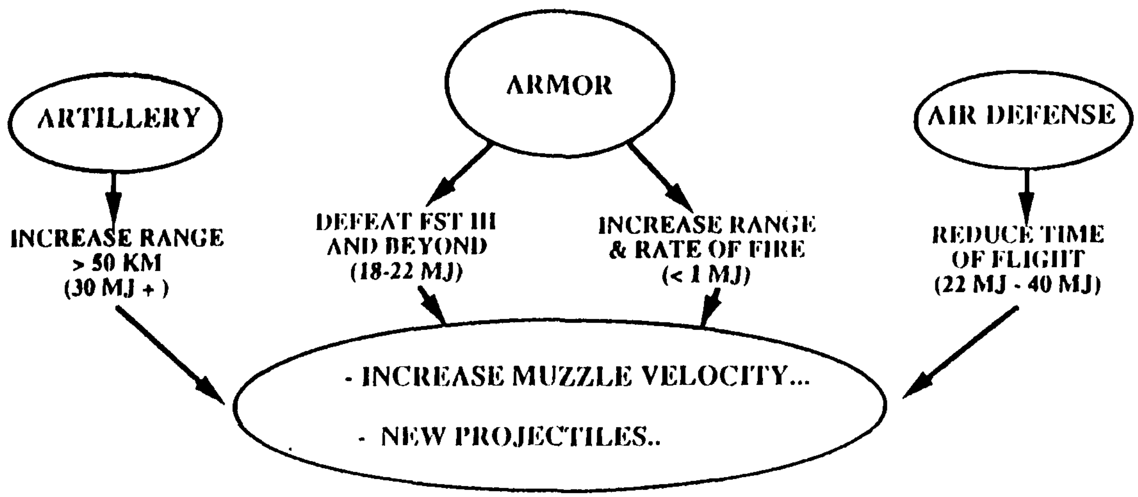
Background

Potential Applications

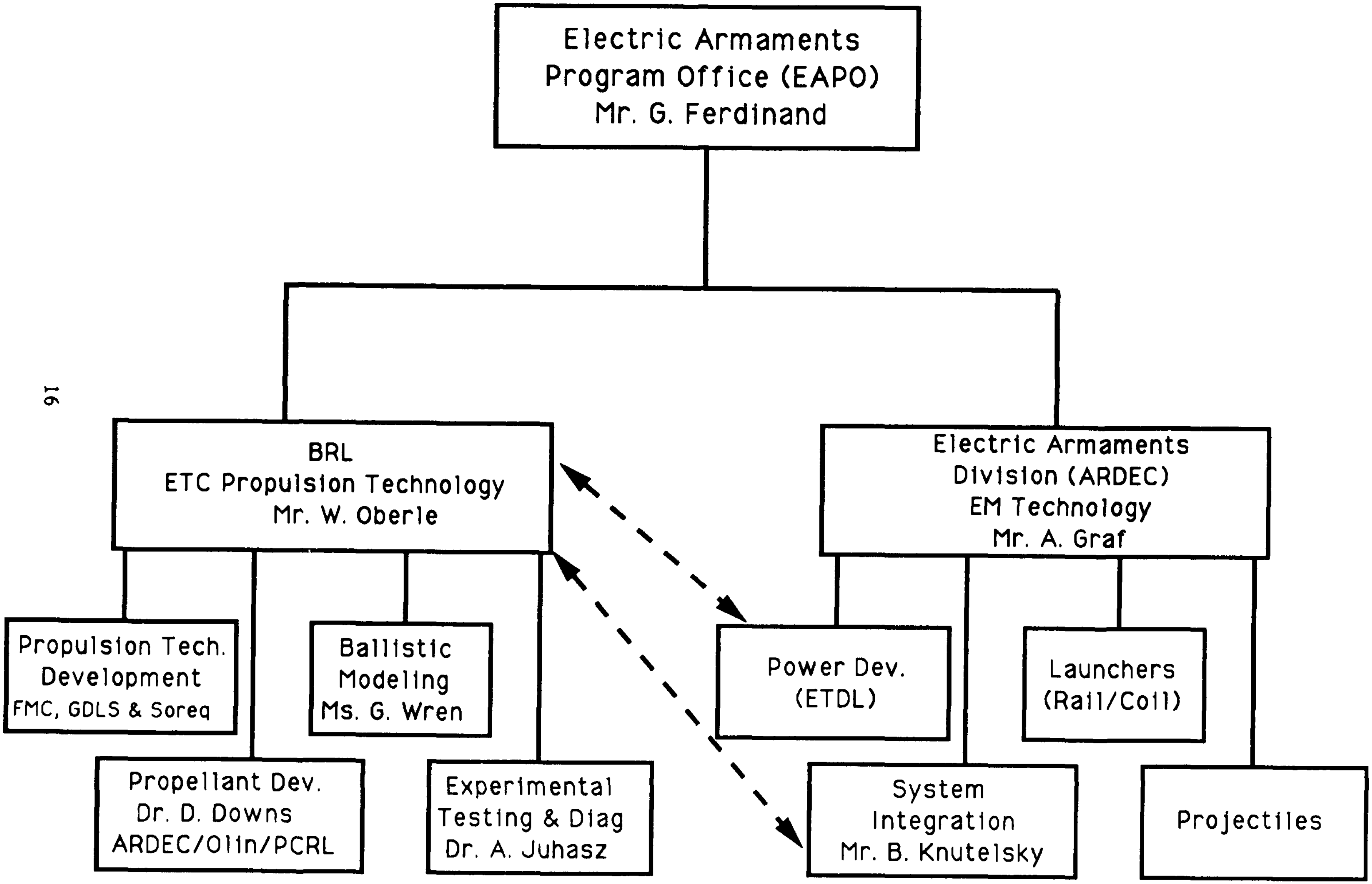
CURRENT CAPABILITIES

	ARTILLERY	ARMOR 120mm Tank gun	ARMOR 25mm Bushmaster	AIR DEFENSE
PROJECTILE MASS	43.6 KG	8.9 KG (KE)	.360 KG (KE)	0.1 KG
MUZZLE VELOCITY	826 M/SEC	1,590 M/SEC (KE)	1,345 M/SEC	1,040 M/SEC
MUZZLE ENERGY	15 MJ	11 MJ	.325 MJ	0.05 MJ
MAXIMUM RANGE	30 KM	TARGET DEPENDENT	TARGET DEPENDENT	1.6 KM

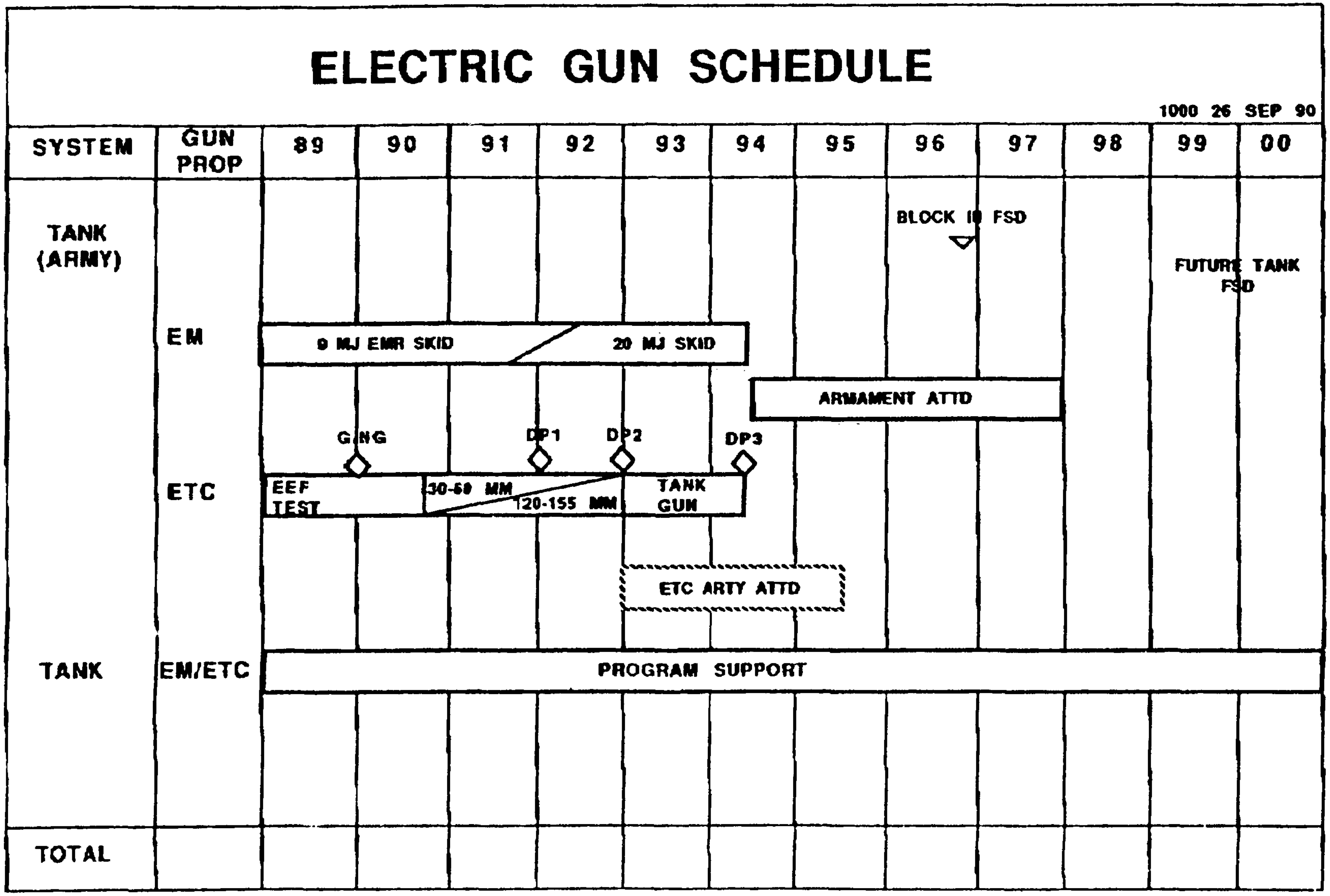
FUTURE CAPABILITIES



Army Electric Gun Program Structure &Responsibilities



Army ETC Roadmap
Middle 1990



National E.G. Reviews

High Visibility - - - -

- IAT Technology Review (Jan. 1991)
- Army Science Board (Jan. 1991, final report)
- HAC S&I Review (April 1991)
- DDR & E Electric Gun Review (May 1991)
- ADPA Electric Launch Symposium (May 1991)

Additional Program Structure & Focus Revisions Anticipated

IAT Review
ETC Launchers

Assume: We are given power and output "plug"

<u>The Components:</u>

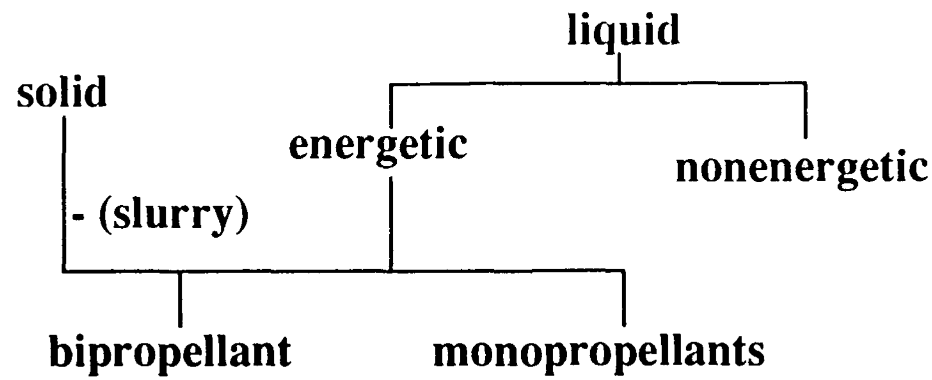
- Plasma Generator
- Working Fluid/Propellant
- Launch Package
- Power Transfer
- Barrel/Autoloader

PLASMA GENERATOR

Characteristics	Organization	Risk Level
• **If reuseable (breech-integrated)** - High temperature metals - High strength/toughness dielectics	FMC: IRD & CRI Israel (modest levels)	high
• **If disposable (round integrated)** - if confined discharge: high energy density discharge (20+ kJ/cc) - if unconfined discharge: electrodynamics of plasmas (T, density, conductivity, stability)	FMC GDLS Israel Rheinmetal (intense levels)	moderate
• **Phenomenology** - ignition studies - mixing studies - theory/modeling	All above plus BRL, DoE (high levels)	low-moderate
• **Configuration** - number of injectors - energy/power per injector	FMC GDLS	low

Working Fluids/Propellants

Identify/characterize the taxonomy:



GDLS
FMC
Israel
Germany
ARDEC
BRL
SDC
Olin

Issue Area	Organization
• Performance: energy density (5 - 10kJ/g); impetus (1000 - 1500 J/g) • Ignition/Combustion Characteristics	GDLS FMC Soreq Olin
• Militarization Issues - Logistics/Handling/Packaging - Bore Residue - Muzzle Signature - Shelf Life - Vulnerability - Toxicity - Environmental - Temperature Range	BRL, ARDEC and all above

Army Science Board

- Study mandated by Congress in 1989
- Year plus review of US electric gun programs

ELECTRIC GUN PROGRAM RESTRUCTURE

US ARMY Electric Armaments

ARMY PROGRAM PRE ASB (90)

- Anti-Armor Application
- Near-Term System Demos
- ETC Emphasis

ARMY SCIENCE BOARD RECOMMENDATIONS

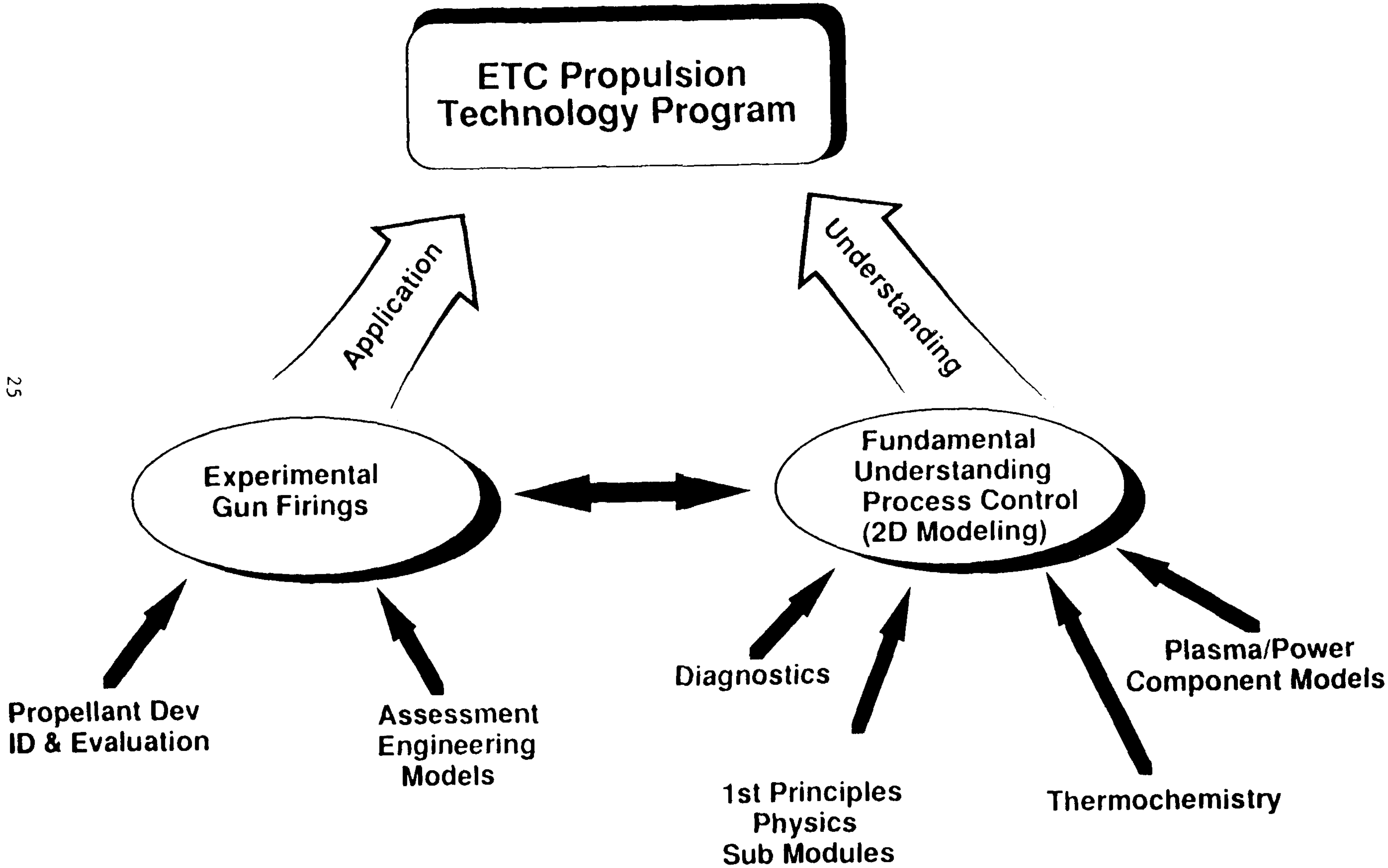
- Pursue Long-Term Prospects
- Revise Strategy
  - o Fundamental Understanding
  - o EM Emphasis
  - o Improved Components
  - o Multiple Applications

ARMY PROGRAM POST ASB (91)

- New Concept Exploration
- FFRDC in Electromechanics, Hypervelocity
- EM Emphasis
- Critical Component Development
- Explore Alternate Missions

Army Response To ASB Recommendation ETC

- Maintain "cautious optimism" in technology
- Potential for near term high payoff
- Extend timeline to mature technology
- Concept validation in small caliber
- Level "playing field" with EM (funding)



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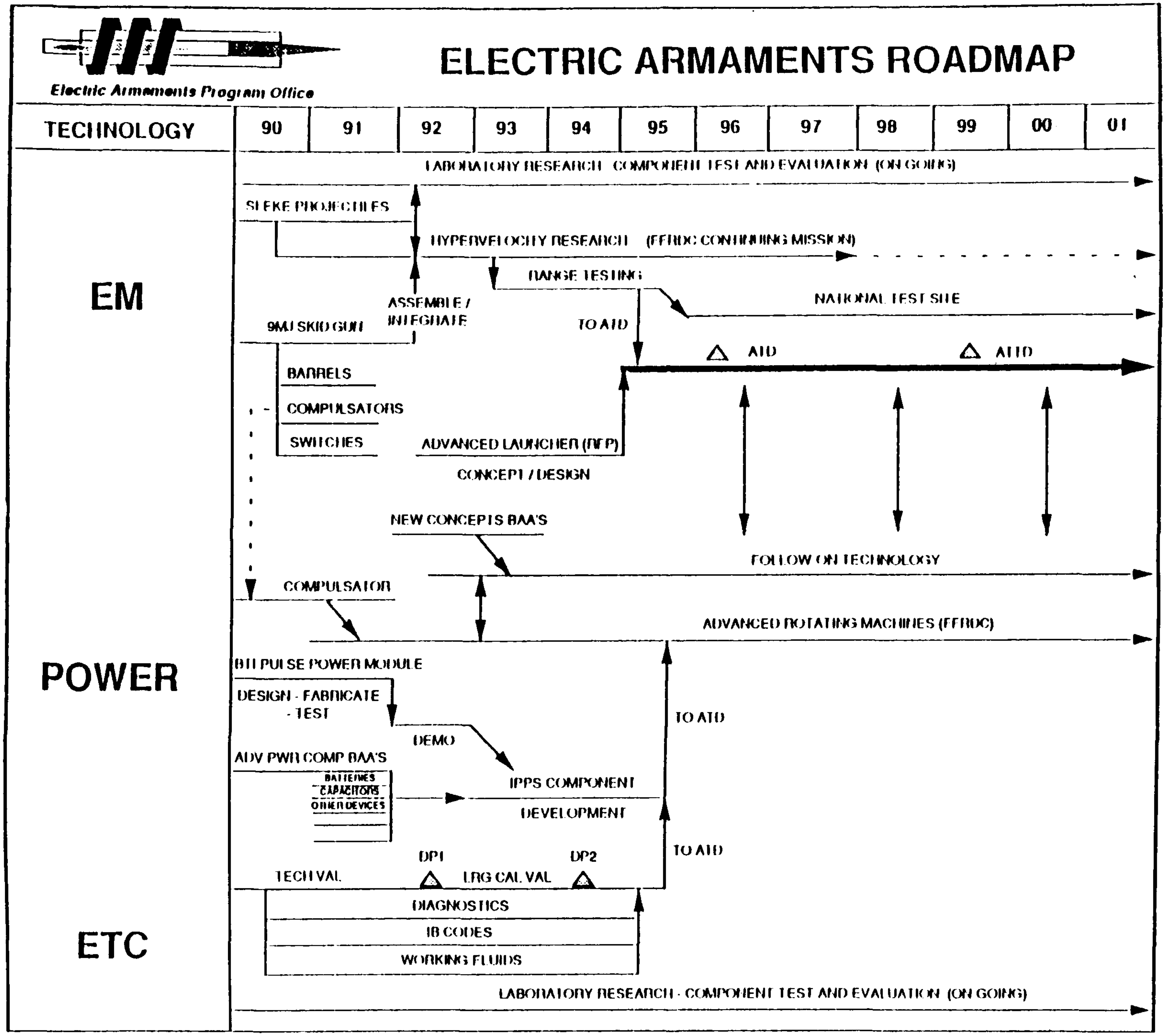
ELECTRIC ARMAMENTS ROADMAP
Electric Armaments Program Office
TECHNOLOGY
90
91
92
93
94
95
96
97
98
99
00
01
EM
POWER
ETC
LABORATORY RESEARCH COMPONENT TEST AND EVALUATION (ON GOING)
SLEKE PROJECTILES
HYPERVELOCITY RESEARCH (FFRDC CONTINUING MISSION)
RANGE TESTING
ASSEMBLE / INTEGRATE
9MJ SKID GUN
TO ATD
NATIONAL TEST SITE
ATD
ATTD
BARRELS
COMPULSATORS
SWITCHES
ADVANCED LAUNCHER (RFP)
CONCEPT / DESIGN
NEW CONCEPTS BAA'S
FOLLOW ON TECHNOLOGY
COMPULSATOR
ADVANCED ROTATING MACHINES (FFRDC)
BTI PULSE POWER MODULE
DESIGN - FABRICATE - TEST
DEMO
TO ATD
ADV PWR COMP BAA'S
BATTERIES
CAPACITORS
OTHER DEVICES
IPPS COMPONENT
DEVELOPMENT
TO ATD
DP1
DP2
TECH VAL
LRG CAL VAL
DIAGNOSTICS
IB CODES
WORKING FLUIDS
LABORATORY RESEARCH - COMPONENT TEST AND EVALUATION (ON GOING)

House Appropriation Committee on Surveys & Investigation Review

- Focus
  - electric guns
  - armor/anti-armor (A3)
- Issues Examined
  - program status
  - program costs
  - extent of coordination
  - cost effectiveness
- Output
  - report to Congress by 1 June 1991
- Conclusions
  - just status of program
  - supported ASB report

DDR & E Review

- Focus
  - electric guns
- Issues Examined
  - determine effectiveness & efficiency of current program
  - ascertain that the program is properly structured
  - provide advice as to any change in direction necessary to improve effectiveness & efficiency
  - determine if adequate funding is being applied to most critical projects
  - determine if there are non-critical projects that can be eliminated or delayed
- Output
  - final report August 1991
- Conclusions
  - N/A

US ARMY Electric Armaments

ADPA SYMPOSIUM

MANY OPINIONS EXPRESSED ON DIRECTION AND FOCUS OF ARMY PROGRAM . . .

MG WATSON, DNA - ETC ARTILLERY IS NEAREST TERM USE FOR ELECTRIC GUNS

LTG(RET.) WOODMANSEE - FOCUS ON AIR DEFENSE AND SPINOFF TO ANTI-ARMOR

MR. HARDISON - DON'T ATTEMPT TO DO GOOD FOR EVERYTHING. FOCUS ON ONE MISSION AREA AND GO DO IT. YOU CAN'T AFFORD MORE THAN ONE.

MR. SINGLEY'S REMARKS INDICATED THAT ARMY RESTRUCTURED PROGRAM IS PROPERLY FOCUSED AND COMPLIES WITH ASB RECOMMENDATIONS.

Joint Electric Armaments Committeee (JEAC)

Mission: The mission of the JEAC is to be the primary forum for the Department of Defense to identify and resolve issues and to facilitate coordination of DoD S & T programs concerning electric armament technologies.

- **Charter approval June 1991**
- **Interagency/Interservice Coordination Committee**
- **Membership**
  - Army (Chair)
  - Air Force
  - Navy
  - SDIO
  - DARPA
  - DNA
- **Reports to DDR & E**
- **Fiscal and program database**

Summary

- EG programs under intense scrunity
    - five major reviews in 1991
- Reviews impact programs
    - focus/direction
    - scheduling
    - funding
- Army Science Board (ETC)
    - Army maintains "cautions optimism"
    - basic understand of physics to be emphasized
- JEAC
    - interagency/interservice coordination committee

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ELECTROTHERMAL GUN DEMONSTRATION PROGRAM

- - -

NAVY BTI

- - -

PROGRAM STATUS

PRESENTED BY:
CDR CRAIG DAMPIER
NAVSEA 06KR12
ADVANCED CONCEPTS BRANCH

INTRODUCTION

- CURRENT GUN WEAPON SYSTEMS LARGELY OUTDATED TECHNOLOGY

  - WILL REMAIN IN FLEET BEYOND 2010
  - LIMITED EFFECTIVENESS AGAINST CURRENT THREAT
  - PROBABLE INEFFECTIVE AGAINST 21st CENTURY THREATS

- INCREASED RANGE, RATE OF FIRE, ACCURACY, PROJECTILE LETHALITY REQUIRED

- POTENTIAL FOR NEW MISSION AREAS - STRIKE, SEAD, ATBM

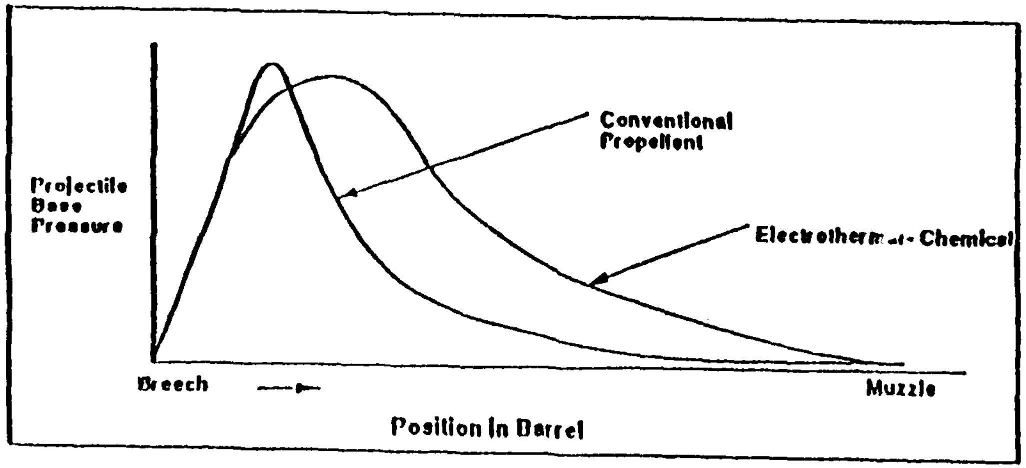
- ADVANCED GUN PROPULSION NECESSARY FOR MOST SCENARIOS -

  - ETC DEVELOPMENT MOST ADVANCED
  - POSSIBLE TO TRANSITION TO EM AFTER ETC INTRODUCTION

- GUIDED PROJECTILES ESSENTIAL

POTENTIAL ADVANTAGES OF ELECTROTHERMAL TECHNOLOGY

- GREATER PROJECTILE KINETIC ENERGY
  - HIGHER MASS (LETHALITY)
  - HIGHER VELOCITIES (RANGE/TIME OF FLIGHT)
  - INCREASED BATTLESPACE (EFFECTIVE LETHAL RANGE)
- TAILORED ACCELERATION PROFILES
- REDUCED VULNERABILITY
- NEARER TERM/LESS COSTLY THAN EM DEVELOPMENT



WHY COMMAND GUIDED PROJECTILES FOR ASCM DEFENSE

HIGH SPEED, RANDOM MANEUVERING TGTS
LESS ROUNDS/MORE SUSTAINABILITY
SINGLE SHOT HITS - KILLS
NEEDED KEEPOUT RANGES

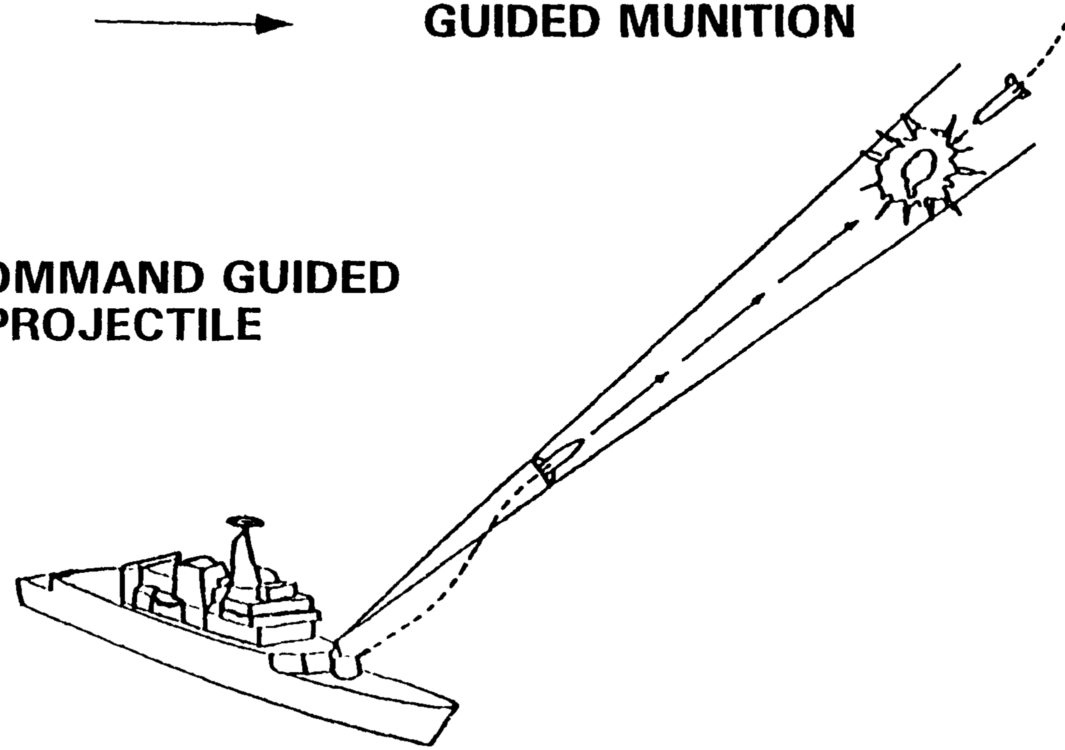
→ **GUIDED MUNITION**

LOW ROUND COST
LARGE MAGAZINE LOADOUT
SHORT MINIMUM RANGE
REDUCED WEIGHT/VOLUME
LESS COMPLEX

→ **COMMAND GUIDED PROJECTILE**

↑

FACILITATING TECHNOLOGIES
- TRK RADAR IMPROVEMENTS
- SHOCK HARDENING ELECTRONICS



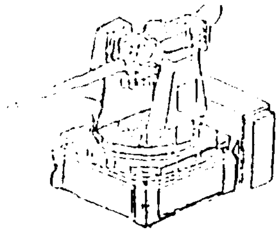
ET GUN DEMONSTRATION PROGRAM OBJECTIVES

- DEMONSTRATE
  - RAPID FIRE ELECTROTHERMAL GUN
    - CARTRIDGE CONFIGURATION
    - POWER TRANSFER
    - POWER GENERATION/PULSE FORMING
  - SHIPBOARD COMPATIBILITY
    - CIWS ENVELOPE
    - WEIGHT & SPACE FOR GENERATOR & PFN
    - COMPATIBILITY WITH SHIP'S POWER
  - COMMAND GUIDED PROJECTILE
    - PERFORMANCE VERSUS LOW E, OVERWATER TARGET
    - ET LAUNCH SURVIVABILITY
    - TASD/EO TRACKING ACCURACY
    - POTENTIAL FOR REQUIRED Pk AGAINST FUTURE THREAT
- POSITION TECHNOLOGY FOR FULL SCALE DEVELOPMENT DECISION

ET GUN DEMONSTRATION PROGRAM

60mm ET Gun/Autoloader

- Rapid fire ET/Conventional round capability - 10 round burst
- Integrated into CIWS mount
- Development underway - FMC

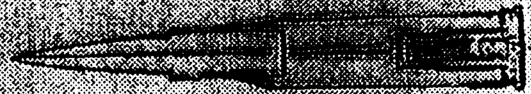


Studies/Analysis

- Design Definition Studies
- Operational Requirements Analysis
- Shipboard Integration Studies
- Projectile Design analysis
- Other Service/Agency Program Data

60mm ET Cartridge

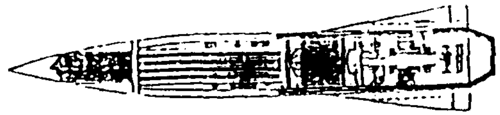
- 3.5 Kg projectile, ... muzzle energy
- 1Km/sec (min) muzzle velocity
- Development underway - FMC/GDLS



INTEGRATE

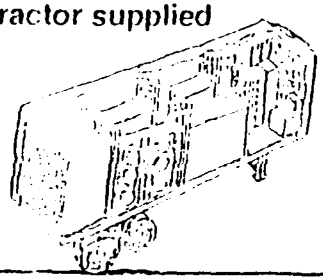
60mm Smart ... /FCS

- Command-Guided
- Development start July 1991



Power System

- Capacitor based PFN
- 2 MJ pulse energy
- Mobile, trailer mounted
- Contractor supplied

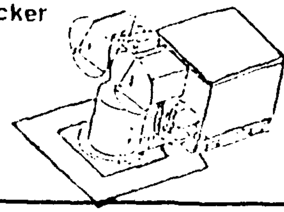


Demonstration

- Rapid fire conventional *and ET rounds*
- Fire guided projectiles at stationary and airborne targets using TASD radar
- Complete gun system *demonstration* CY 1993

Radar/EO Tracker

- Dual band Tracking Radar
- EO Tracker



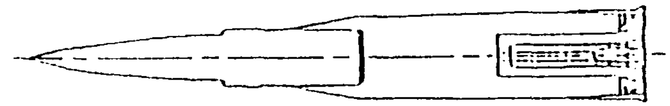
ET CARTRIDGE DEVELOPMENT

Program Description

PHASE I
- Two Sole Source R&D Contracts
- Analyze/Model ET Cartridge Technology
- Design/Fab Two 60mm Designs
- Conduct Preliminary Test Series
- Final Eval Both Designs

PHASE II
Cartridge Optimization

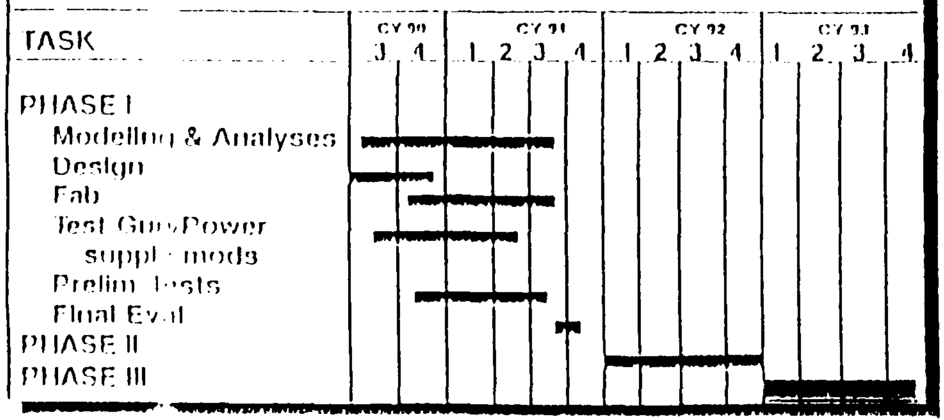
PHASE III
DEMO Cartridge Procurement



Program Objectives

- Develop 60mm Rapid Fire ET Cartridge with
  - Projectile mass = 3.5 Kg
  - Muzzle Velocity = 1 Km/sec (min)
  - Peak acceleration < 25,000 g(max)
  - Muzzle Energy = 1.75 MJ
  - Electric Energy Input = 2MJ (max)
- Interface with ET Gun and Enable High Rep Rate Operation

Program Schedule



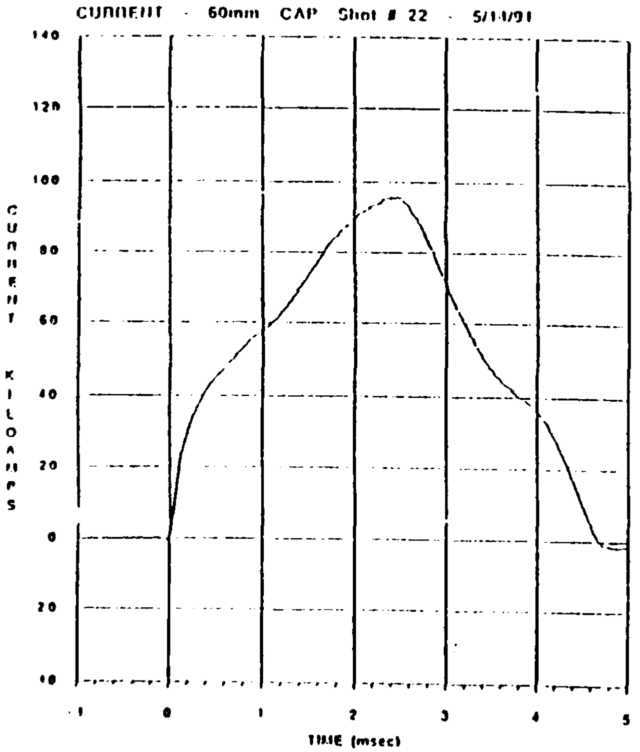
Program Status 6/18/91

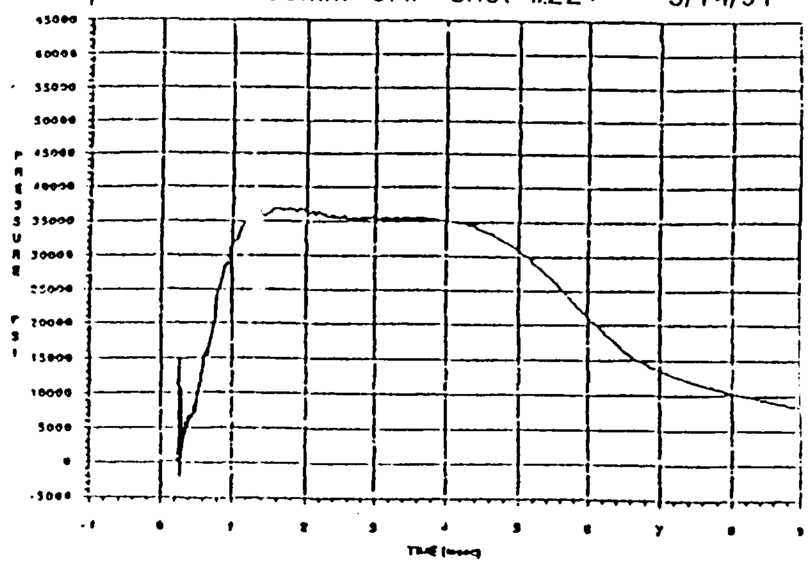
- Analysis - 85% Complete
- Designs - 95% Complete
- Fabrication - Ongoing
- Test Gun Interfaces - Complete
- Preliminary Tests - 60% Complete

FMC 60mm CARTRIDGE TEST RESULTS

- SHOT #22 5/14/91
- 4.7msec PFN PULSE
- 5MJ MOBILE POWER SUPPLY

	DEMONSTRATED	REQUIREMENT
MUZZLE ENERGY (MJ)	1.43	1.75
MUZZLE VELOCITY (Km/s)	.904	1.0 (min)
PROJECTILE MASS (Kg)	3.5	3.5
ELECTRICAL ENERGY (MJ)	1.056	2.0 (max)
PEAK CURRENT (KA)	95.1	
PEAK BREECH VOLTAGE (KV)	5.675	
PEAK CHAMBER PRESSURE (KPSI)	37	60 (max)





GDLS 60mm CARTRIDGE TEST RESULTS

- SHOT #4 6/14/91
- 4.0msec PFN PULSE
- 2.7MJ POWER SUPPLY (INTERIM)

	DEMONSTRATED	REQUIREMENT
MUZZLE ENERGY (MJ)	1.8	1.75
MUZZLE VELOCITY (Km/s)	1.015	1.0 (min)
PROJECTILE MASS (Kg)	3.5	3.5
ELECTRICAL ENERGY (MJ)	0.278	2.0 (max)
PEAK CURRENT (KA)	75.0	
PEAK BREECH VOLTAGE (KV)	4.8	
PEAK CHAMBER PRESSURE (KPSI)	56.7	60 (max)

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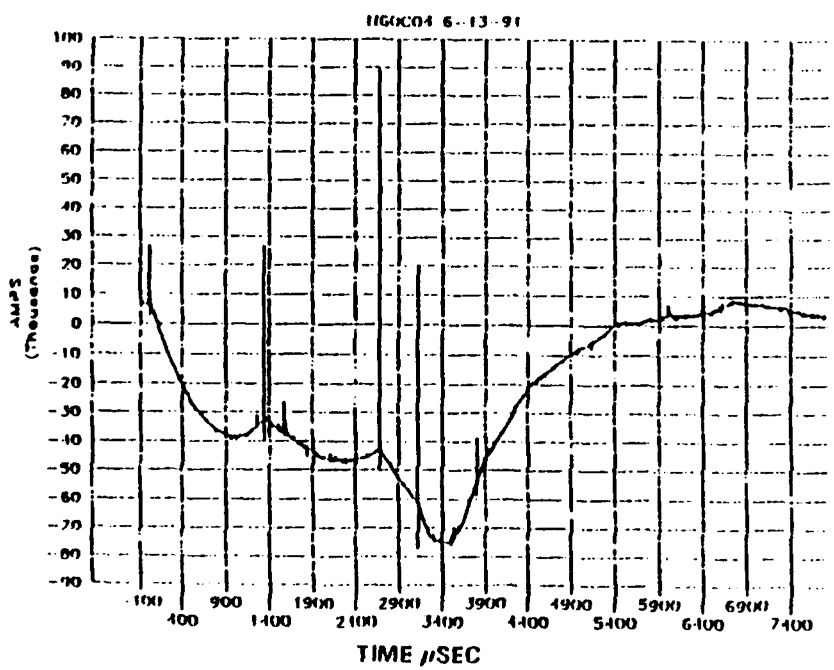
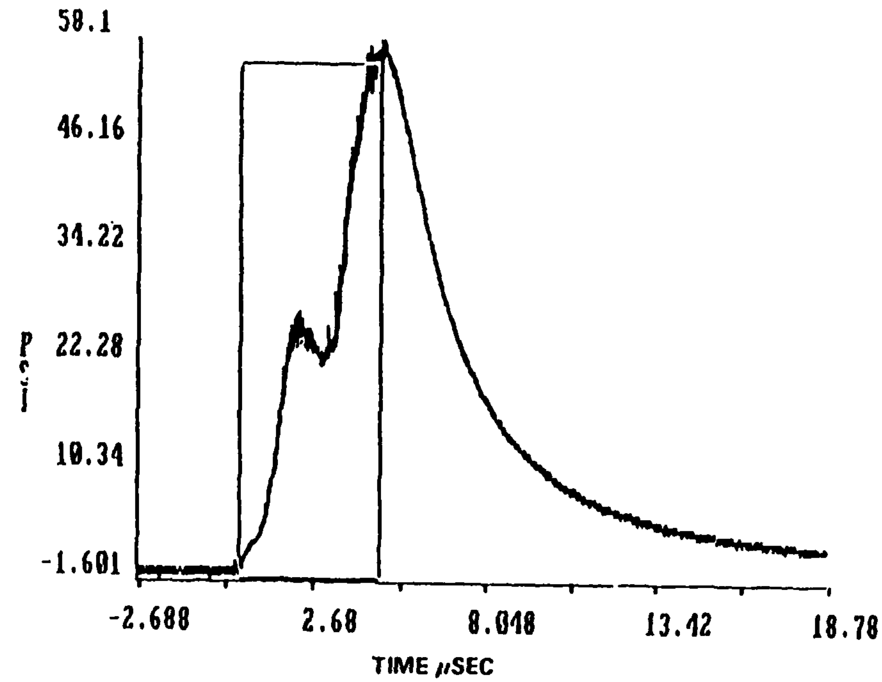
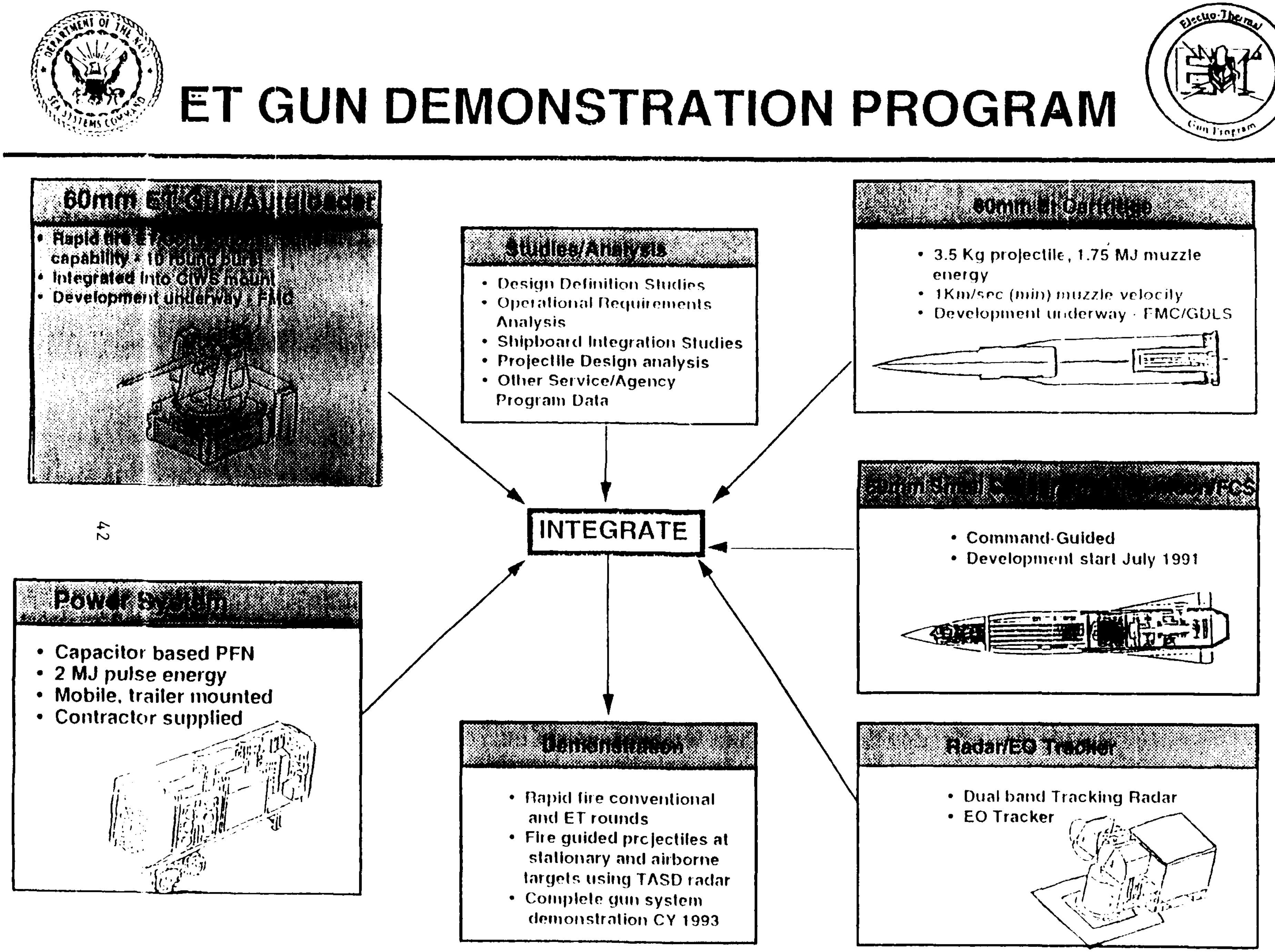
BREECH CURRENT






ET GUN DEMONSTRATION PROGRAM
60mm ET Gun/Autoloader
Integrated into CIWS mount
Development underway - FMC
Studies/Analysis
• Design Definition Studies
• Operational Requirements Analysis
• Shipboard Integration Studies
• Projectile Design analysis
• Other Service/Agency Program Data
• 3.5 Kg projectile, 1.75 MJ muzzle energy
• 1Km/sec (min) muzzle velocity
• Development underway - FMC/GDLS
INTEGRATE
• Command-Guided
• Development start July 1991
Power System
• Capacitor based PFN
• 2 MJ pulse energy
• Mobile, trailer mounted
• Contractor supplied
• Rapid fire conventional and ET rounds
• Fire guided projectiles at stationary and airborne targets using TASD radar
• Complete gun system demonstration CY 1993
Radar/EO Tracker
• Dual band Tracking Radar
• EO Tracker

ET GUN/AUTOLOADER DEVELOPMENT

Program Description

- Design and Fabrication 60 mm, rapid fire gun and autoloader
- Preliminary testing - single fire and rapid fire
- Integrate with PHALANX mount and leased power supply
- Final integration and ET Gun System testing at NAVSWC

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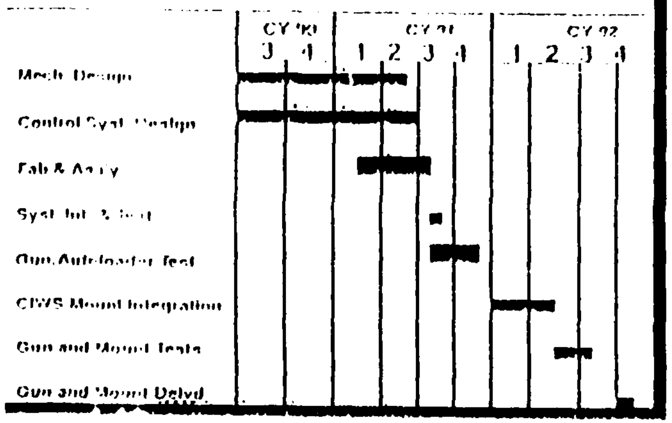
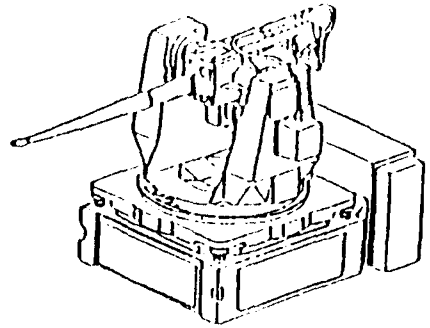
Program Schedule





Program Objectives

- Demonstrate applicability of electrothermal technology in Navy Gun system
- Meet Gun Specifications:
  - 60 mm
  - 10 round burst
  - High rate-of-fire
  - Train ± 45°
  - Elevation - 5° to +30°
  - 61,00 PSI service pressure
  - Pass 2.0 MJ electrical pulse through breech
  - Fire both ET and conventional rounds

Program Status 6/18/91

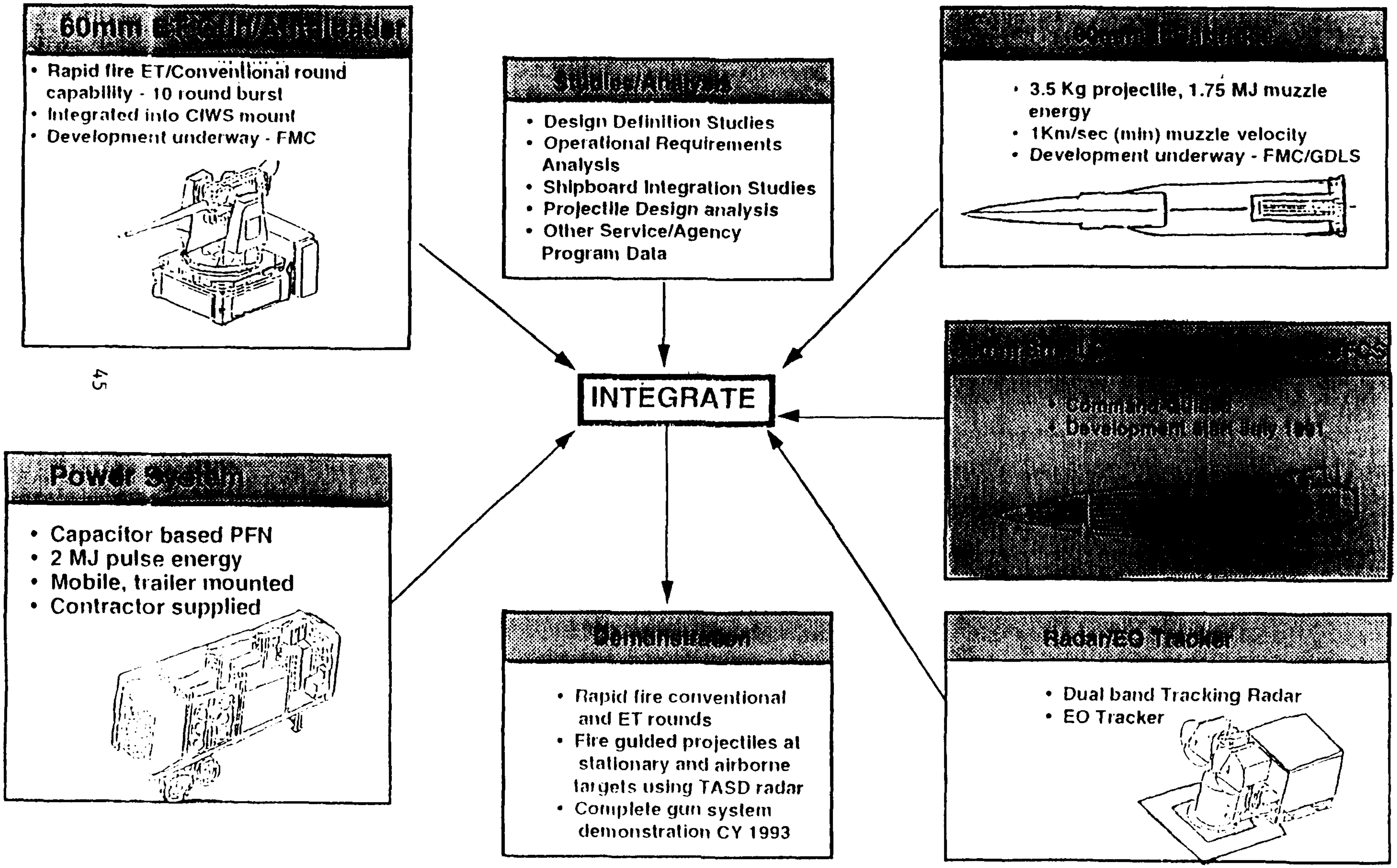
- Detail Design 100% Complete
- Component Fab 55% Complete
- Assembly starts 1 July 91
- Safety Analysis 65% Complete

GUN MOUNT TESTING STATUS

DESIGN EVALUATION TESTS IN PROGRESS AT FMC

- BREECH PROOF TESTS
  15% OVER MAX SERVICE PRESSURE
  FIRST FIVE WK 8 JUL
- POWER XFER TESTS
  TEST FIXTURE - SIM ET CARTRIDGES/LOADBANK
  2MJ/2 SHOTS
  BEGIN WK 10 JUN
- AUTOLOADER TEST
  CYCLING CAPABILITY DEMO/SIM ET CARTRIDGES
  SKED MID AUGUST
- RAPID FIRE CONVENTIONAL ROUNDS
  10 ROUND BURST
  SKED OCTOBER
- RAPID FIRE ET ROUNDS
  2-3 ROUND BURST
  SKED DECEMBER

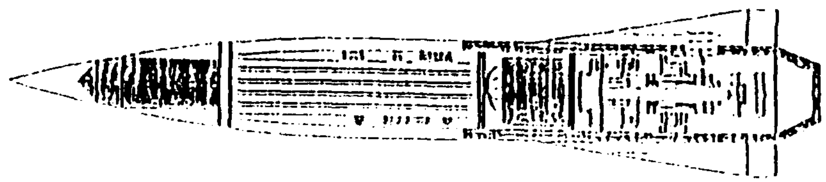
ET GUN DEMONSTRATION PROGRAM



60mm SCSM DEVELOPMENT

Program Description

- Design and Fabricate Proof of Principle 60mm Command Guided Projectile
- Design and Fabricate Associated Fire Control System and Comm Link
- Integrate and Test with 60mm Gun Mount and RF/EO Sensor
- System Demonstration with Subsonic, Maneuvering Target
- Trade Studies/System Effectiveness Analyses



Program Schedule

TASK	CY 90 3	CY 90 4	CY 91 1	CY 91 2	CY 91 3	CY 91 4	CY 92 1	CY 92 2	CY 92 3	CY 92 4	CY93 1	CY93 2	CY93 3	CY93 4
Contract Award				▲										
Prelim Design/Study				■	■	■	■	■						
Proj/FCS/Comm Fab/Assy								■	■	■	■	■		
System Int and Test									■	■	■	■	■	
System Demo														■

Projectile Specifications

- 3.5 Kg Max Projectile Weight
- 1.2 Km/sec Minimum Muzzle Velocity
- 40g Maneuver at Mach 3
- 25-30 Kg Setback Acceleration
- Acquired by Tracker 200-500 mtrs

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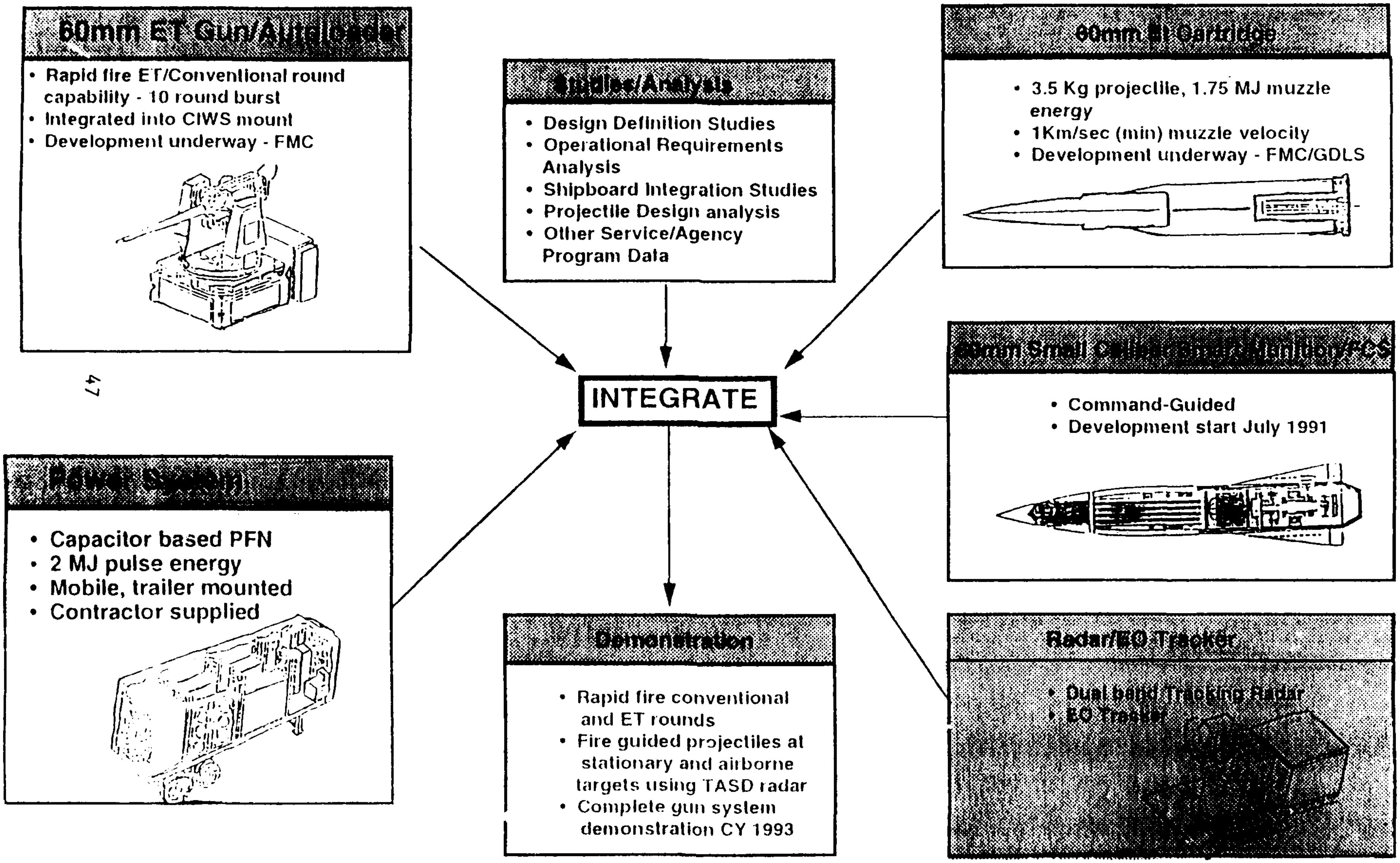
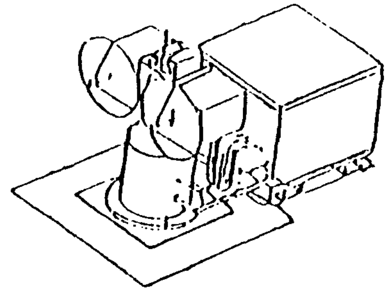
ET GUN DEMONSTRATION PROGRAM



RF/EO SENSOR INTEGRATION



Program Purpose

Demonstrate feasibility of precision differential tracking accuracy required to support small caliber command guided projectiles

Program Objectives

- In Sea Cutter, Multipath Environment Demonstrate:
  - Tgt Detection/Acquisition/Tracking
  - Projectile Acquisition/Tracking
  - Sensitivity to Tgts and 60mm Projectile at 1-3 Km
  - Differential Track Angles Accuracies with Incoming Tgt/Outgoing Projectile

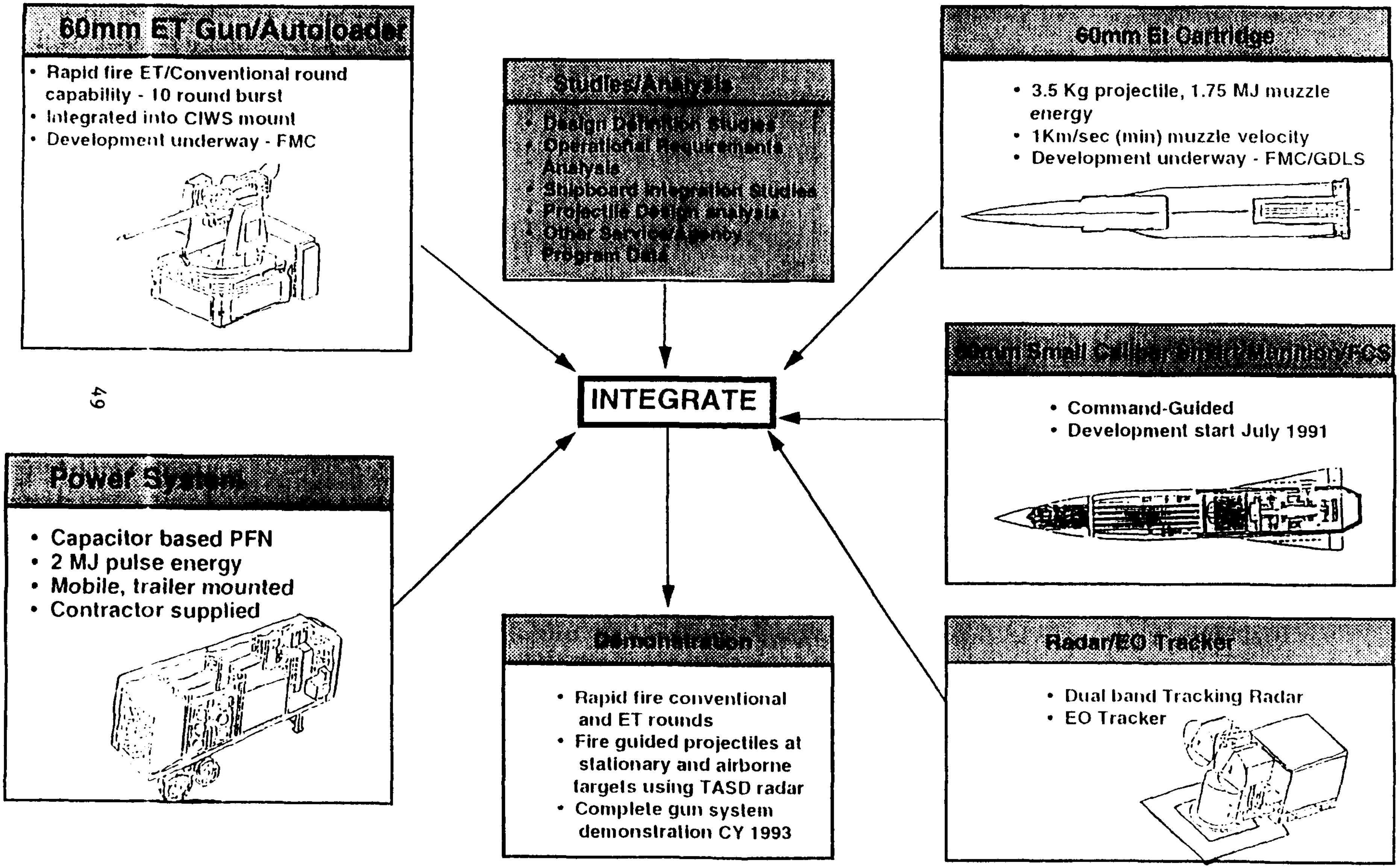
Program Description

- Evaluate Tracking Accuracy of Candidate RF/EO Systems
- Modify Selected System to support Demo System
- Integrate with 60mm Gun and Associated FCS
- Demonstrate Capability with ETG System Using Live, Subsonic Tgt in Multipath Environment

Status

- TASD Tests Delayed
- 60mm PROJ/EO Acquisition Test Completed
- Static EO Imaging Tests Complete
- Dynamic/Stationary EO Imaging Tests Ongoing
- Dual Target(Dynamic) Imaging Tests - July

ET GUN DEMONSTRATION PROGRAM



DESIGN DEFINITIONS STUDIES/ TESTS STATUS

SELF DEFENSE STUDY
- ON GOING AT NSWC
- PRELIMINARY RESULTS AVAILABLE

PROJECTILE DESIGN ANALYSIS
- SCSM CONTRACT TASK

VULNERABILITY/LETHALITY TESTING
- 5" FRAG TESTS WK 3 JUN - ANALYSIS IN PROGRESS
- 60mm PENETRATOR TESTS WK 15 JUL

SHIPBOARD INTEGRATION STUDY
- ONGOING AT DTRC

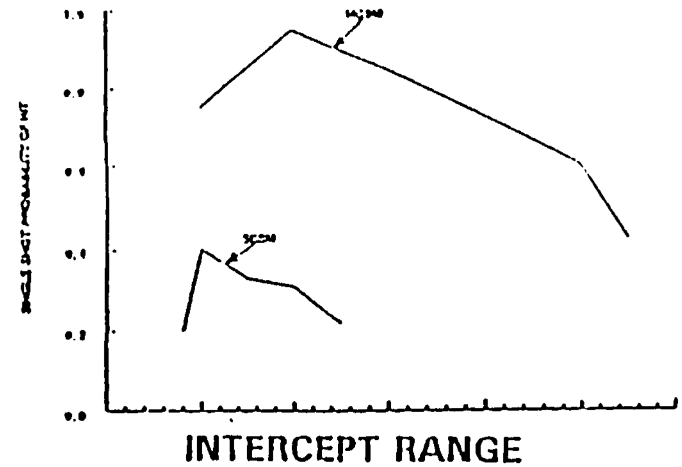
NSWC SELF DEFENSE STUDY
BASELINE SMART MUNITION CONCEPTS

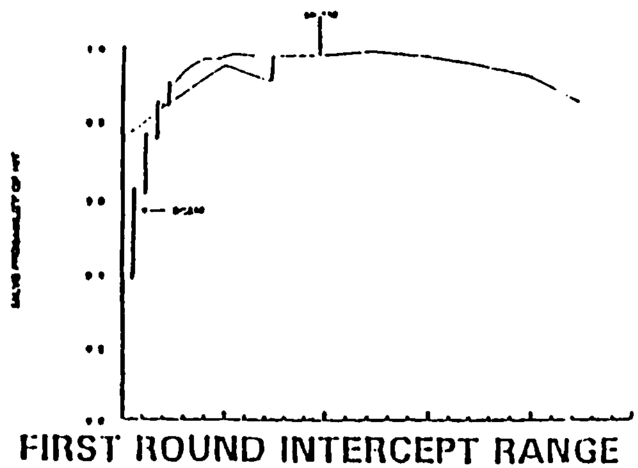
TGT: ASCM LOW/FAST/MANEUVERING
SMART MUNITION GUIDANCE-COMMAND-ALL-THE-WAY

SMALL CALIBER SMART MUNITION (SCSM)- 60MM/ET
- GUNWPN SYS DYNAMICS - SAME AS CIWS BLK II
  - TRACKER ACCURACY - 100μrad
  - FIRING RATE-1rd/.25 SEC
  - MAX RDS/ENGAGEMENT- 10
  - SYSTEM TIE UP/ENGAGEMENT- 2.1 - 4.1 SEC
  - P_{kh} = 1 IF HIT ≤ 0.2 METER
  - BLOCK SPEED = 1 KM/SEC

MEDIUM CALIBER SMART MUNITION (MSCM) - 5 IN/RAP
- GUN WPN SYS DYNAMICS- SAME AS MK 45 MOD 1
  - TRACKER ACCURACY - 400prad
  - FIRING RATE - 11 RDS/MIN
  - MAX RDS/ENGAGEMENT - 2
  - SYSTEM TIE UP/ENGAGEMENT - 3.5 - 10.8 SEC
  - P_{kh} = 1 IF HIT ≤ 2 METERS
  - BLOCK SPEED = 0.5 - 0.8 KM/SEC

(NOT SHOWN)
MEDIUM CALIBUR SMART MUNITION (MCSM/T) - 5 IN/ET
- BLOCK SPEED = 1.2 KM/SEC



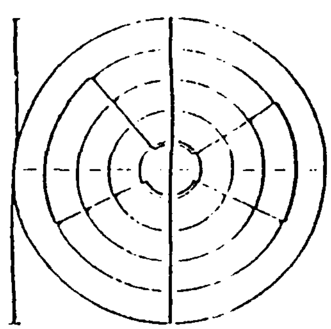


NSWC SELF DEFENSE STUDY VALUE ADDED ANALYSIS

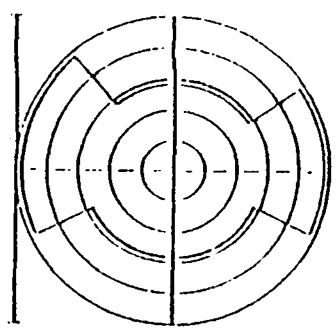
SCENARIO
- SINGLE SHIP - DDG-51
- STREAM OF TGTS - VARIOUS RAID SIZE/SPACING
- FIRM TRACK RANGE - 10KM (6NM)

MOE - PROBABILITY OF KILLING ALL TGTS BY 1KM

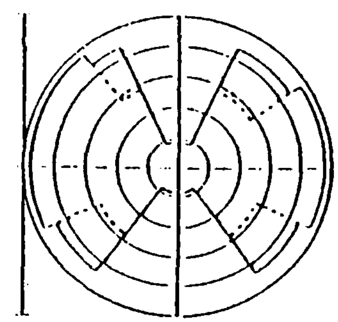
CONFIGURATIONS
- 2 CIWS BLK II (BASELINE)
- 2 SCSM REPLACE CIWS
  KEEPOUT RANGE
- 1 SCSM + 2 CIWS LAYER DEFENSE
- 1 MCSM + 2 CIWS LAYER DEFENSE



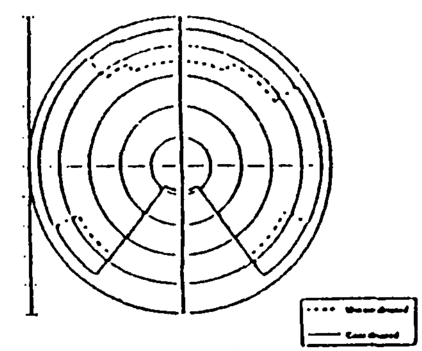
CIWS ONLY



SCSM REPLACE CIWS



SCSM + CIWS

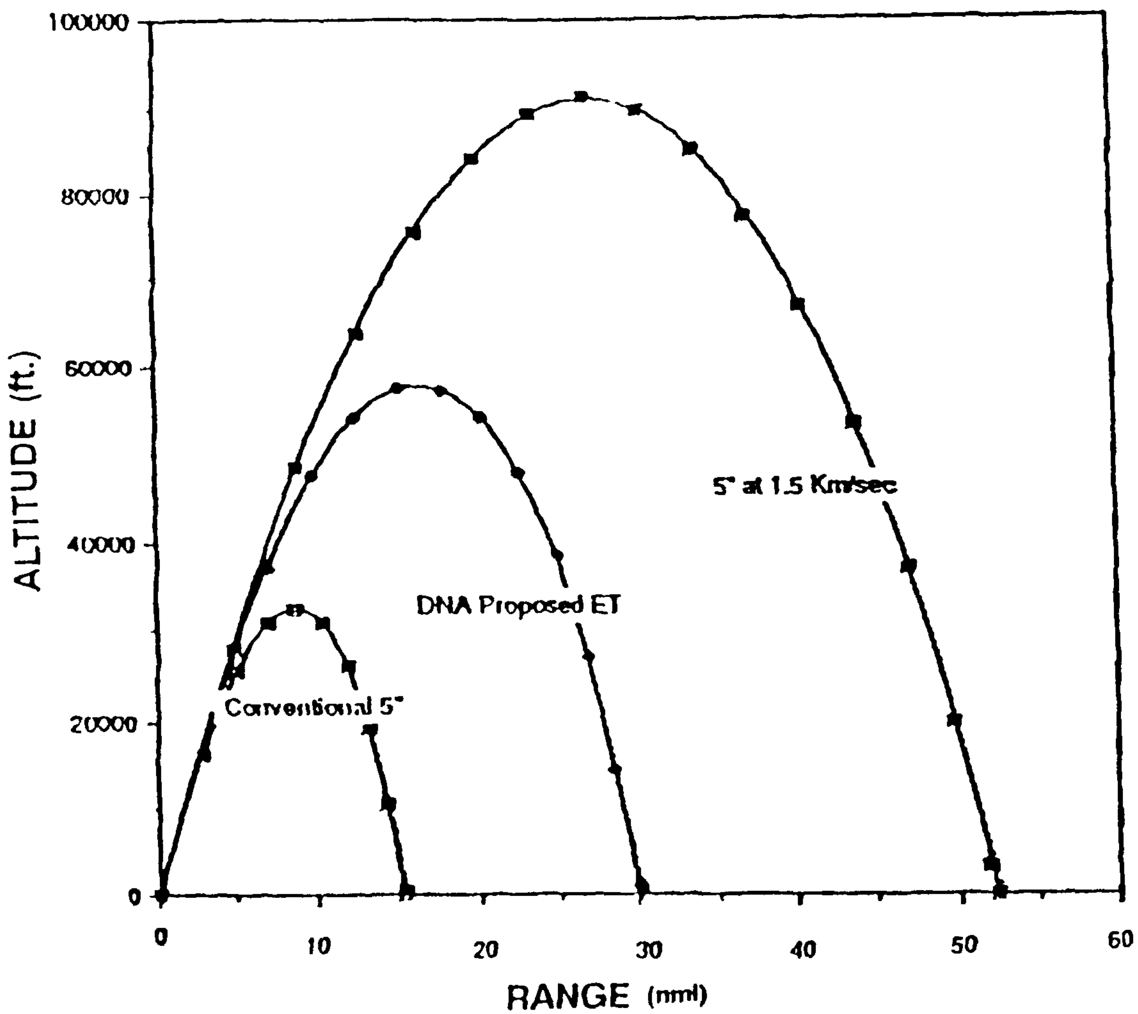


MCSM + CIWS

IDENTIFY PARAMETRIC TRADEOFFS
- FIRING RATE
- PROJECTILE VELOCITY
- ENGAGEMENT RANGE
- TRACKER ACCURACY
- KILL PROBABILITY
- OTHER

OTHER POTENTIAL SENSITIVITIES
- FIRM TRACK RANGE
- KILL ASSESSMENT DELAY
- MINIMUM RANGE
- OTHER

PROJECTED PERFORMANCE 5"/54 GUN SYSTEM



CONV HI FRAG PROJ
CONV WT 70 lbs (32 Kg)
ET WT 51 lbs (23 Kg)

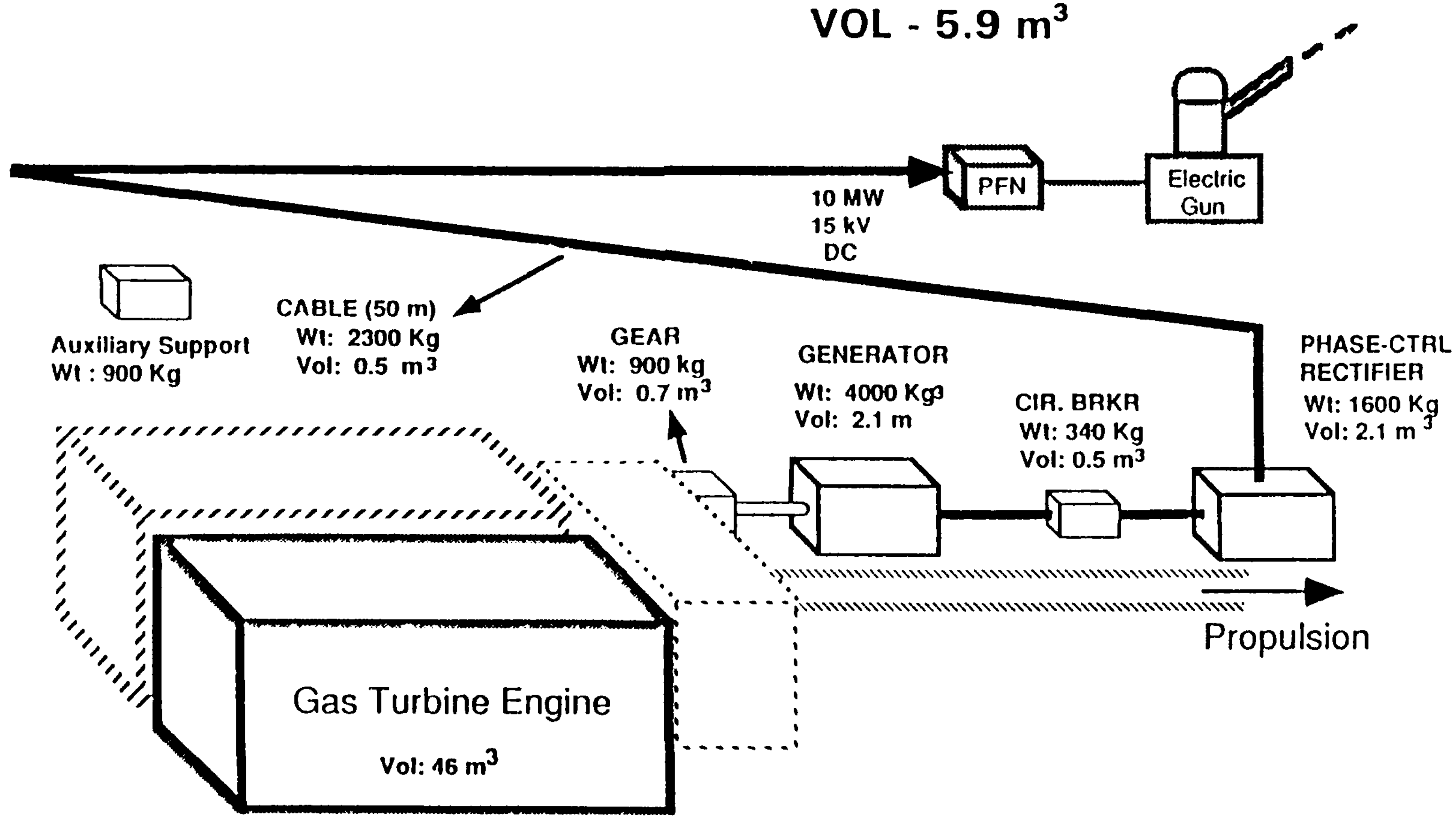
10-30% ADDITIONAL RANGE W/GUIDED ROUNDS

SHIP INTEGRATION OF PULSED POWER

- EVALUATE COMPONENT SIZING: 4, 10, AND 20 MW SYSTEMS
  - CIWS APPLICATION — 2MJ PER PULSE STORED
10 SHOT BURST @ REP-RATE
  - 5" GUN APPLICATION — 12MJ PER PULSE STORED
20 RNDS/MIN CONTINUOUS
5 SHOT BURST @ 40 RNDS/MIN (ONE TIME)
  - PRELIMINARY ARRANGEMENT PLANS DDG-51, DD 963, CVN, LSD/LHD
  - ROTATING MACHINE ALTERNATIVES
- INVESTIGATE AUXILIARY SYSTEM IMPACTS
  - ARRANGEMENTS/COMPONENT COOLING SYSTEMS
  - CONTROL SYSTEMS LAYOUT
  - 15 KVDC DISTRIBUTION
- IDENTIFY CRITICAL COMPONENT TECHNOLOGIES

PULSED POWER SYSTEM CONFIGURATION FOR MECHANICAL DRIVE WITH AUXILIARY GENERATOR

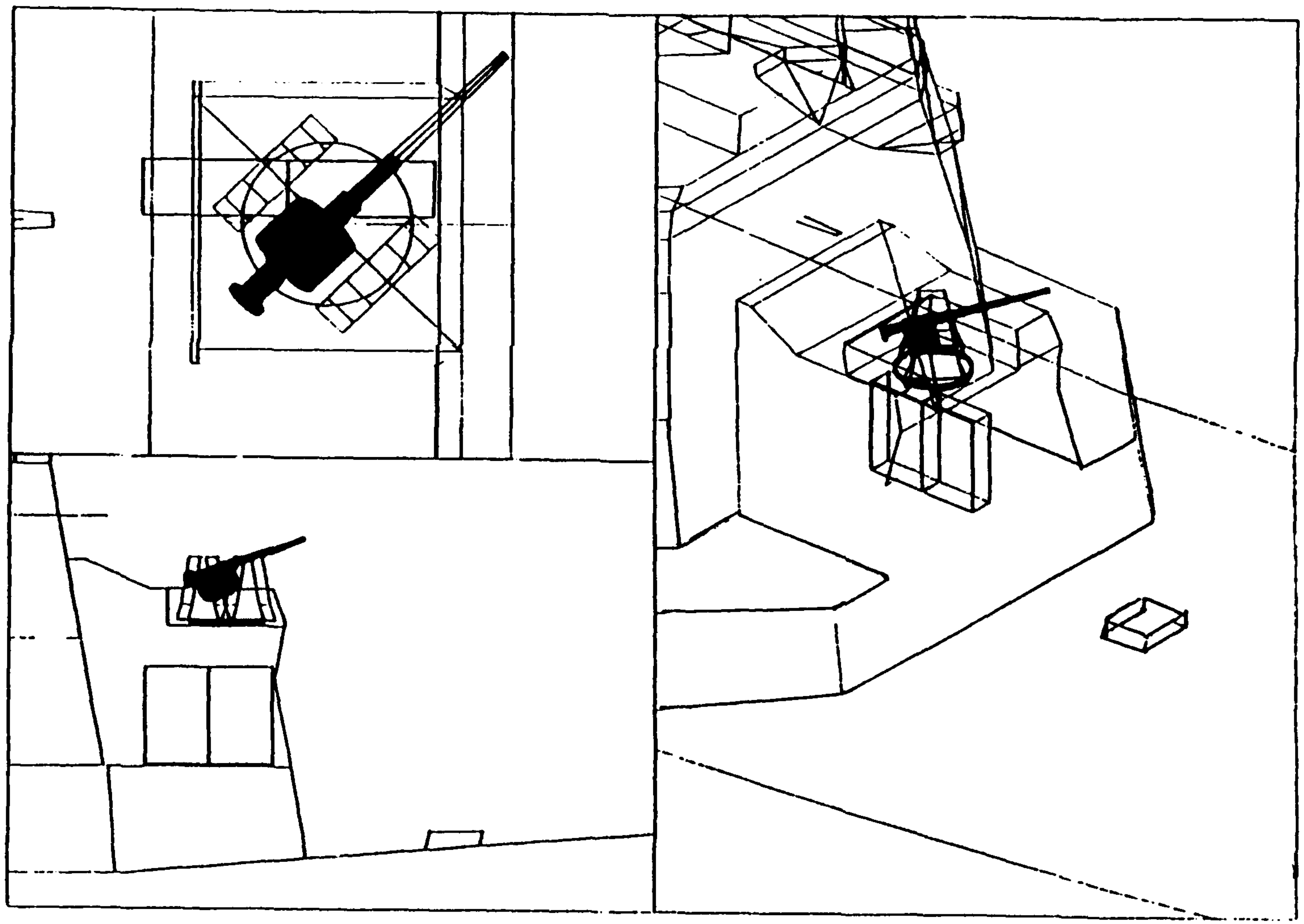
10 MW SYSTEM TOTALS: WT - 10,000 KG
VOL - 5.9 m^3



NOTE: Components drawn to scale

1000 kg ≈ 1 LT

ELECTRIC ARMAMENTS PROGRAM
U.S. NAVY

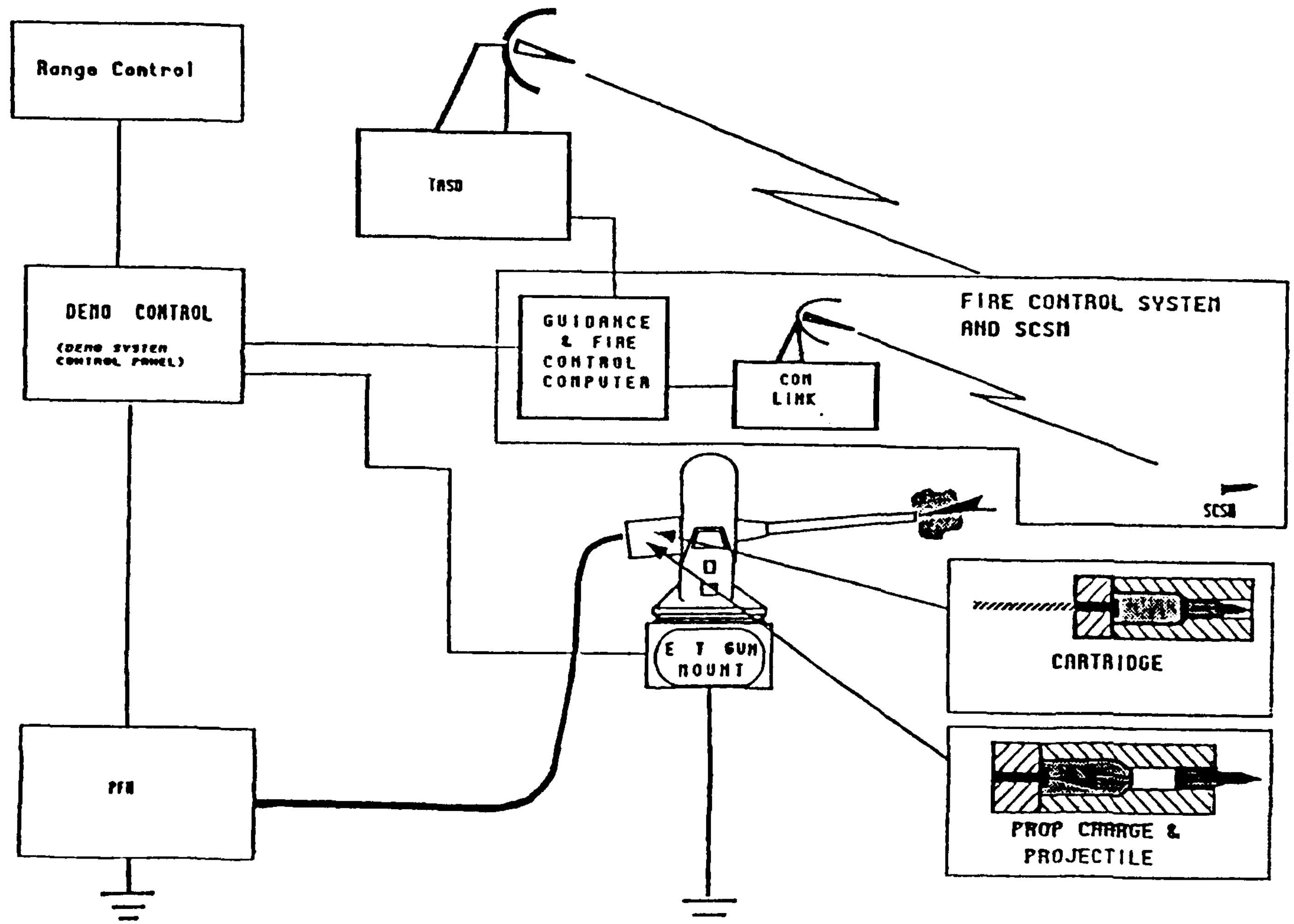


ELECTRIC ARMAMENTS PROGRAM
U.S. NAVY

FROM DATA DEVELOPED THUS FAR:

- DDG 51 FIRST ORDER SHIP INTEGRATION ASSESSMENT
  - REPLACE 2 CIWS W/ ET GUN AND ASSOCIATED PULSE POWER SYSTEM
  - DISPLACEMENT INCREASE 37 LT
  - STABILITY CHANGE (KG) +0.03 FT
- TURBINE-DRIVEN AUXILIARY GENERATORS APPEAR TO BE THE PREFERRED METHOD OF POWERING ELECTRIC GUN PFNs FROM SHIP PROPULSION EQUIPMENT
  - COMPACT OVER WIDE POWER RANGE
  - EQUALLY ATTRACTIVE WITH EITHER ELECTRICAL OR MECHANICAL DRIVES
  - RETROFIT POTENTIAL INTO THE PRESENT FLEET
- HIGH FREQUENCY GENERATORS ALLOW FOR LIGHTWEIGHT POWER CONDITIONING EQUIPMENT FOR ALL PULSED POWER LOADS
- HIGH VOLTAGE DC TRANSMISSION PROVIDES DRAMATIC SAVINGS IN SYSTEM SIZE & WEIGHT AS WELL AS ENHANCING PLATFORM STABILITY

ETG DEMONSTRATION SYSTEM ARCHITECTURE



TRANSITION POTENTIAL

- CIWS BLOCK II UPGRADE
  - POTENTIAL UPGUN CANDIDATE
- 76mm AAW UPGRADE
  - OTO MELARA COURSE CORRECTED SHELL
- LARGE CALIBER
  - ADVANCED GUN WEAPON SYSTEMS TECHNOLOGY PE0603795N
    - FIRE SUPPORT GUIDED ROUND
    - AAW GUIDED ROUND
  - DNA EFFORT

CONCLUSIONS

- NEED TO BRING GUN TECHNOLOGY INTO 21st CENTURY
  - ADVANCED GUN PROPULSION
  - GUIDED PROJECTILES
- ETC TECHNOLOGY SHOWS PROMISE FOR MEETING NEAR TERM REQUIREMENTS
  - AAW
  - ASUW
  - FIRE SUPPORT/STRIKE
- GROWTH POTENTIAL TO ACCOMMODATE THREAT
- POWER REQUIREMENT WITHIN NEAR TERM CAPABILITY
- STABLE FUNDING/NAVY COMMITMENT NEEDED

U.S.ARMY
STRATEGIC DEFENSE COMMAND

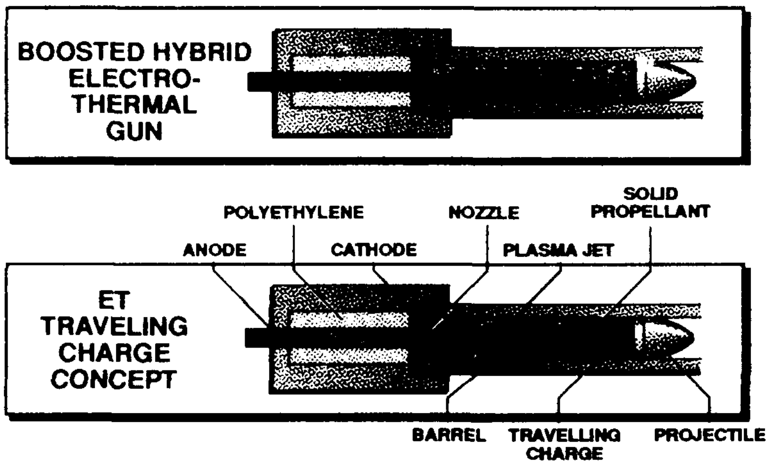
M-910311-21U (1070)

ELECTROTHERMAL (ET) GUN PROGRAM

ET GUN TECHNOLOGY PROGRAM OVERVIEW

M-910214-91U (C) (1189)

ET ACCELERATION CONCEPTS



DESCRIPTION/TECHNICAL APPROACH

- PLASMA - BOOSTED HYBRID GUN: INJECT HIGH ENERGY PLASMA JETS INTO PROPELLANT CHARGE TO INCREASE THE BURNING RATE AND EXTEND THE PRESSURE PROFILE
- TRAVELING CHARGE CONCEPT: AFTER PLASMA IGNITION OF PRIMARY PROPELLANT CHARGE, IGNITE SECOND PROPELLANT CHARGE (TRAVELING CHARGE) AT PROJECTILE BASE WITH ET PLASMA JET TO FURTHER BOOST THE PROJECTILE

ADMINISTRATIVE ELEMENTS

- PERFORMER: ISRAEL'S SOREQ NUCLEAR RESEARCH CENTER
- SDIO CONTRACT #84-89-C-0017
  - COVERED UNDER BROAD SDI MOU/ NO SEPARATE MOA
  - COST: $2.88M/80 - 20 GOI COST SHARE
  - POP: 3/89 - 6/92
  - SEPARATELY FUNDED CONTRACT TASKS
    - FRG - $3M - 2 1/2 YEARS
    - BRL: $1M - 1 1/2 YEARS

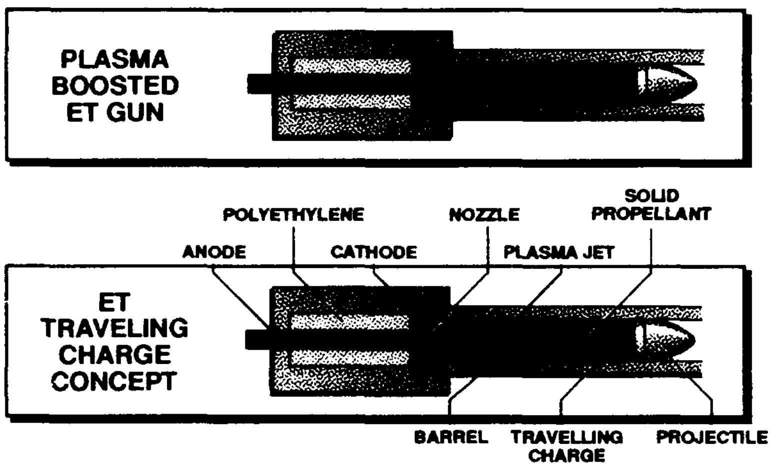
CONTRIBUTION/PAYOFF

- BASIS FOR POTENTIAL LOW COST ATM POINT DEFENSE SYSTEM
- POTENTIAL FOR PROGRAM "SPILLOVER" TO OTHER APPLICATIONS
  - ANTI-ARMOR
  - LONG RANGE FIRE SUPPORT

ET GUN TECHNOLOGY PROGRAM OVERVIEW

M-910206-29U-B (C) (1132)

ET ACCELERATION CONCEPTS



CRITICAL ISSUES

- DESIGN AND FABRICATION OF RELIABLE ET INJECTORS AT REQUIRED ENERGIES
  - SCALE UP 3 - 4X REQUIRED FOR 2 -3 MJ INJECTION ENERGY
  - INJECTOR DETERIORATION FROM HIGH ENERGY
- SCALE UP OF ET PROCESS TO WEAPONIZABLE SIZES

PROGRAM OBJECTIVES

ATBM:
- DEMONSTRATE REQUIRED ATBM LAUNCH MASS/VELOCITY GOALS IN STAGES:
  - 60 mm - 1 Kg AT 2.0 km/sec (INTERMEDIATE)
  - 105 mm - 1 Kg AT 2.5 km/sec (FINAL)
- DESIGN FOLLOW TECH PROGRAM FOR:
  - 3 - 4 Kg AT 2.5 km/sec
  - TRANSPORTABLE POWER

BRL: 60 mm - DEMONSTRATE 25-50% INCREASE IN MUZZLE ENERGY OVER OPTIMIZED BALLISTICS USING STANDARD PROJECTILE

SCHEDULE

	FY89	FY90	FY91	FY92	FY93	FY94	FY95
TC SCALE UP			▲ 3Q91				
TC: 1 Kg 2 km/sec			▲ 4Q91				
HYBRID: 1 Kg 2 km/sec			▲ 3Q91				
CONCEPT DOWNSELECT			▲ 4Q91				
105 mm BARREL TESTED			▲ 3Q91				
FINAL OBJECTIVE: 1 Kg, 2.5 km/sec				▲ 3Q92			
FOLLOW-ON PROGRAM 3 - 4 Kg, 2.5 km/sec TRANSPORTABLE POWER						▲	▲

WHY ET?

M-910304-08U (C) (1143)

- PROVIDE SUBSTANTIAL NEAR TERM (5-10 YEARS) IMPROVEMENT OVER CONVENTIONAL CHEMICAL GUN PERFORMANCE BY COMBINING ELECTRICAL AND CHEMICAL PROPULSION

- ADVANTAGES COMPARED TO ELECTROMAGNETIC
  - LOWER DEVELOPMENT COST
  - SMALLER TECHNOLOGY HURDLES, e.g. PULSE POWER, BARRELS
  - "RETROFIT" OPTION ON EXISTING BARREL STOCK
  - EVOLUTIONARY RATHER THAN REVOLUTIONARY TECHNOLOGY PATH

- PROVIDE FOR A RANGE OF TACTICAL APPLICATIONS

ATBM:	3-4 Kg	– 2.5 km/sec
ANTI-ARMOR:	6 Kg	– 2.2 km/sec
FIRE SUPPORTY:	50 Kg	– 1.3 km/sec

STATUS AND FUTURE OBJECTIVES

M-910416-66U (C) (1106)

OBJECTIVES

- 60mm GUN

PROJECTILE MASS	MUZZLE VELOCITY OBJECTIVE	MUZZLE VELOCITY (ACHIEVED)
0.5 Kg 1.0 Kg	2.5 km/s 2.0 km/s	2.25 km/s 1.83 km/s

- 105mm GUN

FINAL OBJECTIVE: 1.0 Kg AT 2.5 km/s (FY92)

FUTURE SCALE-UP

- 105/ 120mm GUN: 3-4 Kg AT 2.5 km/s (FY95)
- INTEGRATE WITH D-2 LIKE PROTOTYPE PROJECTILE

HIGHLIGHTS OF IPR #8
1 MAR 91

M-910311-20U (C) (1070)

MAIN CONTRACT

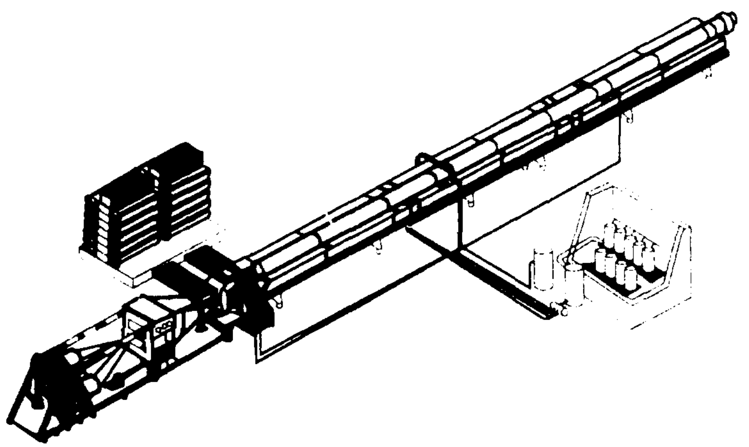
- ADDITIONAL 1.6 MJ ADDED TO PFN (3.6 MJ NOW AVAILABLE)
- INJECTOR OPERATIONAL AT 1 MJ LEVEL
- ADDITIONAL 60mm BARREL ORDERED - EDD LATE MAR 91
  - WILL FACILITATE TRAVELING CHARGE EXPERIMENT LATER IN THE YEAR
- 105mm GUN BARREL
  - GUN CRADLE SUPPORT INSTALLED BY END OF THE MONTH
  - BARREL ALREADY AT SOREQ

BRL TASK

- FINAL DETAILS OF EXPERIMENTAL PROGRAM WORKED OUT
- INITIAL TEST SERIES IN APR 91

HIGH ENERGY RAILGUN INTEGRATION DEMONSTRATION

M-910409-15U (C) (1099)



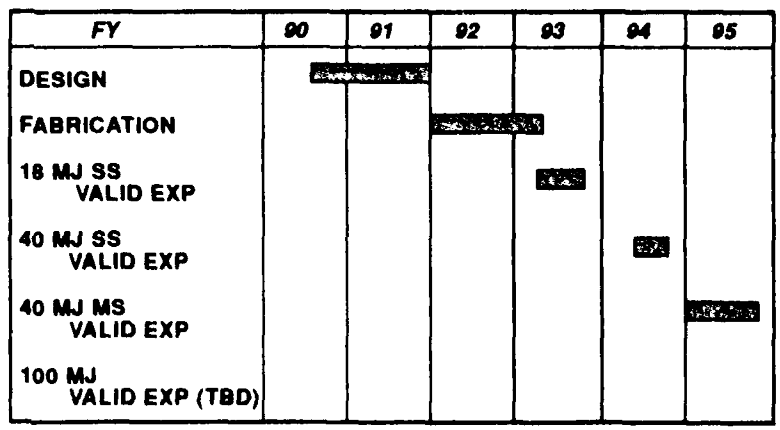
PROGRAM OBJECTIVES

- DEVELOP AN INTEGRATED HIGH ENERGY RAILGUN CAPABLE OF MEETING TERMINAL AND THEATER MISSILE DEFENSE REQUIREMENTS
- DEMONSTRATE 18 MJ SINGLE-SHOT BY 1993
- DEMONSTRATE 40 MJ SINGLE-SHOT BY 1994
- DEMONSTRATE 40 MJ MULTI-SHOT BY 1995
  - 3 SHOT BURST AT 1 Hz
  - D2 PROJECTILE REPLICA

CRITICAL ISSUES

- BARREL SEGMENTATION AND JOINTED RAILS
- THERMAL MANAGEMENT OF RAILS
- RECOIL MANAGEMENT
- LOW INDUCTANCE BREECH
- HIGH CURRENT OPENING SWITCHES
- SWITCH / BREECH / ARMATURE INTERFACE
- D2 INTERFACE

SCHEDULE



PLASMA DISCHARGE IN THE ELECTROTHERMAL GUN

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ABSTRACT

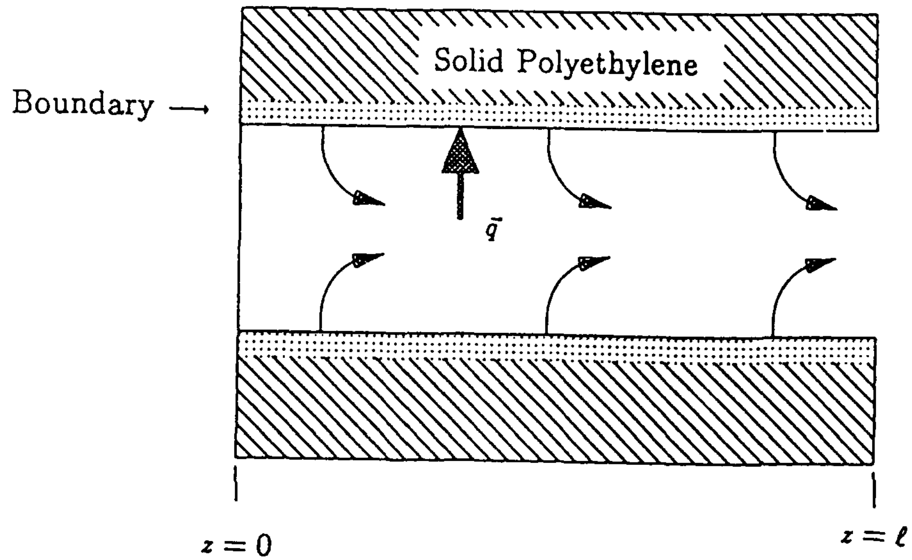
We discuss a simple, one-dimensional, steady-state model for analyzing the properties of the plasma discharge in an ET capillary. The purpose of the calculations is to provide information concerning the plasma which can ultimately be used as input in more general and more comprehensive electrothermal gun models. Assumptions and approximations germane to the calculations, particularly those which lead to a significant simplification of the model, are discussed in some detail. The results of some calculations are then compared with various experimental data and possible causes for discrepancies discussed. Particular emphasis will be devoted to a discussion of recent improvements in the model, as well as to plans and the rationale for future extensions.

Plasma Discharge in the Electrothermal Gun

John D. Powell
Ballistic Research Laboratory

- Objectives
  - Discuss simple model for capillary discharge.
  - Indicate recent improvements.
  - Compare results with some available experimental data.
- Previous and Related Work
  - Kovitya and Lowke
  - Ibrahim
  - Loeb and Kaplan
  - Tidman et al.
  - Gilligan et al.

MODEL



ASSUMPTIONS

- 1D, Axial direction
- Quasi-stationary $\tau_i >> \tau_H$
- Polyethylene arc
- Negligible pinch force
- Choked flow

GOVERNING EQUATIONS

- Mass, Momentum, and Energy Conservation
- Equations of State
  - $P(\rho,T)$
  - $e(\rho,T)$
- Ionization Degree -- Saha
- Electrical Conductivity
  - Electron–neutral collisions
  - Electron–ion collisions
- Energy Transport -- Blackbody to walls
- Ablation Rate -- Mass and energy conservation across boundary for small δ

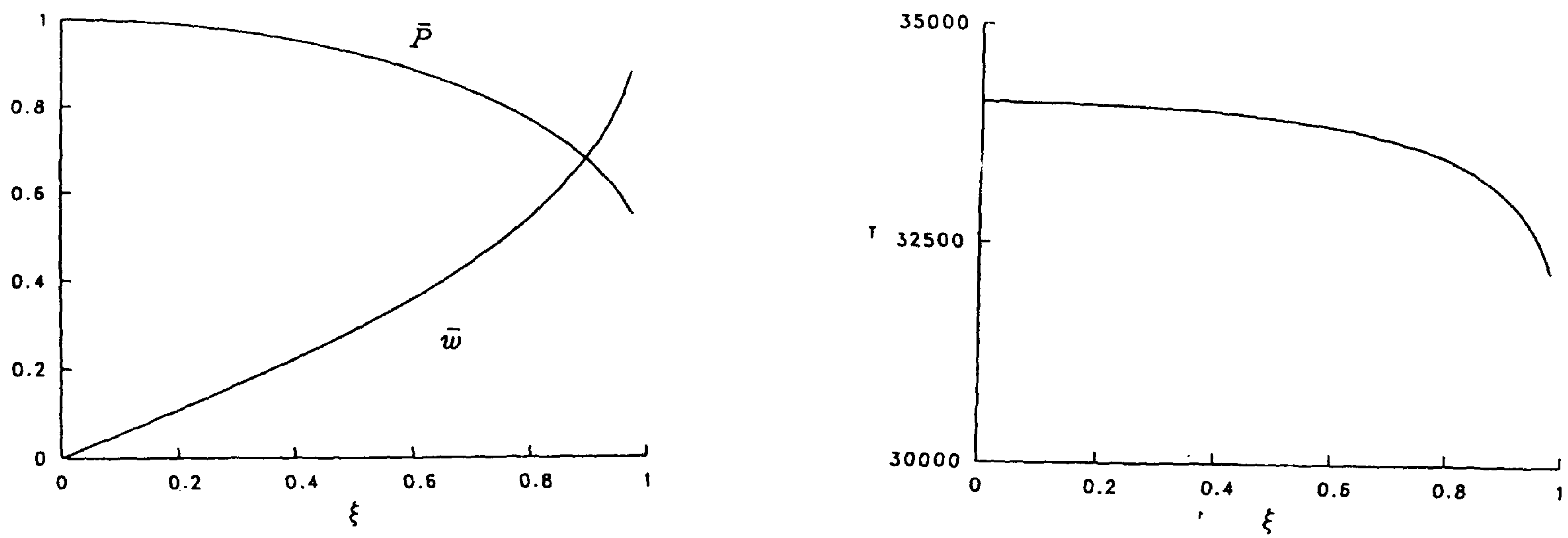
CALCULATIONS

- **General Model**
  - Account for position dependence of all variables.
  - Solve governing equctions point by point iteratively.

- **Isothermal Model**
  - Neglect position dependence of T, σ, and Z.
  - Neglect kinetic energy relative to internal energy.
  - Leads to significant computational simplification.

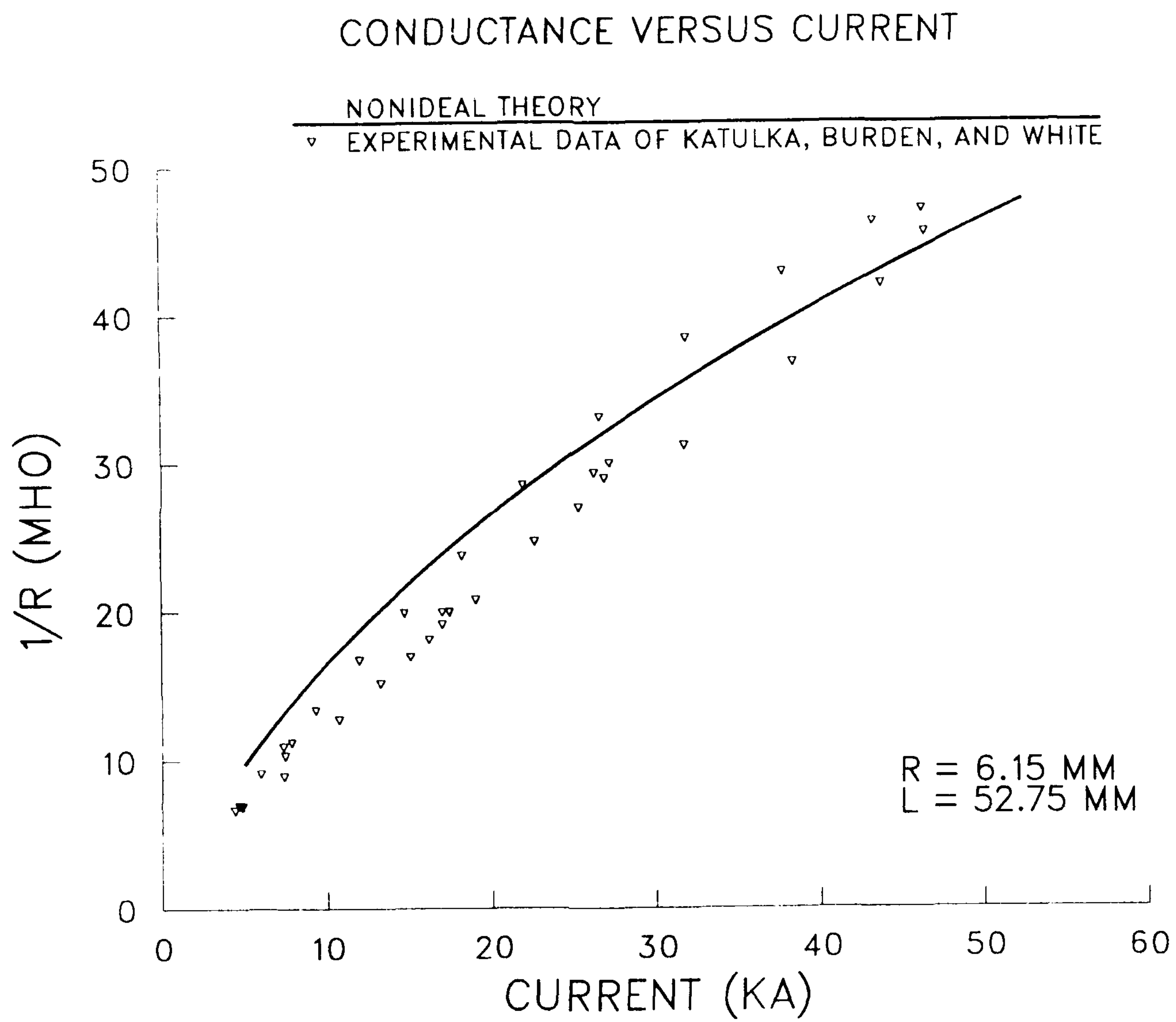
PRESSURE, VELOCITY, AND TEMPERATURE PROFILES
GENERAL MODEL

L = 6.09 cm, r = 3.90 mm, i = 58.6 kA



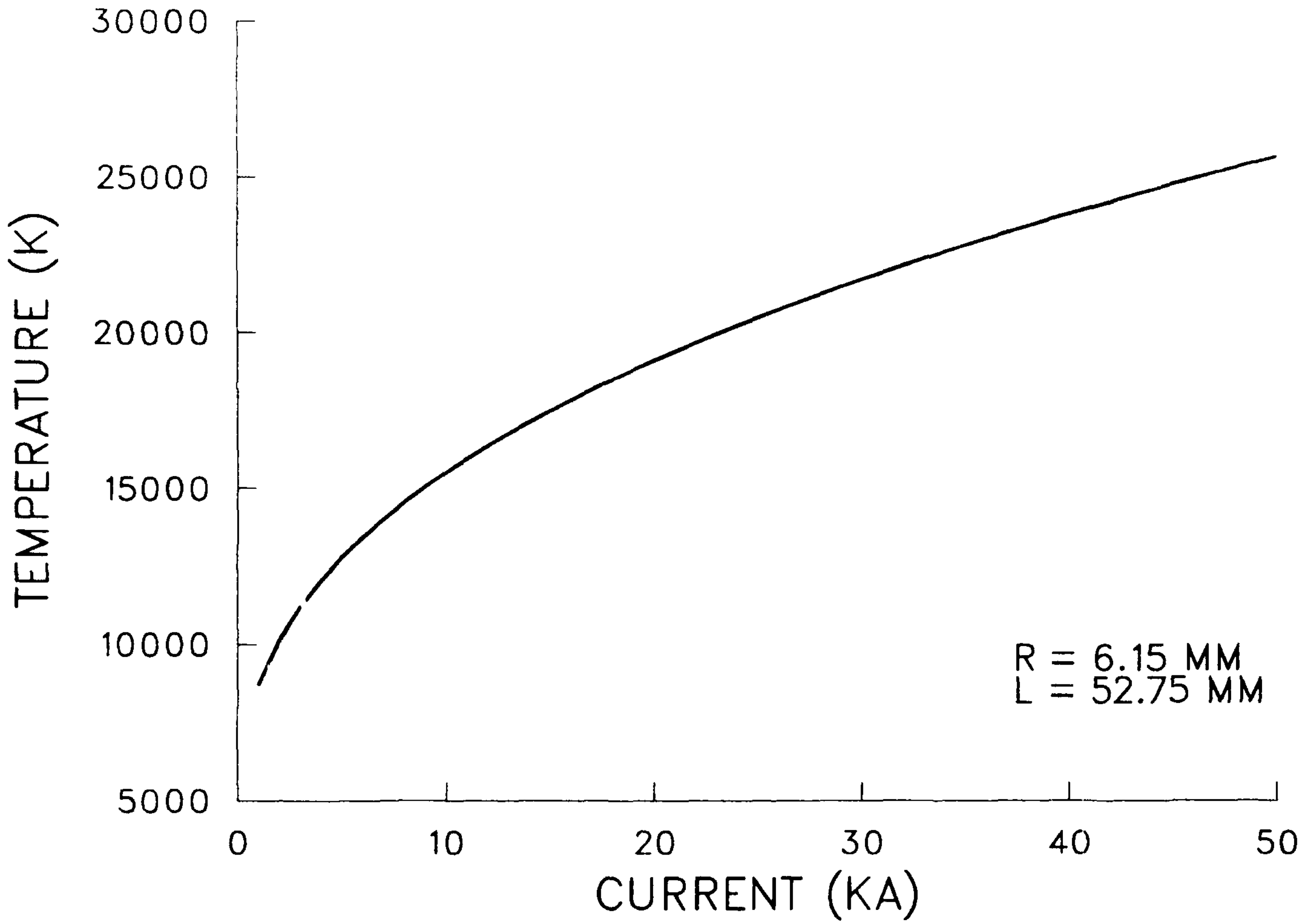
NONIDEAL EFFECTS

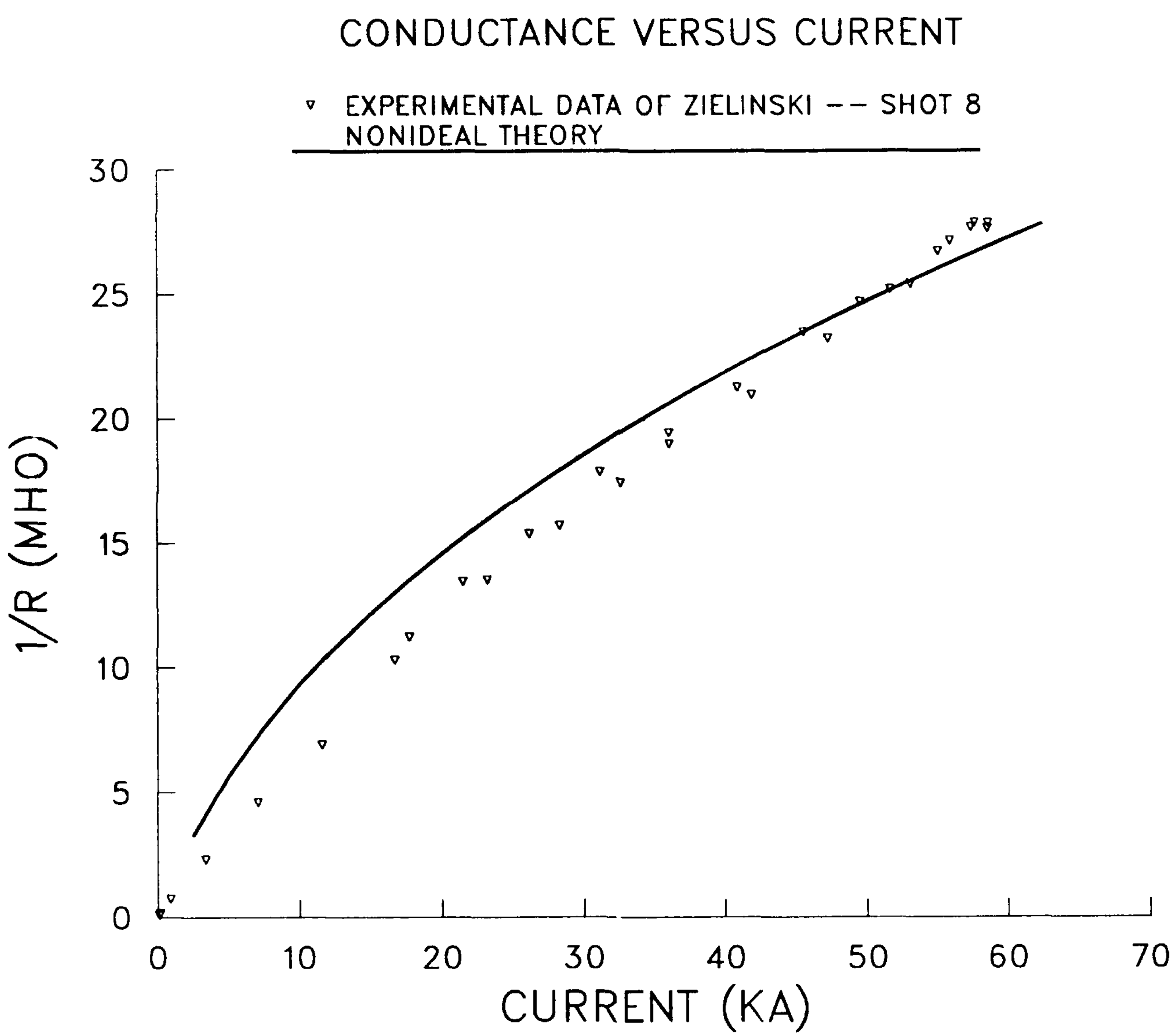
- Cccur for low–temperature, high–density plasmas
- Coulomb interactions lead to:
  - Lowering of effective ionization potential
  - Pressure reduction
  - Contribution to internal energy
- Short–range interactions decrease electrical conductivity.



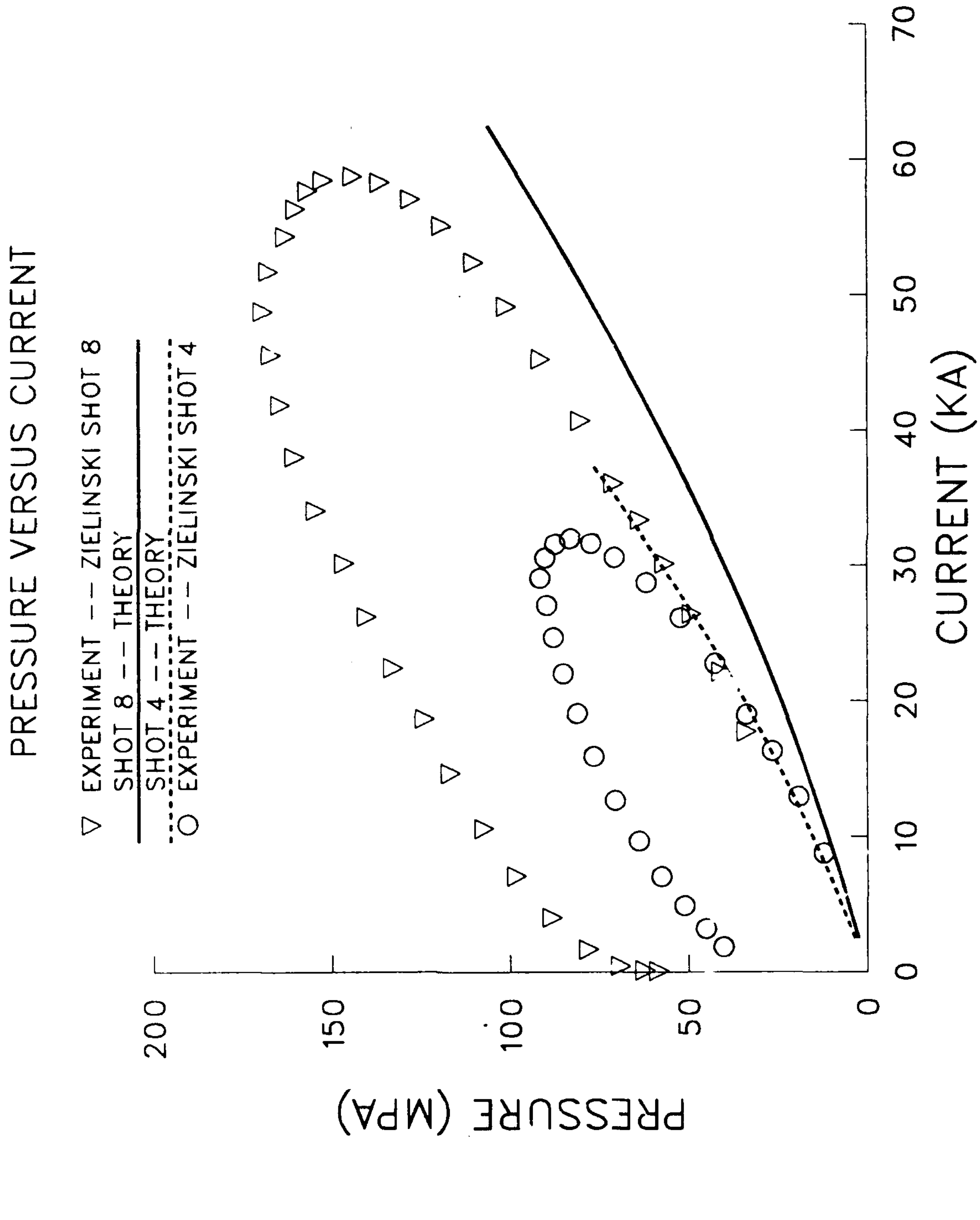
CONDUCTANCE VERSUS CURRENT
NONIDEAL THEORY
EXPERIMENTAL DATA OF KATULKA, BURDEN, AND WHITE
1/R (MHO)
CURRENT (KA)
R = 6.15 MM
L = 52.75 MM
0
10
20
30
40
50
60

TEMPERATURE VERSUS CURRENT





CONDUCTANCE VERSUS CURRENT
EXPERIMENTAL DATA OF ZIELINSKI -- SHOT 8
NONIDEAL THEORY
1/R (MHO)
0
5
10
15
20
25
30
CURRENT (KA)
0
10
20
30
40
50
60
70


PRESSURE VERSUS CURRENT
▽ EXPERIMENT -- ZIELINSKI SHOT 8
SHOT 8 -- THEORY
SHOT 4 -- THEORY
○ EXPERIMENT -- ZIELINSKI SHOT 4
PRESSURE (MPA)
0
50
100
150
200
CURRENT (KA)
0
10
20
30
40
50
60
70

POSSIBLE EXPLANATIONS AND MODIFICATIONS TO MODEL

- Flow becomes unchoked -- include coupling
- Boundary layer changes on large time scale -- investigate time-dependent, two-zone model
- Plasma composition changes -- include electrode behavior

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DIAGNOSTICS AND MODELING OF AN ELECTROTHERMAL PLASMA SOURCE EXPERIMENT (SIRENS)

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ABSTRACT

The electrothermal gun SIRENS was designed to explore plasma-surface interaction phenomena and has had over 250 successful shots over a three year period. Current diagnostic techniques include discharge current and potential measurements, erosion depth measurements of the different components (discharge cathode, source insulator, barrel and target materials), heat flux measurement (from temperature rise of the target), emission optical spectroscopy (along the axis and from the side), chamber pressure, and average plasma velocity. Additional diagnostics will be added for plasma-fluid interaction measurements to measure the resistance of various capillary configuration with different fluids, potential drop and heat flux along the axial direction, axial velocity distribution, plasma temperature and density, and evaluation of drag forces. This will include a series of thermocouples, B-dot probes, absolute pressure transducers, fiber optics (to Photomultipliers and OMA), He-Ne laser cut off and X-ray radiography.

Modeling within the group has focussed on plasma-surface interaction and source plasma behavior. A 1-D, time dependent MHD code (MAGFIRE) including radiation transport has been developed and used to predict energy transport through a plasma boundary layer. A global, time-dependent code (ZEUS) which includes non-ideal plasma effects has been developed and successfully used to predict plasma conditions in the electrothermal plasma source as temperature, pressure and erosion rate of the insulator. A 1-D version of ZEUS will be needed for future large devices where pressure and combustion oscillations and coupling with the combustion chamber will become important. A model and code for plasma-liquid interaction is currently under development at the droplet interface level that will emphasize the role of radiation transport in predicting propellant combustion rates. This model should become a part of a larger combustion chamber model that includes cavity formation, droplet formation, combustion processes and momentum transfer.

JANNAF Workshop on Electrothermal Chemical Modeling and Diagnostics

July 9 - 11, 1991

U.S. Army Ballistic Research Laboratory, Aberdeen, MD

DIAGNOSTICS AND MODELING OF AN ELECTROTHERMAL PLASMA SOURCE EXPERIMENT (SIRENS)

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Department of Nuclear Engineering, North Carolina State University,

Raleigh, NC 27695-7909

Current Projects

EXPERIMENT

Erosion measurements in high heat flux plasma device--SIRENS

Development of plasma diagnostics (heat flux, tempurature, etc.)

Magnetic vapor shield physics

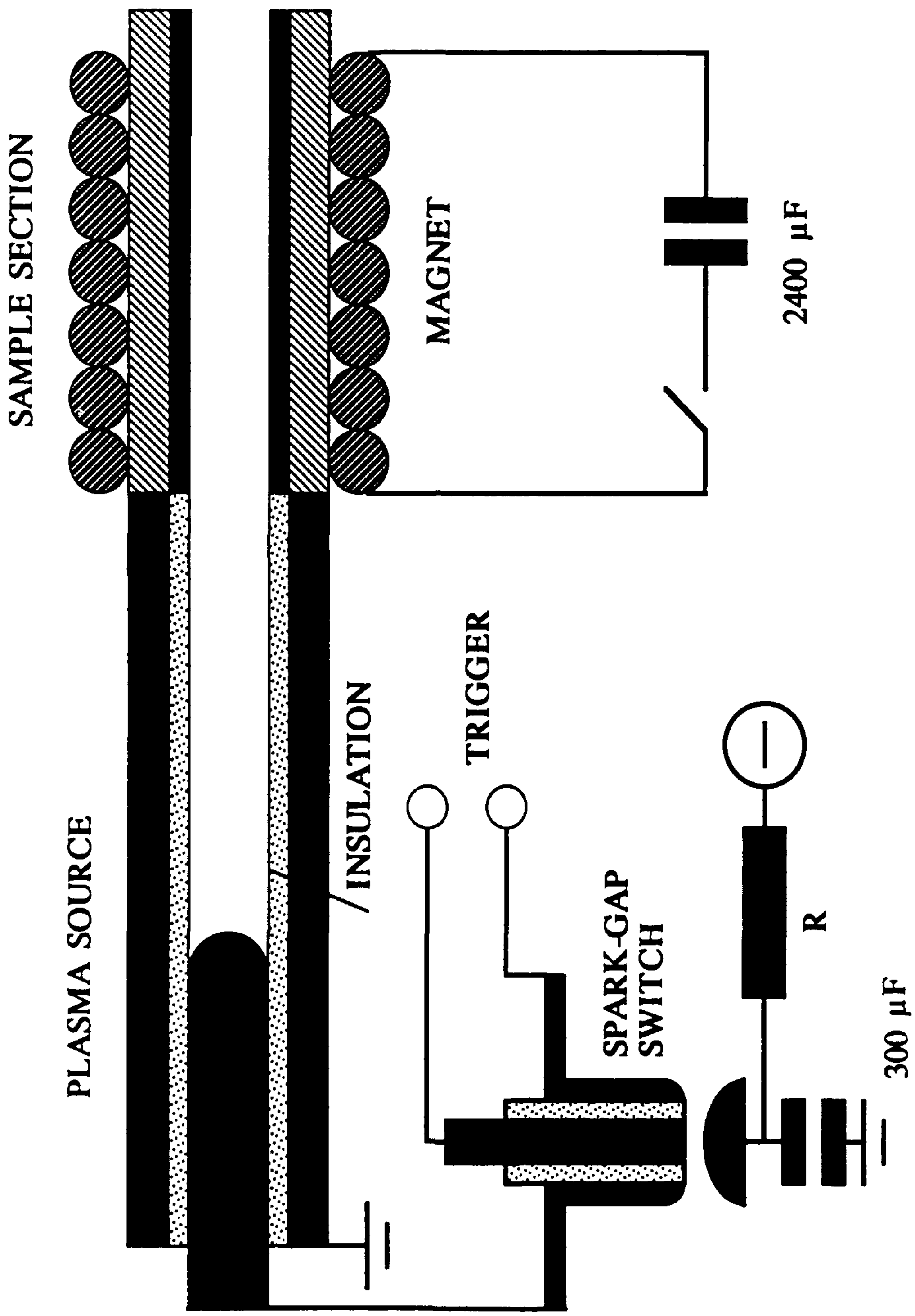
COMPUTATION

Modeling of SIRENS physics

Non-ideal plasma effects

Ablation physics at surface

Turbulent plasma boundary layer analysis

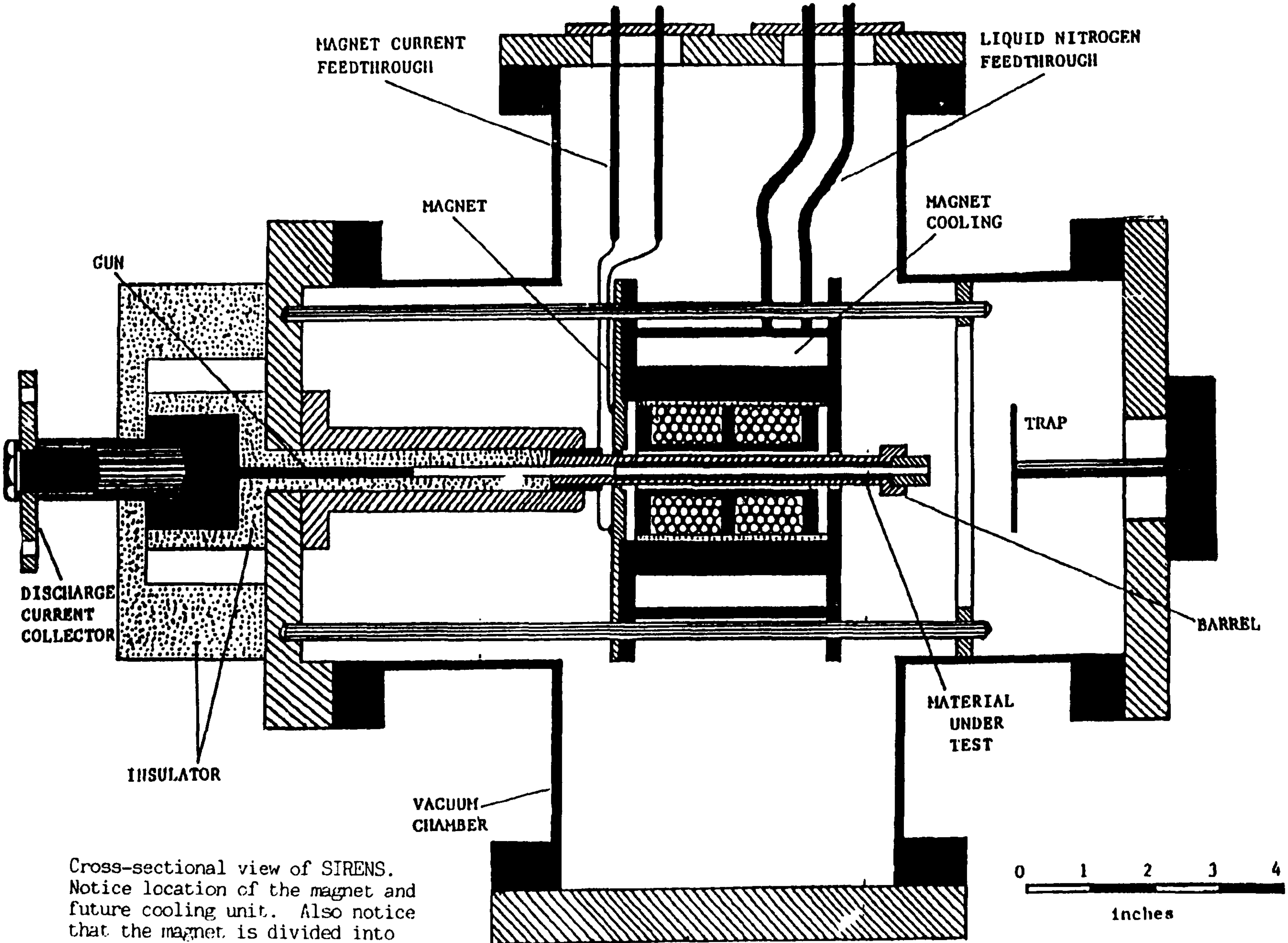


SAMPLE SECTION
MAGNET
2400 μF
PLASMA SOURCE
INSULATION
TRIGGER
SPARK-GAP SWITCH
R
300 μF

SIRENS Operational Characteristics

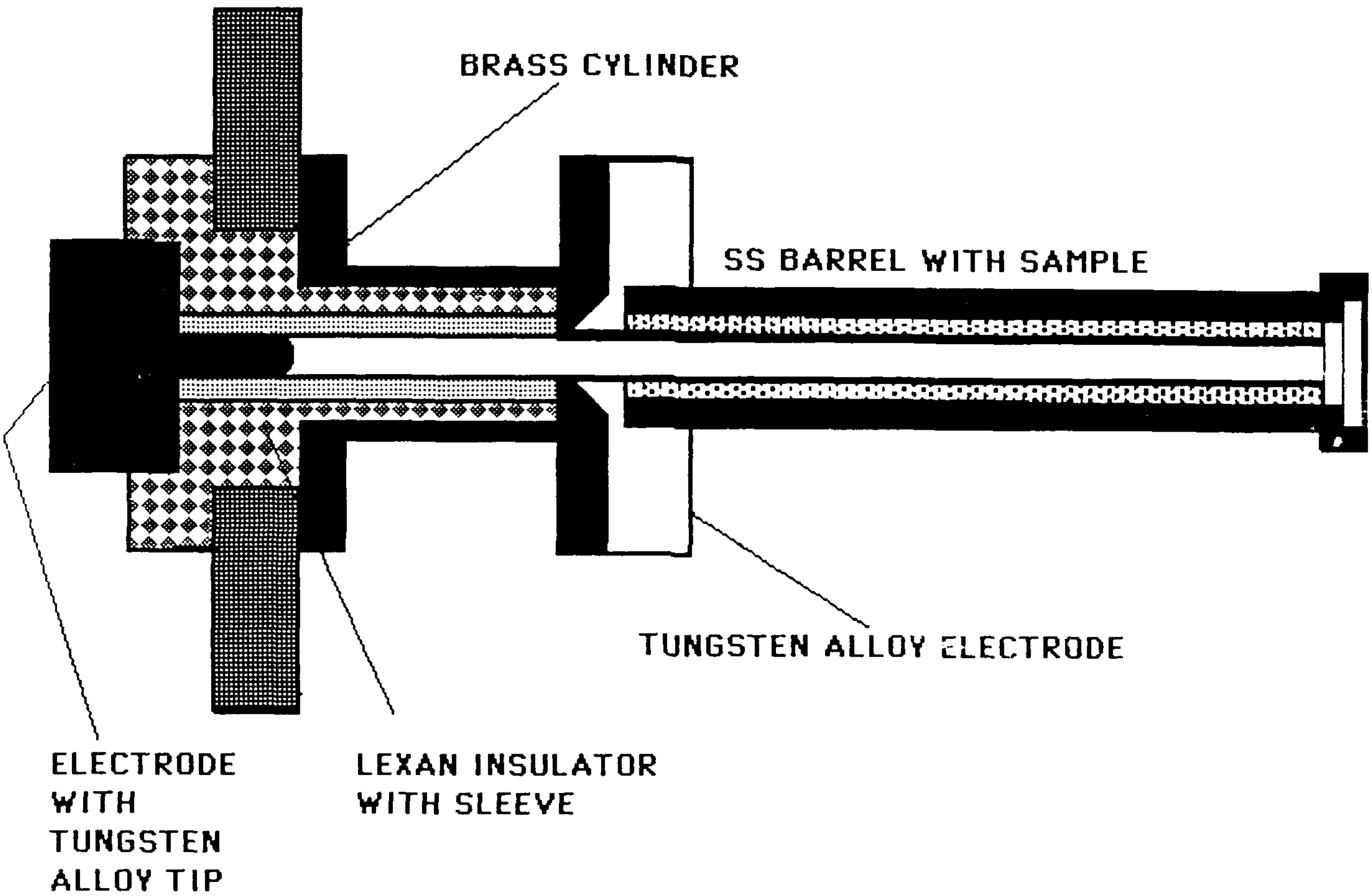
Discharge potential	1-6 kV(10kV max.)
Peak current	up to 100 kA
Peak pressure	> 1-33 kbar
Discharge period	100 μsec
Plasma density	10^{25}-10^{26} m^{-3}
Peak plasma temperature	4-6 eV
Average plasma temperature	1-3 eV
Average plasma velocity	9-19 km/sec

INPUT ENERGY (kJ)	RADIATED POWER (GW/m^2)
1	2.8
2	8.5
3	15.6
4	23.6
5	32.5
6	43.8
7	59.4



Cross-sectional view of SIRENS. Notice location of the magnet and future cooling unit. Also notice that the magnet is divided into two sections (allowing for diagnostics through the magnet).

PLASMA GUN ASSEMBLY



The plasma source and the barrel assembly

SIRENS Simulates EML Conditions

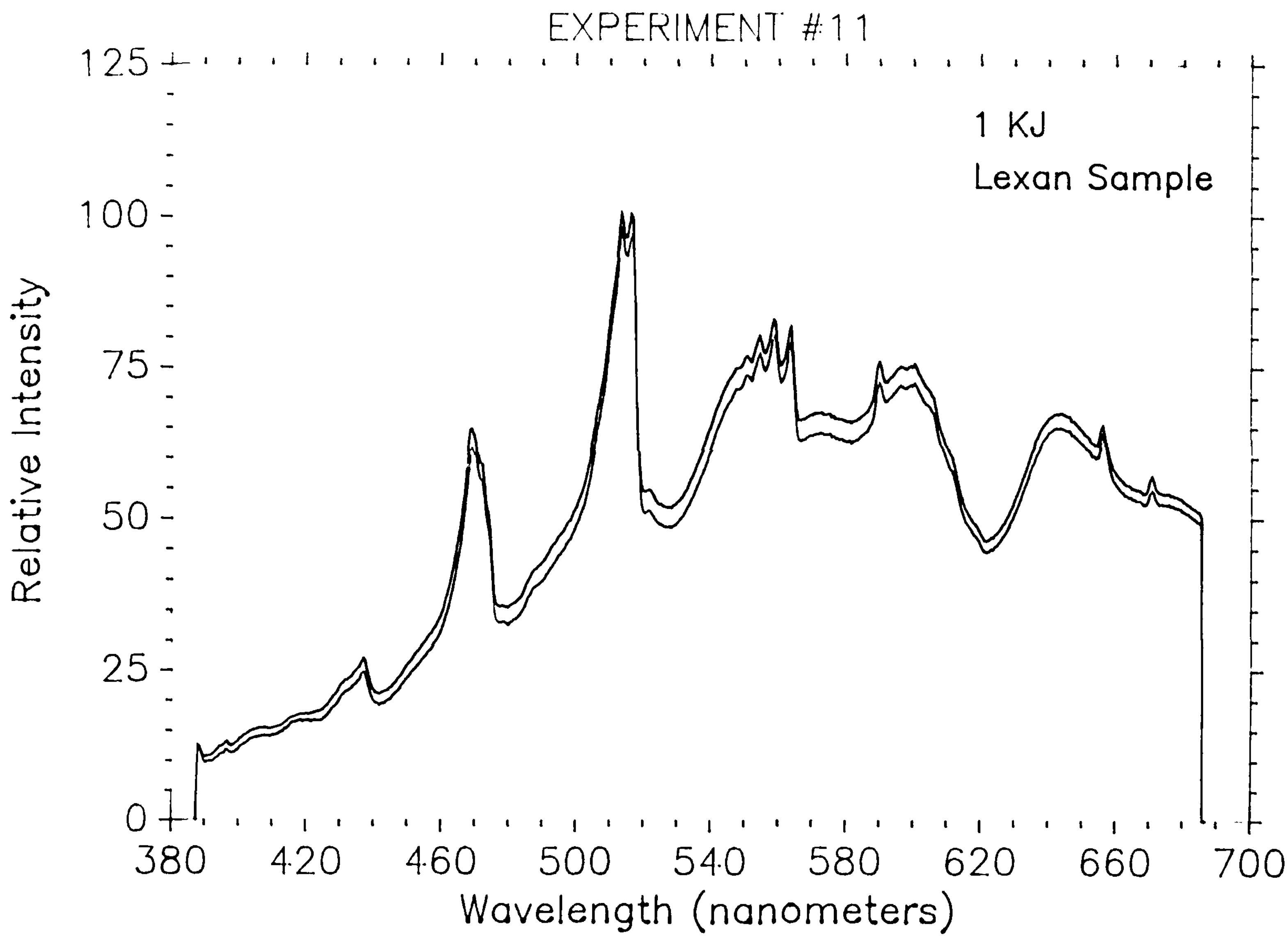
- plasma temperature up to 5 eV
- plasma density up to 10^{26} per cu. meter
- plasma pressure up to 1 kbar
- exposure times 10 - 100 microsec
- plasma velocities up to 12 km per sec
- heat fluxes up to 10^{11} W per sq. meter
- similar ablation boundary layer physics

PLASMA DIAGNOSTICS (up to 15 channels)

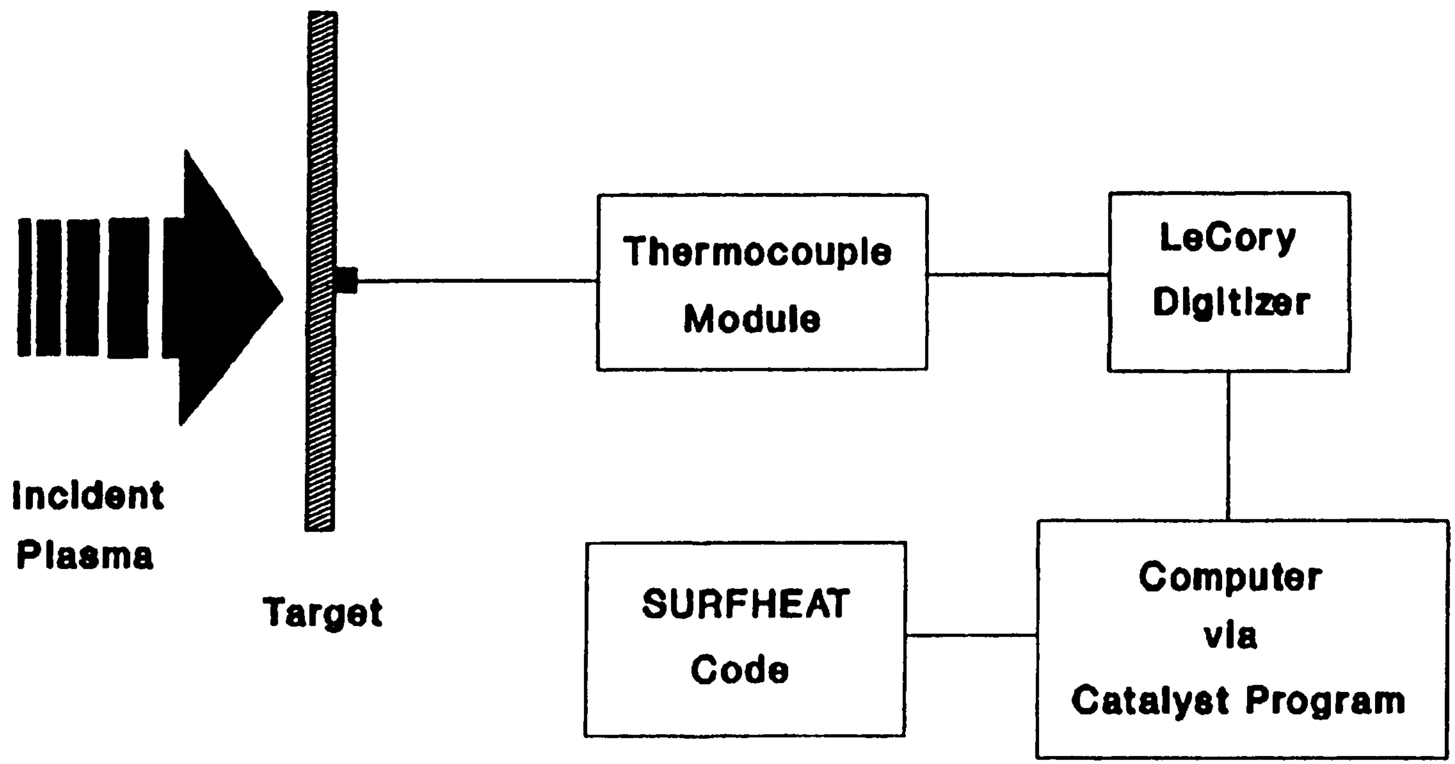
- Rogowski Coils (4) (discharge current, plasma current, magnet current)
- B-Dot Loops (4) (without barrel or with special barrel)
- Potential Probe (discharge potential)
- Monochromators (2) w/ fiber optics (time-resolved spectral lines)
- Optical Multichannel Analyzer (time-integrated visible spectrum)
- Magnetic Probe (magnet B-field)
- Thermocouples (2) (heat flux)
- Pressure Tranducers (4) (time-resolved absolute pressure)
- Lasers with Photo-Transistors (2) (plasma/projectile velocity)

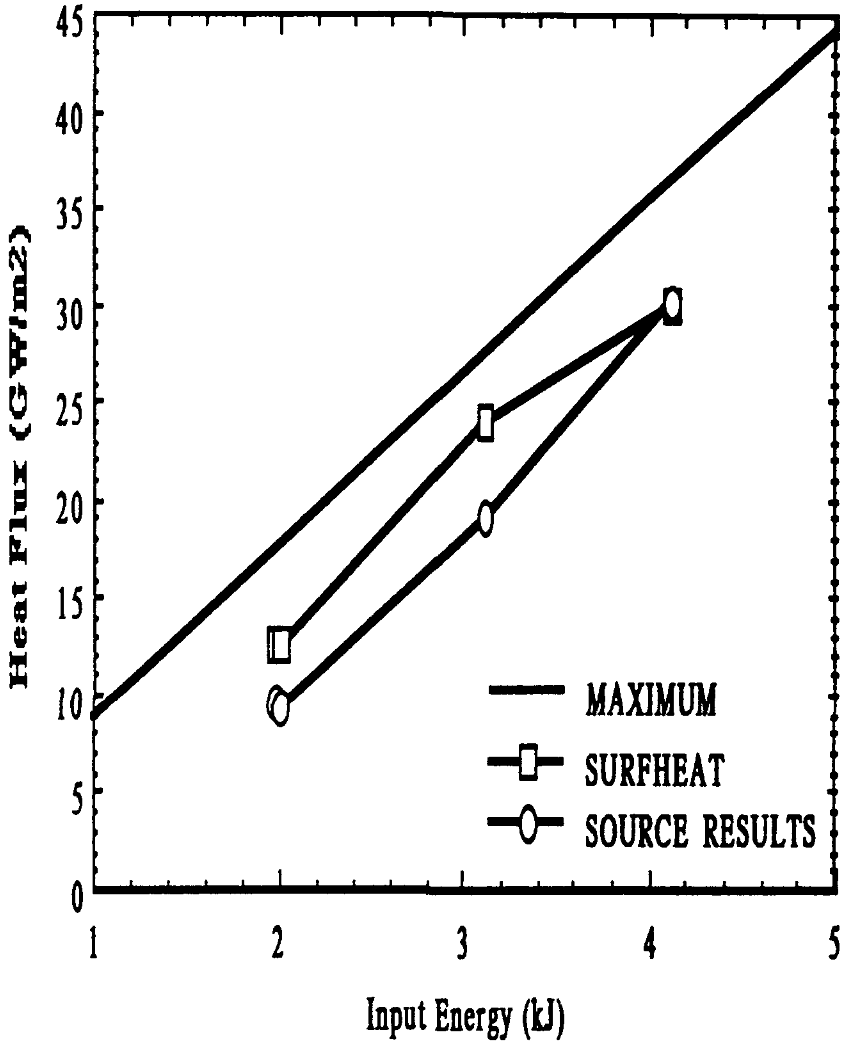
MATERIAL DIAGNOSTICS

- Microbalance (weight loss)
- Scanning Electron Microscopy (SEM)
- Energy Dispersive X-ray Analysis (EDXA)
- Auger Electron Spectroscopy (AES)

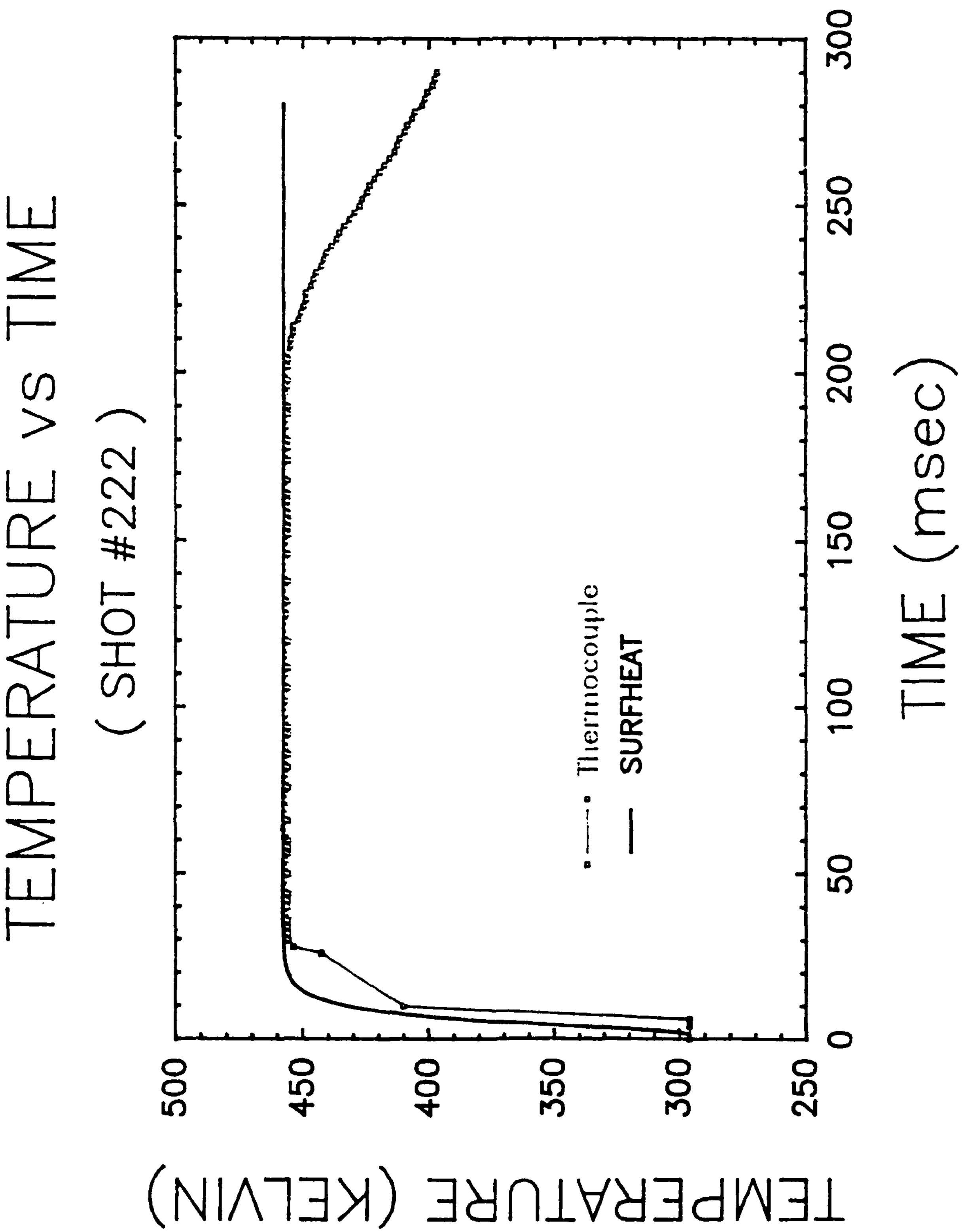

EXPERIMENT #11
1 KJ
Lexan Sample
Relative Intensity
125
100
75
50
25
0
380
420
460
500
540
580
620
660
700
Wavelength (nanometers)

Experimental Schematic of Heat Flux Measurements





Heat flux calculated by SURFHEAT according to the measured temperature profile, compared to the source fluence calculated from the source ablation and the transmission factor. The maximum corresponds to the heat flux produced by the net input energy to plasma.



TEMPERATURE vs TIME
(SHOT #222)
Thermocouple
SURFHEAT
TIME (msec)
TEMPERATURE (KELVIN)
0
50
100
150
200
250
300
250
300
350
400
450
500

Insulators

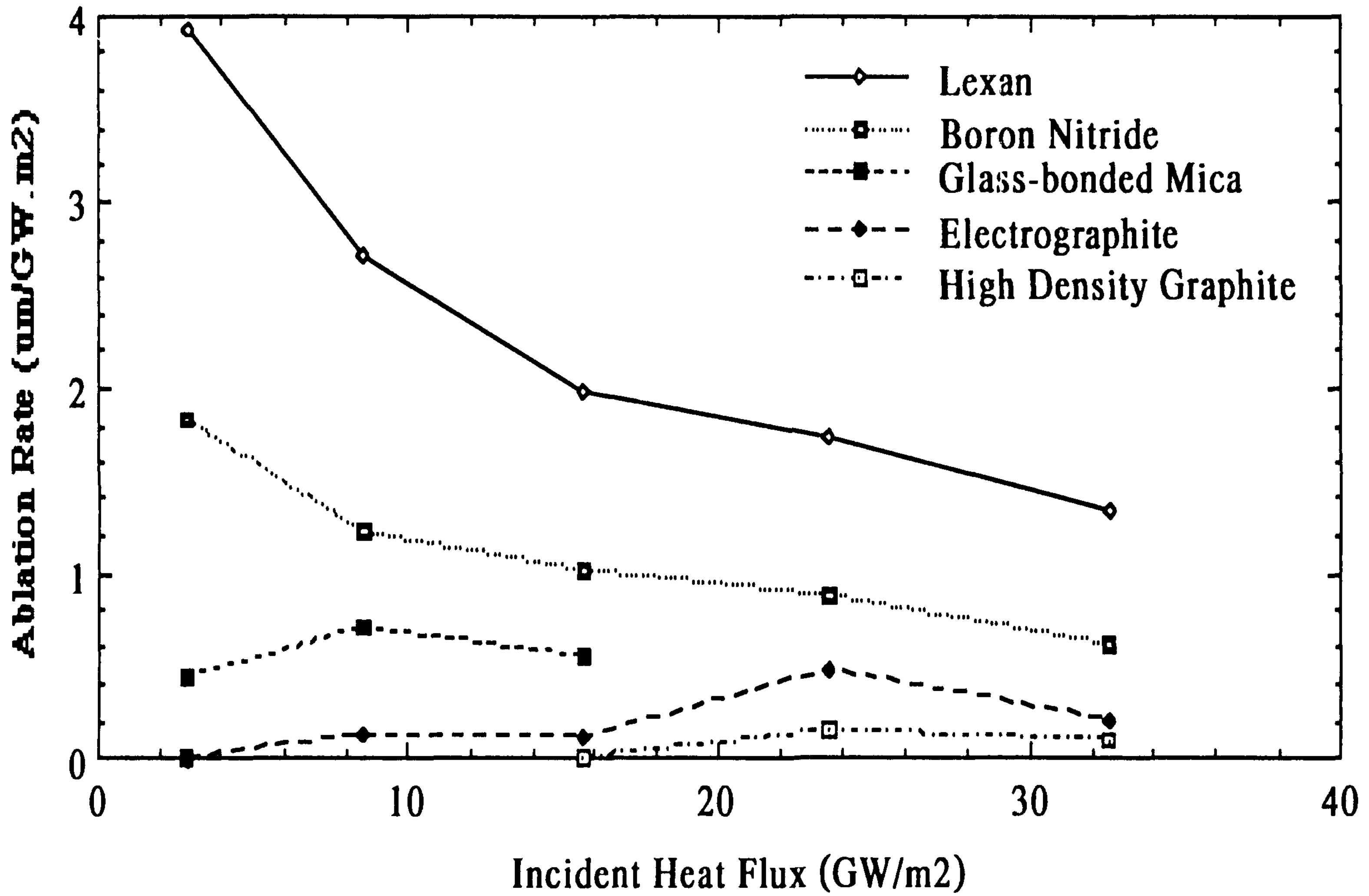
Lexan | Boron Nitride | Glass-Bonded Mica

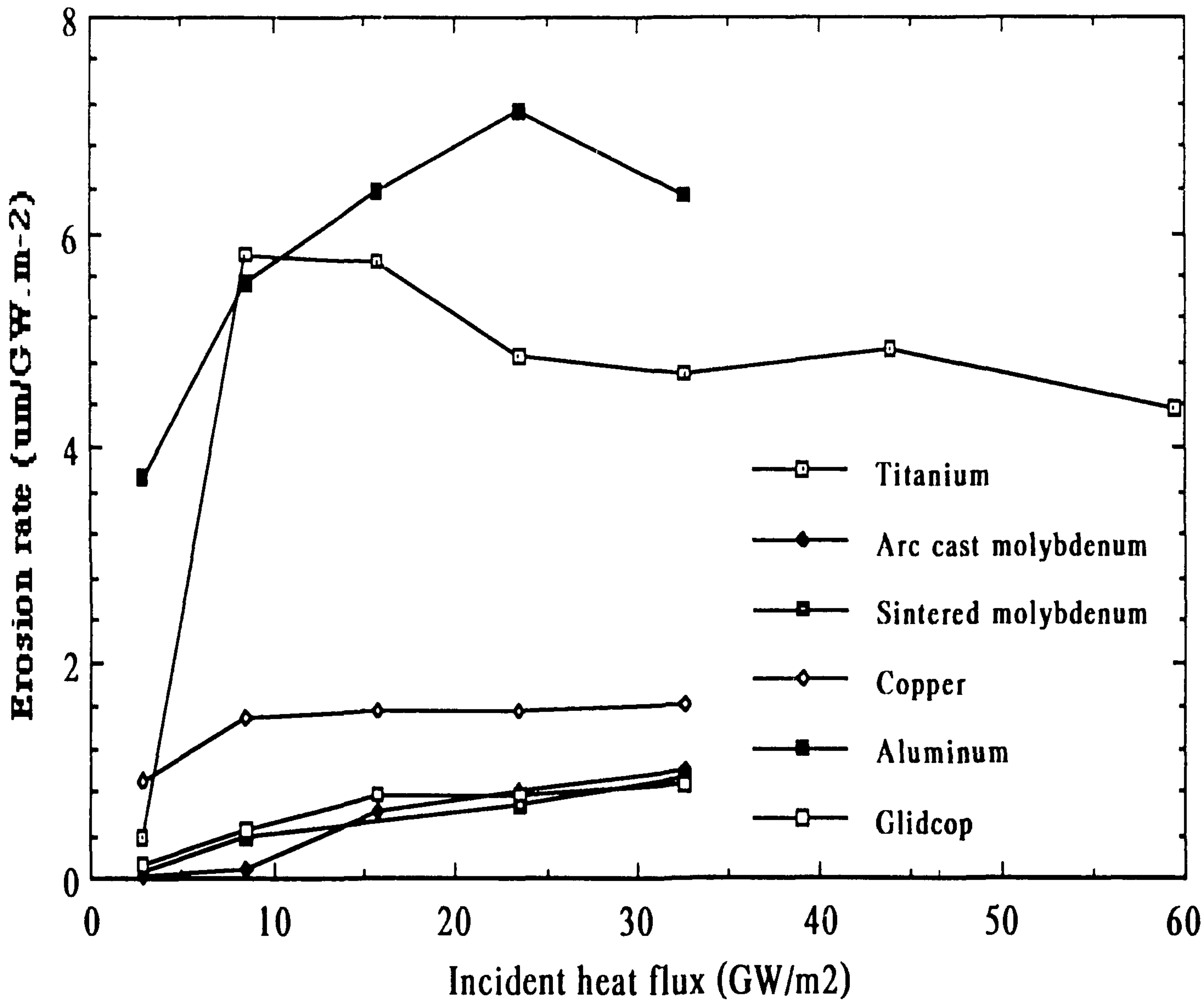
Metallic conductors

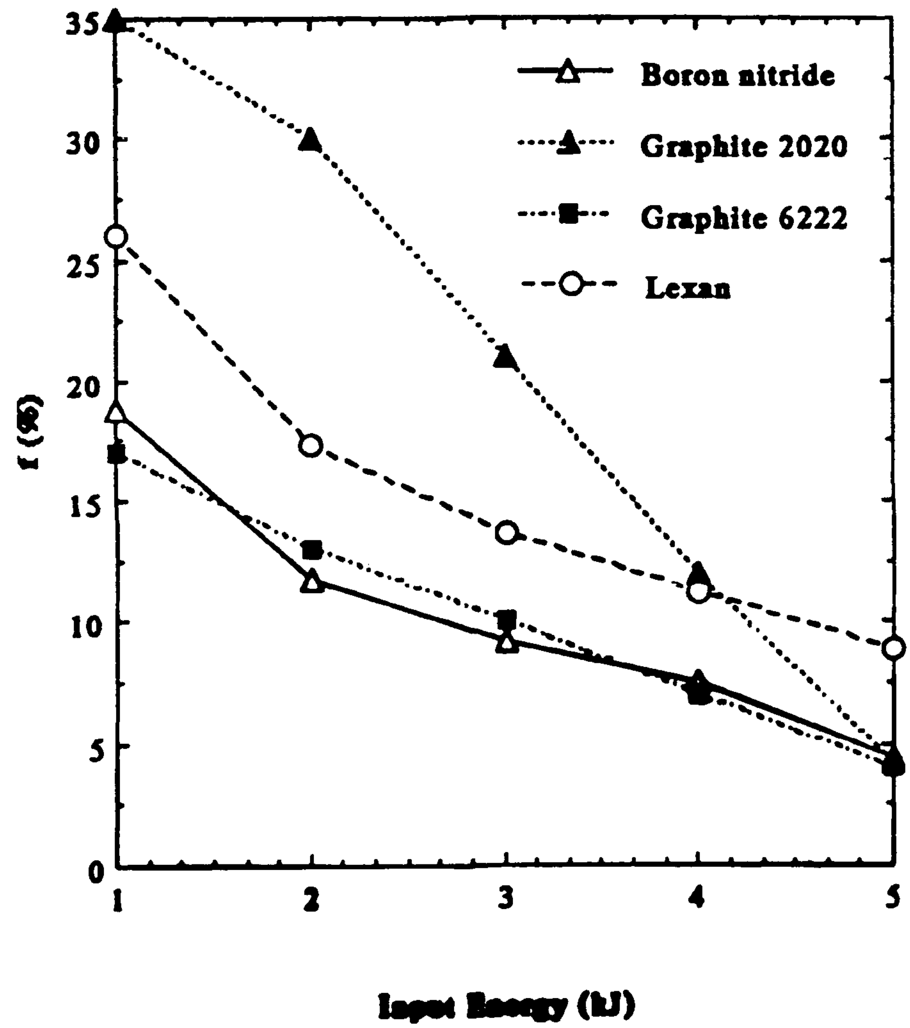
Aluminum	Copper
Glidcop	Titanium
Sintered Molybdenum	Arc Cast Molybdenum

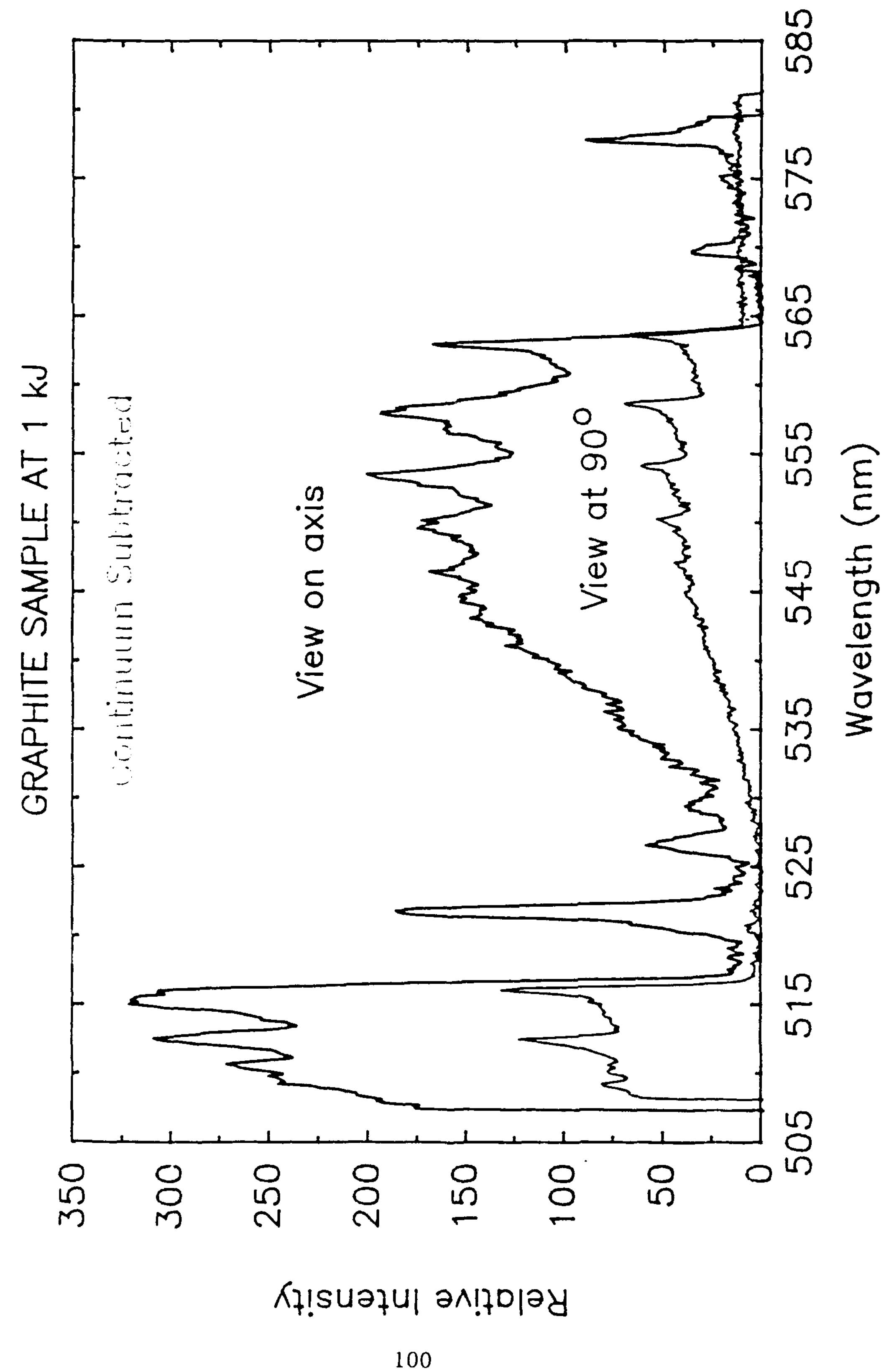
Nonmetallic conductors

Molded dense electrographite (2020)
High Density Graphite (6222)
Very fine grain Isotropic Graphite (2301)

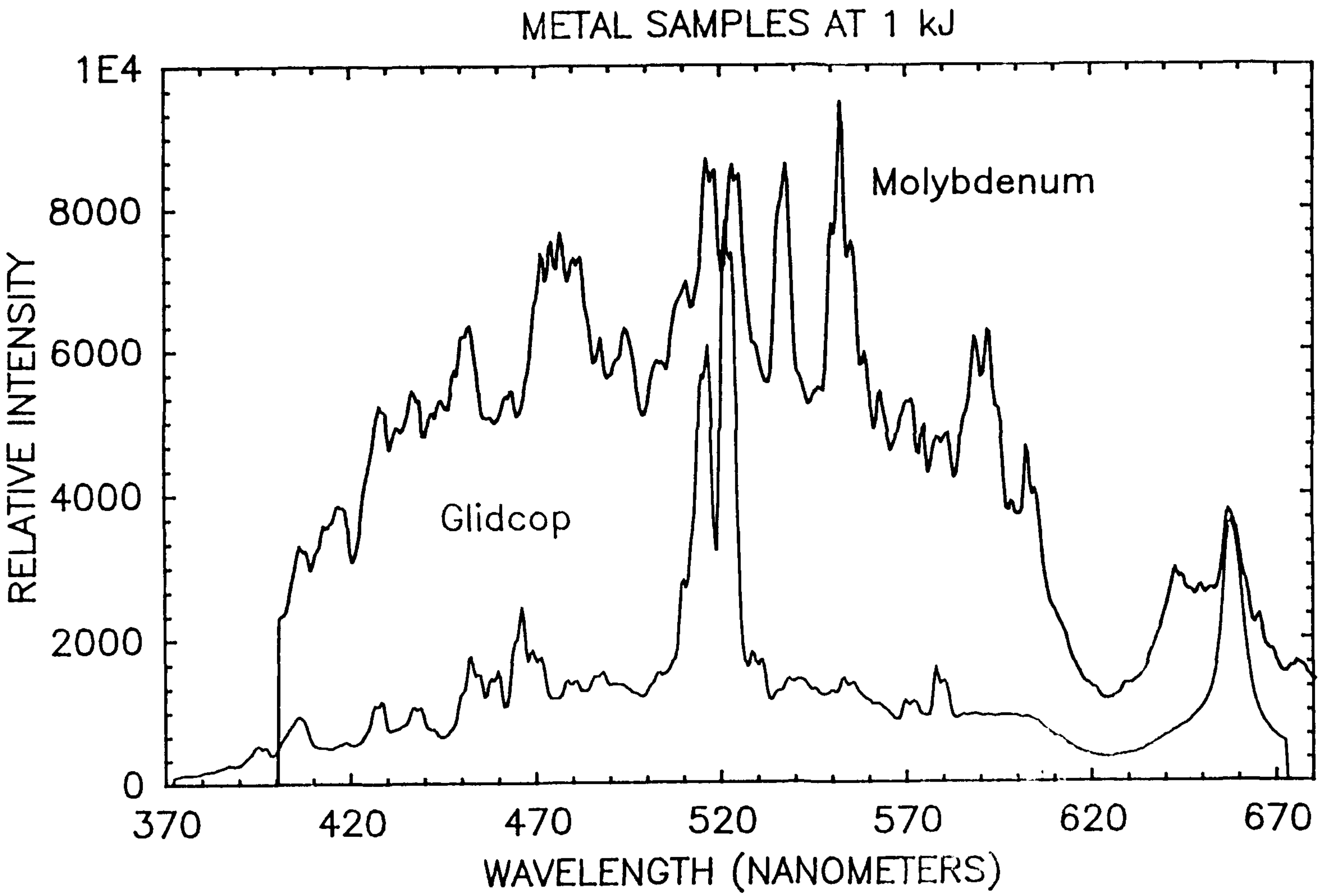

Lexan
Boron Nitride
Glass-bonded Mica
Electrographite
High Density Graphite
Ablation Rate (um/GW.m2)
Incident Heat Flux (GW/m2)
0
1
2
3
4
0
10
20
30
40

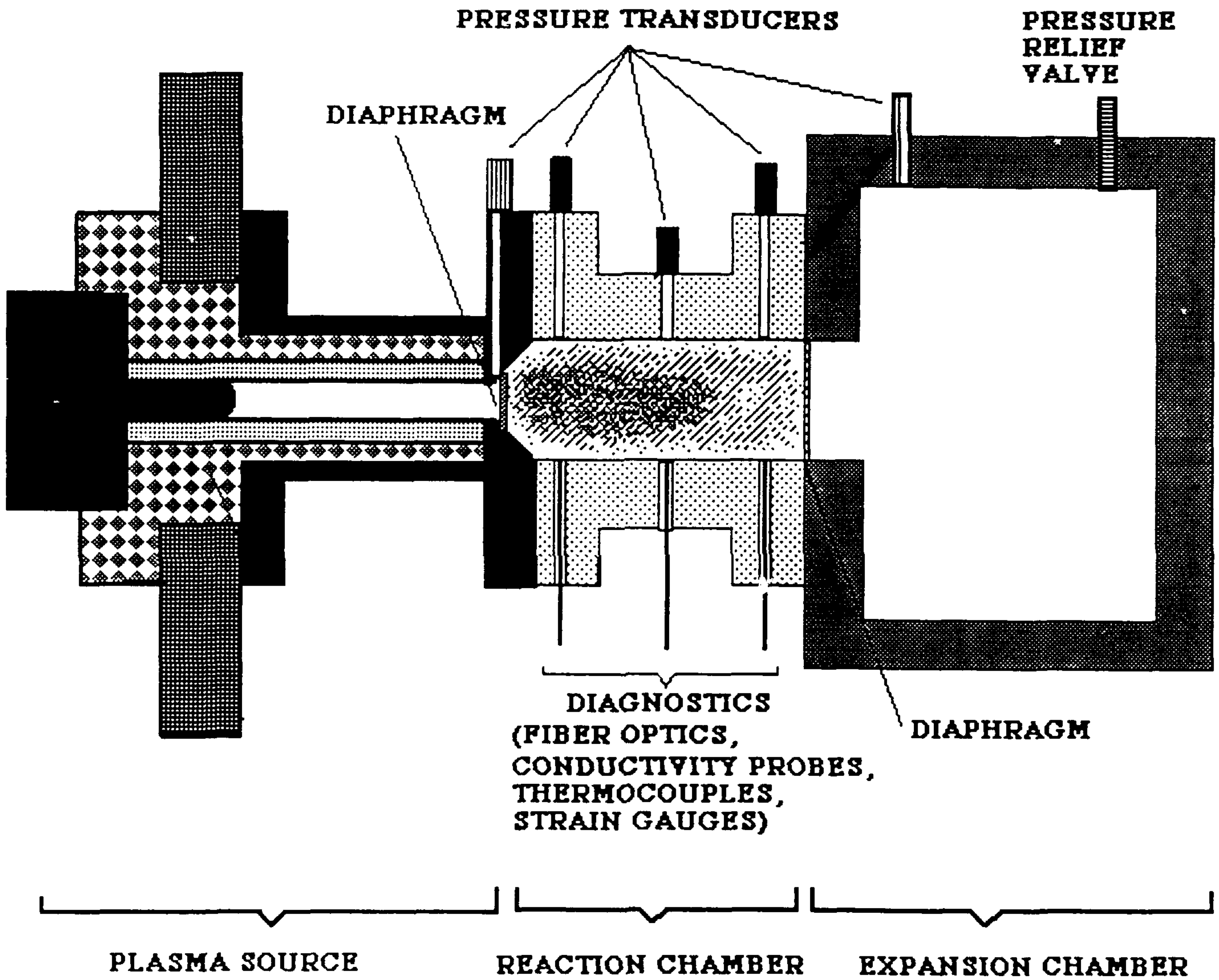

Erosion rate (um/GW.m-2)
Incident heat flux (GW/m2)
0
2
4
6
8
0
10
20
30
40
50
60
Titanium
Arc cast molybdenum
Sintered molybdenum
Copper
Aluminum
Glidcop


Boron nitride
Graphite 2020
Graphite 6222
Lexan
35
30
25
20
15
10
5
0
1
2
3
4
5
f (%)
Input Energy (kJ)

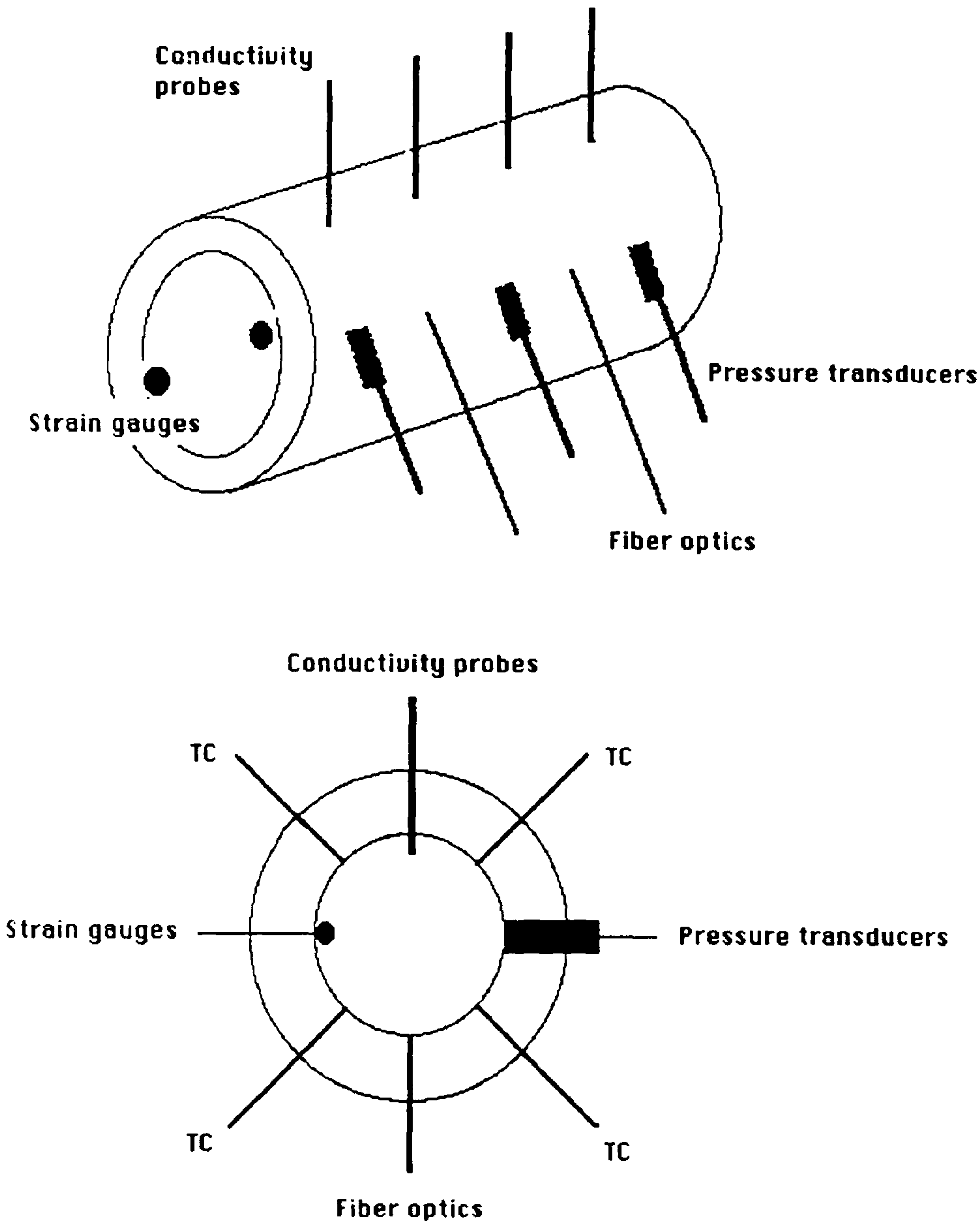


GRAPHITE SAMPLE AT 1 kJ
Continuum Subtracted
View on axis
View at 90°
Relative Intensity
0
50
100
150
200
250
300
350
505
515
525
535
545
555
565
575
585
Wavelength (nm)

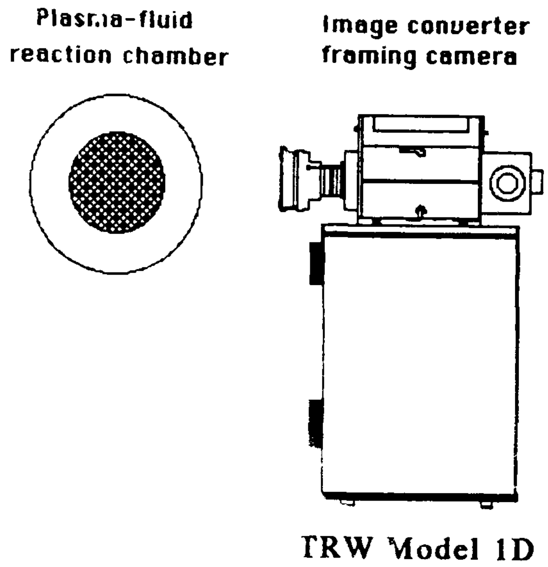

METAL SAMPLES AT 1 kJ
1E4
8000
6000
4000
2000
0
RELATIVE INTENSITY
370
420
470
520
570
620
670
WAVELENGTH (NANOMETERS)
Molybdenum
Glidcop



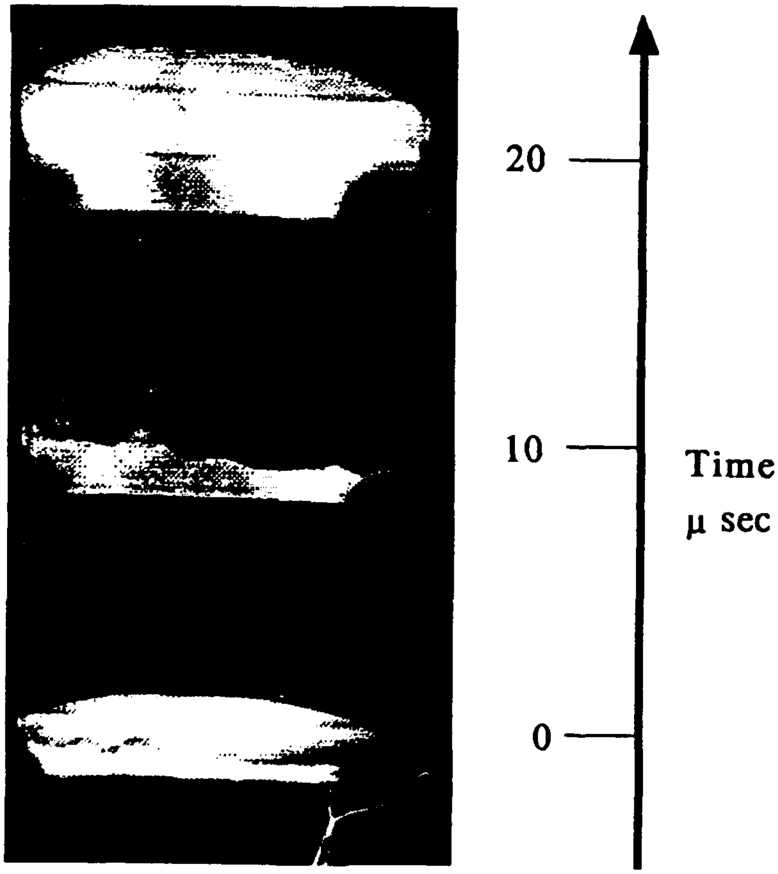
PRESSURE TRANSDUCERS
PRESSURE
RELIEF
VALVE
DIAPHRAGM
DIAGNOSTICS
(FIBER OPTICS,
CONDUCTIVITY PROBES,
THERMOCOUPLES,
STRAIN GAUGES)
DIAPHRAGM
PLASMA SOURCE
REACTION CHAMBER
EXPANSION CHAMBER



Plasma-fluid reaction chamber diagnostics arrangement. Strain gauges, conductivity probes, fiber optics, thermocouples, and absolute pressure transducers are arranged to measure at different locations along the axial direction.



Framing photography arrangement



Framing photography of a water droplet exposed to an arc between two pointed electrodes

OUTLINE

Plasma-Surface (solid,liquid) Interaction Modeling

- Modeling of ET source region

  Non-ideal plasma effects

  Materials erosion studies

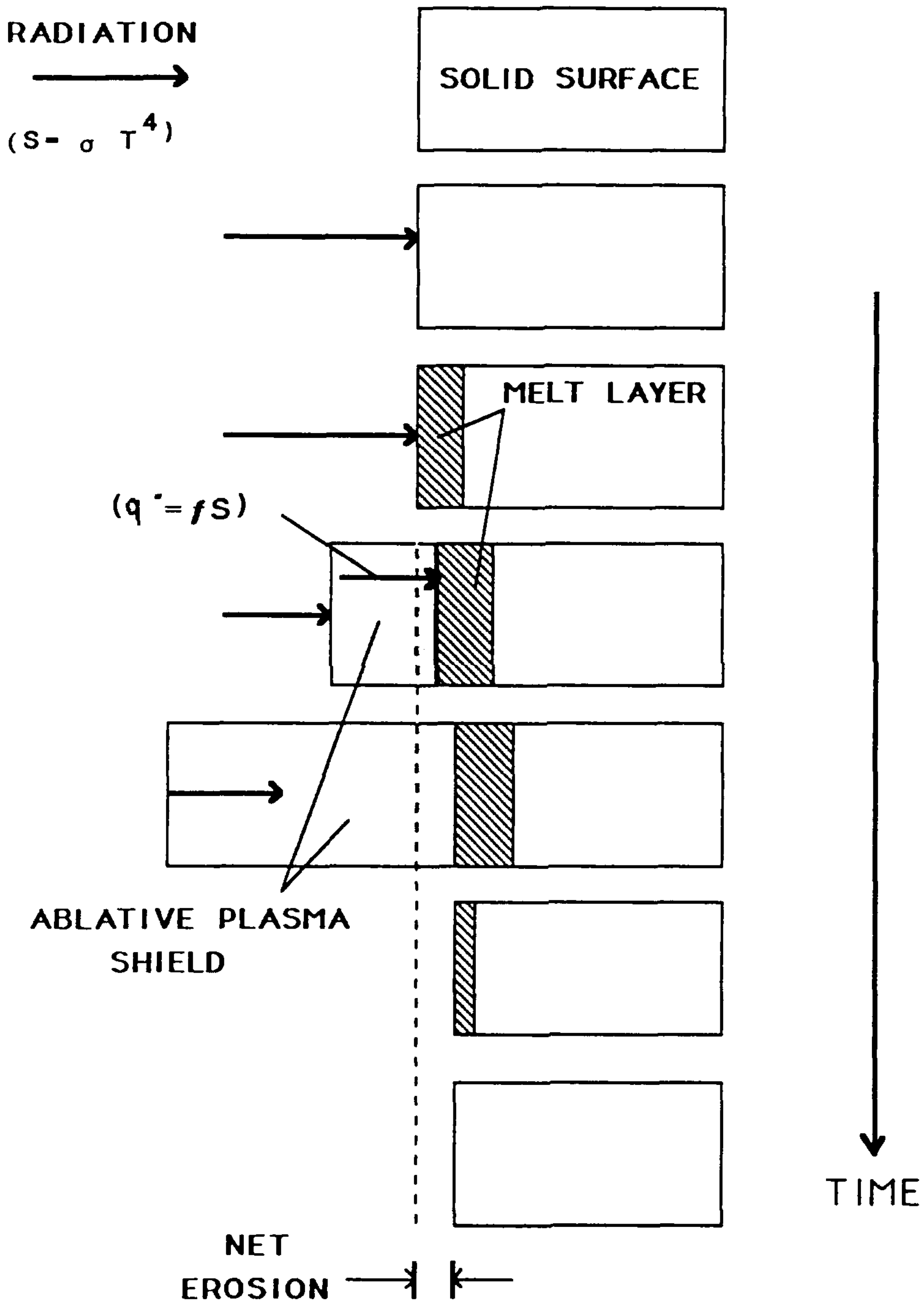
- Modeling of energy transport through the boundary layer in the ET source

  Radiation transport

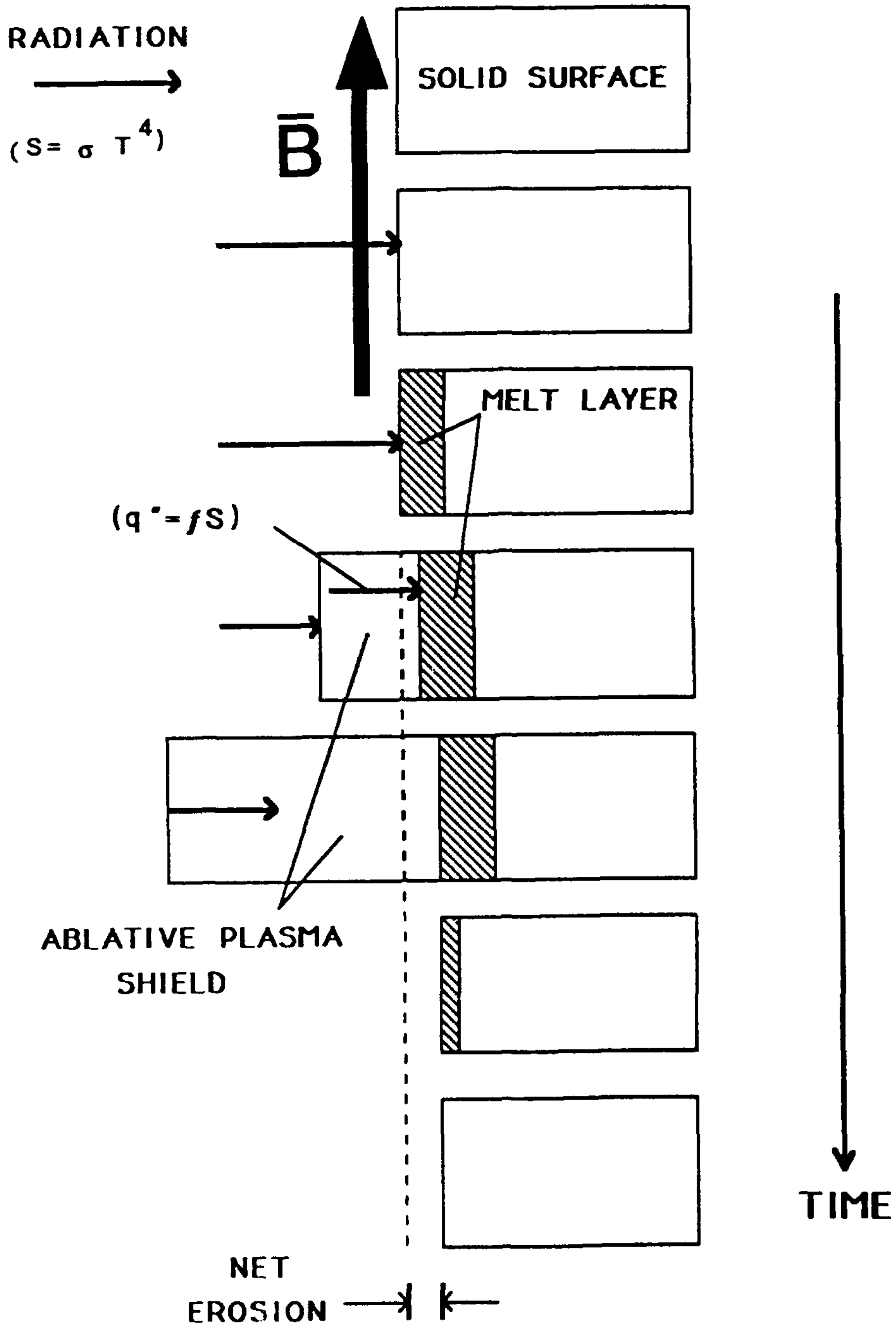
- New boundary layer model for ETC combustion chamber

- What is modeled that can be measured? (or vice versa)

VAPOR SHIELD PROCESS



MAGNETIC VAPOR SHIELD



Equation of Particle Conservation

$$\frac{dn}{dt} = \dot{n} - \frac{n}{\tau}$$

Energy Equations

Plasma

$$\frac{d(nU)}{dt} = \eta J_p^2 - \nabla . q - \frac{nU}{\tau}$$

Radiation

$$q = f \sigma T_p^4$$

Circuit Equation

$$L\frac{dI}{dt} + RI + \frac{q_e}{C} = V_0$$

where

$$\tau = \frac{L_0}{C_s}$$

$$\eta = \eta_{e-i} + \eta_{e-n}$$

$$\frac{dq_e}{dt} = I$$

f = fraction of black-body radiation

Plasma parameters are volume averaged quantities

Method for Determination of Internal Energy

Internal Energy

$$U(T_p, \bar{Z}) = [\frac{3}{2}(\bar{Z} + 1)T_p + \sum_{i=0}^{Z} I_i + (\bar{Z} - Z)I_{Z+1}]$$

Average Charge State

$$I(\bar{Z} + \frac{1}{2}) = T_p ln(\frac{AT_p^{3/2}}{\bar{Z}n})$$

where

$\bar{Z}$: Average Charge State of Plasma

I : Ionization potential (eV)

T_p : Plasma Temperature (eV)

n : Plasma density (m^{-3})

A = 6.04×10^{27} ($eV^{-3/2}$ m^{-3})

POWER LOSS DISTRIBUTION AS A FUNCTION OF TIME

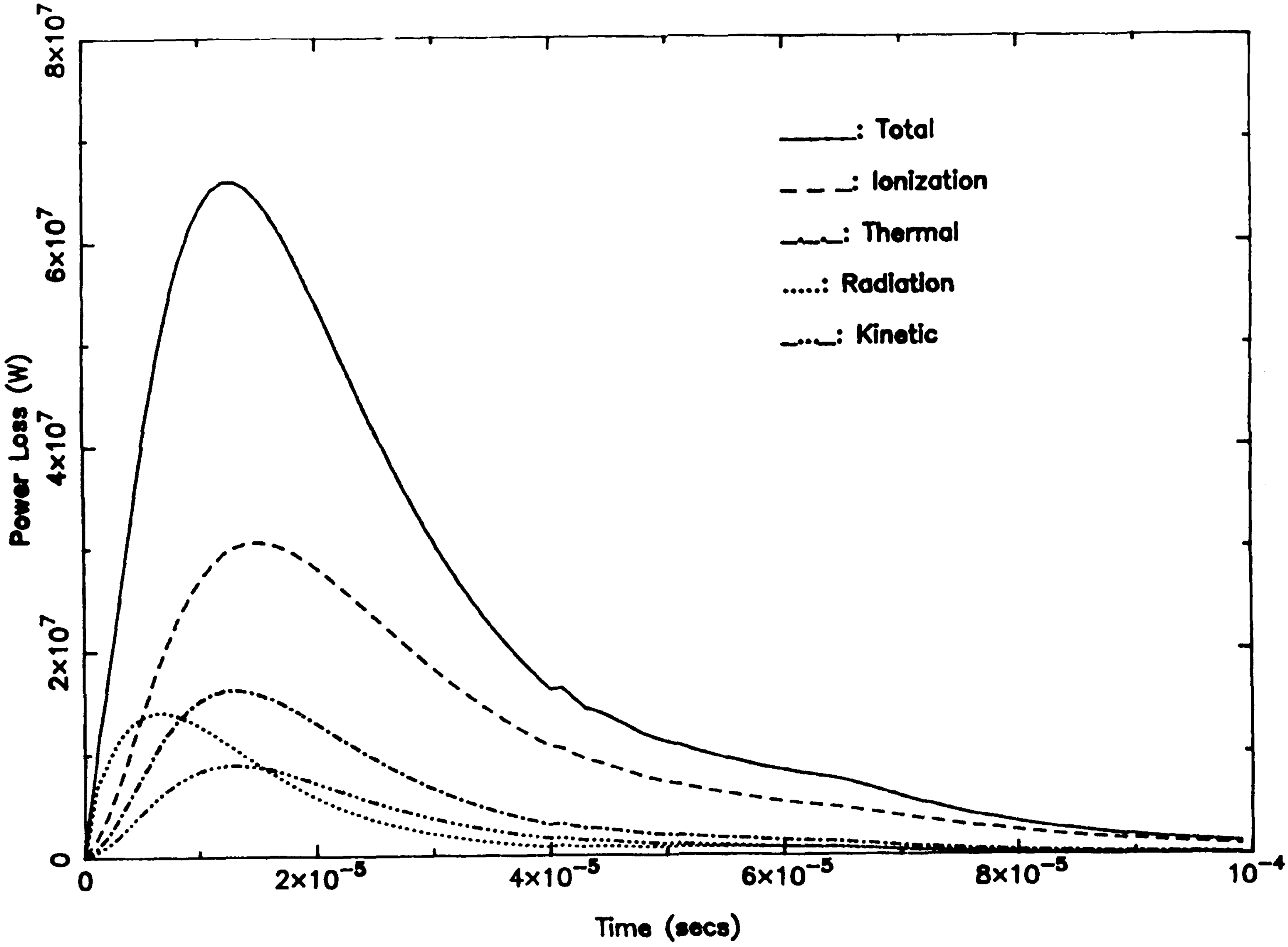


Table 2: Summary of the theoretical results of Powell and Zielinski (ideal plasma)

Shot #	V_{Th} Volts	T (eV)	P_{av} (MPa)	$\bar{Z}$	Δx (μ m)
2	1221	1.78	18.1	0.37	37.0
4	1708	2.51	53.2	0.66	91.0
5	1894	2.75	72.5	0.72	118.0
6	1894	2.79	73.0	0.74	122.0
8	1960	2.94	81.5	0.80	141.0

Table 3: Summary of our theoretical results for an ideal plasma

Shot #	V_{Th} Volts	T (eV)	P_{av} (MPa)	$\bar{Z}$	Δx (μ m)
2	1430	1.60	21.0	0.40	41.0
4	1650	2.43	62.0	0.67	90.0
5	1820	2.72	84.2	0.74	112.0
6	1821	2.75	85.6	0.75	116.0
8	1930	2.93	97.0	0.80	133.0

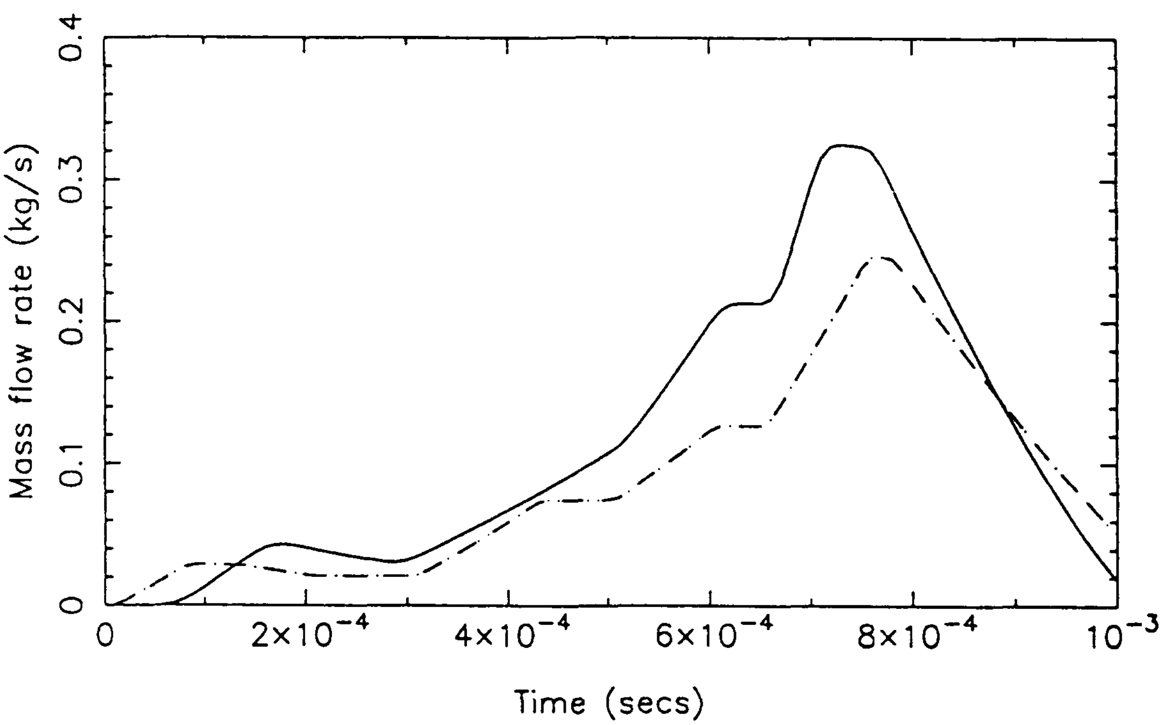
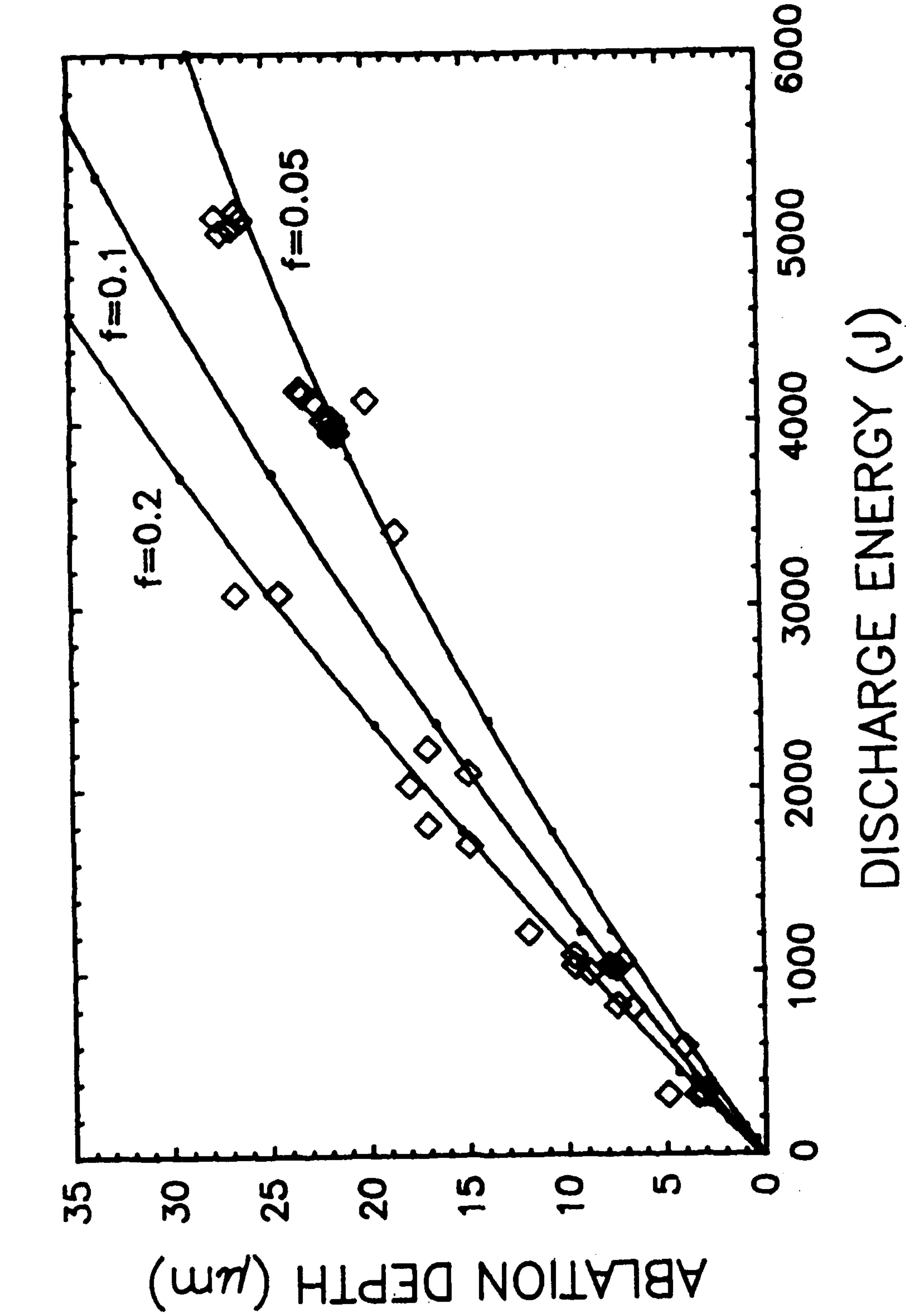
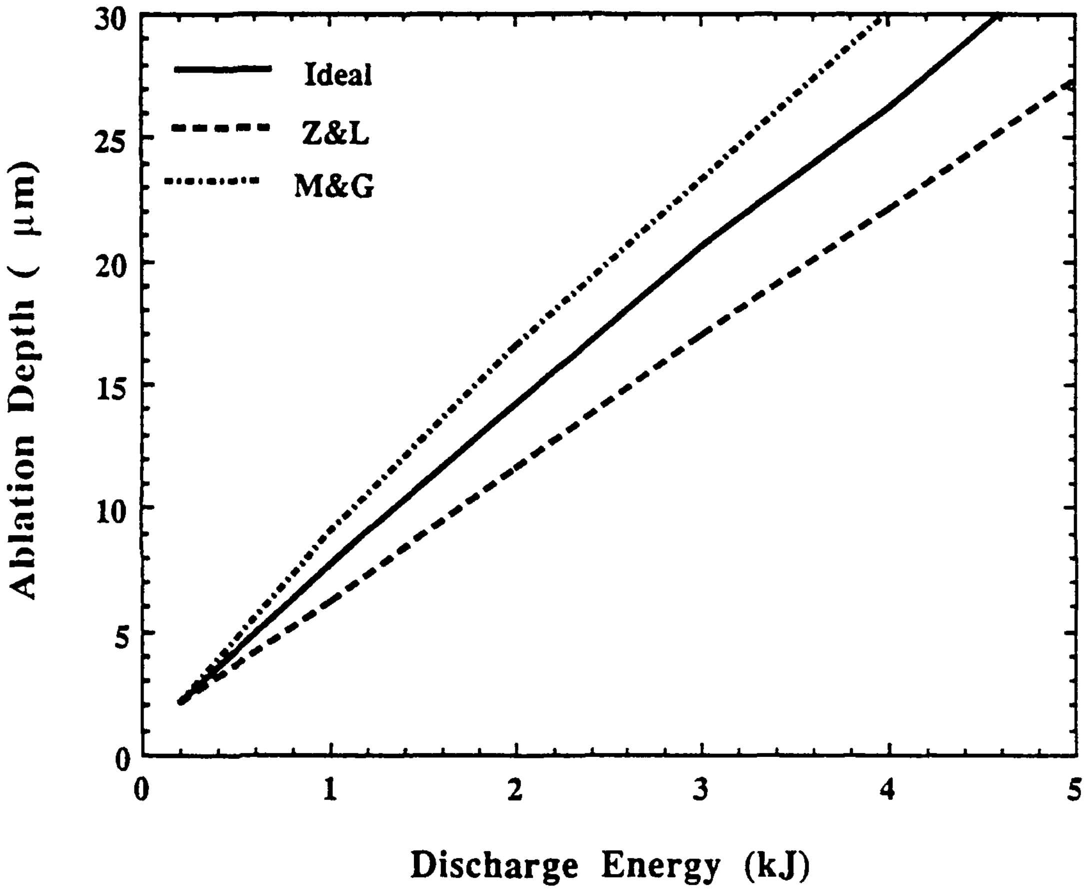


Figure 9: Mass flow rate as a function of time for Case I,II


ABLATION DEPTH (μm)
DISCHARGE ENERGY (J)
0
5
10
15
20
25
30
35
0
1000
2000
3000
4000
5000
6000
f=0.2
f=0.1
f=0.05



Ideal
Z&L
M&G
Ablation Depth (μm)
Discharge Energy (kJ)
0
5
10
15
20
25
30
0
1
2
3
4
5

Fig. 3

Table 5.2: Models for Normalized Electrical Conductivity, σ^*, as given by various authors

Authors	Models for σ
Spitzer	$\frac{\alpha_e}{ln(\Lambda)}$
Zollweg & Liebermann	$\frac{\alpha_e}{ln(1+1.4\Lambda_m^2)^{1/2}}$
Kaklyugin & Norman	$\frac{\alpha_e}{ln(\frac{r_s}{\lambda_D})} e^{\Delta\mu/kT}(1 - \frac{(w/kT)^2}{24})$
Kurilenkov & Valuev	$\frac{1-(1-e^{-(\pi\gamma)^2})e^{-2\gamma}}{\alpha_e^{-1} ln\sqrt{(1+\Lambda^2)}+c_0(1+c_1\gamma^{3/2})^{-1}}$
Present Model	$\frac{\alpha_e}{ln(1+1.4\Lambda_{m1}^2)^{1/2}} e^{\Delta\mu/kT}(1 - \frac{(w/kT)^4}{(w/kT+0.8)^4})$

α_e : correction for electron-electron interactions

$\Lambda = \frac{\lambda_D}{b_0}$

Λ_m : substitute λ_D by modified screening radius [51]

Λ_{m1} : substitute λ_D by r_s

$c_0 = 0.8658$; $c_1 = 0.17$

Equation of Motion

$$\frac{\partial u}{\partial t} = -V\frac{\partial}{\partial r}(P+q) + \frac{V}{c}\hat{r}\cdot\vec{J}_p \times (\vec{B_{ind}} + \vec{B_{ext}})$$

Energy Equations

Plasma

$$C_v\frac{\partial T_p}{\partial t} = \frac{\partial}{\partial m_0}(r\kappa_p\frac{\partial T_p}{\partial r}) - \frac{\partial P_p}{\partial T_p}\dot{V}T_p - q\dot{V} + A - J + \Psi$$

Radiation

$$V\frac{\partial E_R^g}{\partial t} = \frac{\partial}{\partial m_0}(r\kappa_R^g\frac{\partial E_R^g}{\partial r}) - \frac{4}{3}E_R^g\dot{V} - A^g + J^g \qquad g = 1,\ldots,G$$

Magnetic Diffusion Equation

$$\nabla\times\vec{B} = \frac{4\pi}{c}\vec{J}_p \quad ; \quad \nabla\times\vec{E} = -\frac{1}{c}\dot{\vec{B}}$$

$$\eta\vec{J}_p = \vec{E} + \frac{1}{c}\vec{u}\times(\vec{B_{ind}} + \vec{B_{ext}})$$

where

$$\Psi = \eta J_p^2 r\frac{dr}{dm_0}$$

$$A = \sum_{g=1}^{G} A^g = \sum_{g=1}^{G} c\sigma_P^g E_R^g$$

$$J = \sum_{g=1}^{G} J^g = \sum_{g=1}^{G}\frac{8\pi T_P^4}{c^2h^2}\sigma_P^g\int_{x_g}^{x_{g+1}} dx\frac{x^3}{e^x-1} \quad ; \quad x = \frac{h\nu}{T_P}$$

$$\kappa_R^g = \frac{cV}{3\sigma_R^g}$$

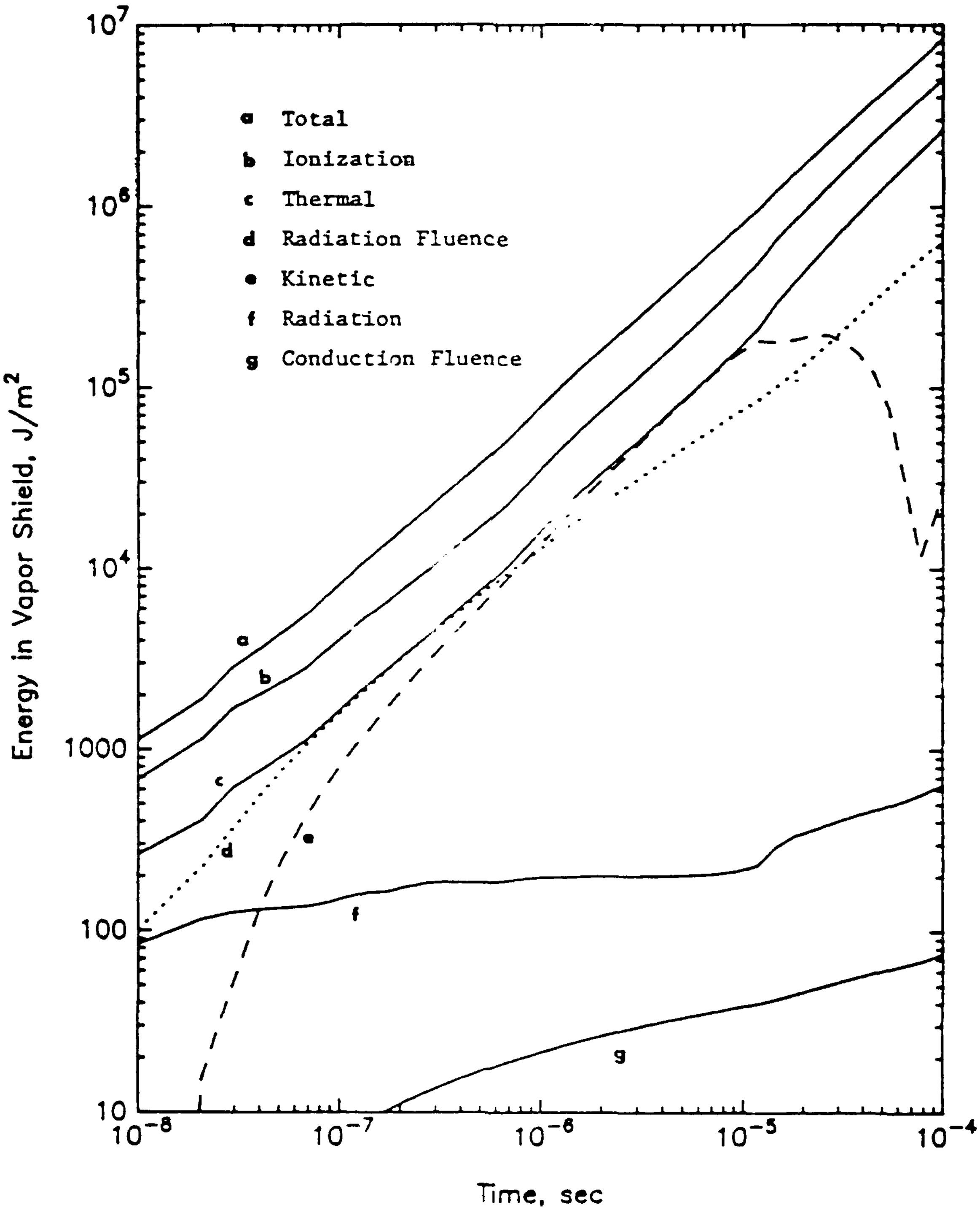


Fig. 5 Energy in Vapor Shield for an Iron Wall with 3 eV Black body Radiation

Table Summary of Parametric Studies for Vapor Shielding Effect

Source	Black body Temp., eV	2	3	5
	Heat Flux, W/m^2	$1.6x10^{10}$	$8.3x10^{10}$	$6.4x10^{11}$
	Pulse Length, μsec	10	10	10
	Energy Fluence, J/m^2	$1.6x10^5$	$8.3x10^5$	$6.4x10^6$
Iron	Energy reaching wall, J/m^2	$3.8x10^4$	$9.0x10^4$	$2.6x10^5$
	Transmission factor f, %	23.0	10.8	4.1
	Erosion Thickness, μm	0.7	1.5	4.5
Graphite	Energy reaching wall, J/m^2	$7.8x10^4$	$1.7x10^5$	$4.5x10^5$
	Transmission factor f, %	47.5	20.5	7.1
	Erosion Thickness, μm	1.1	2.4	6.4
Copper	Energy reaching wall, J/m^2	$3.7x10^4$	$8.9x10^4$	$2.2x10^5$
	Transmission factor f, %	22.7	10.7	3.5
	Erosion Thickness, μm	0.8	1.9	4.6

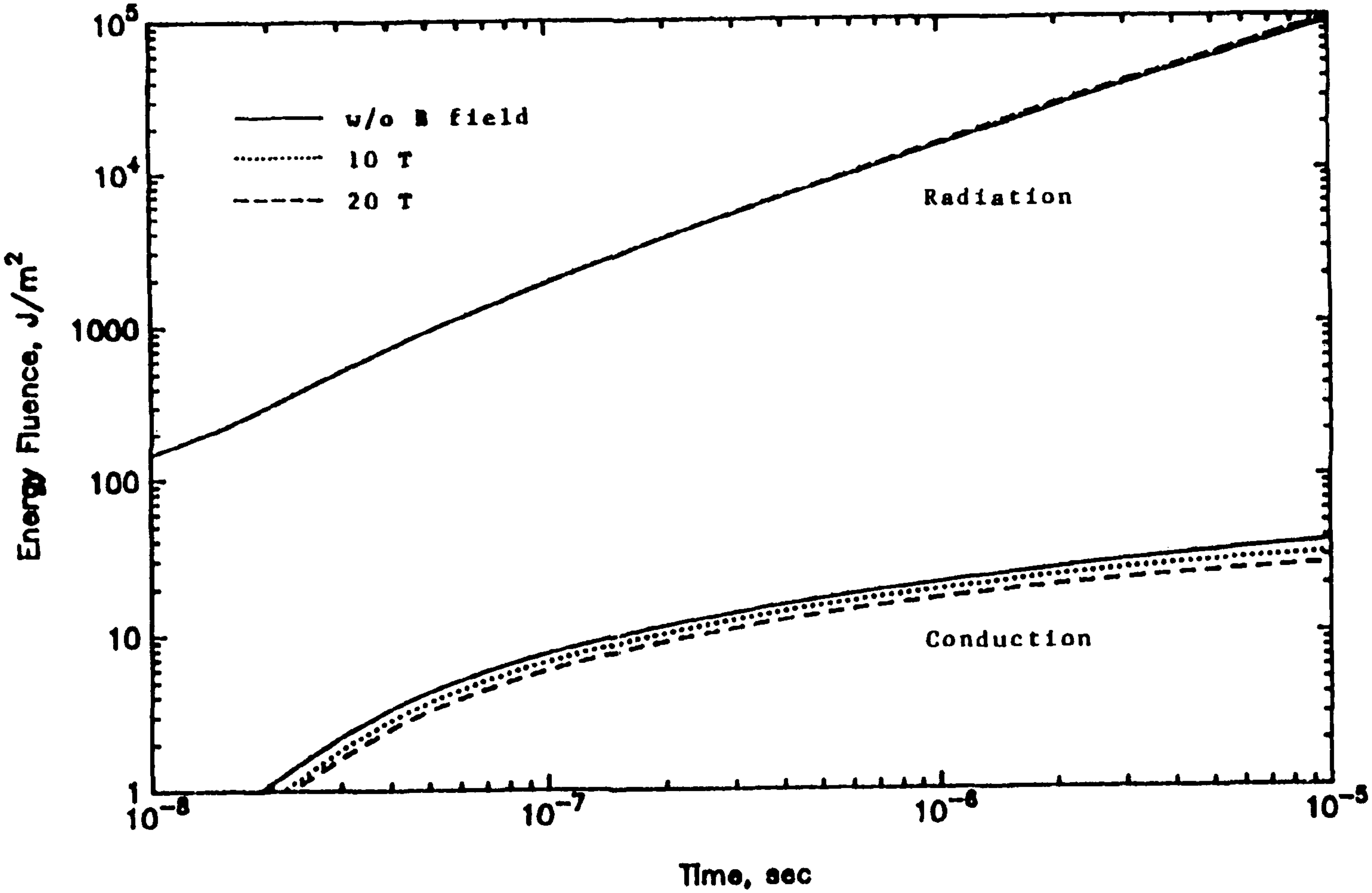


Fig. Energy Fluence at the Surface of an Iron Wall subjected to 3 eV Blackbody Radiation with and without External B Fields of 10 and 20 T

Photon Transport in VS Plasma

- **Radiative Transfer is the dominant mechanism**
- **LTE for VS Plasma**
- **Multigroup Flux Limited Diffusion Model**

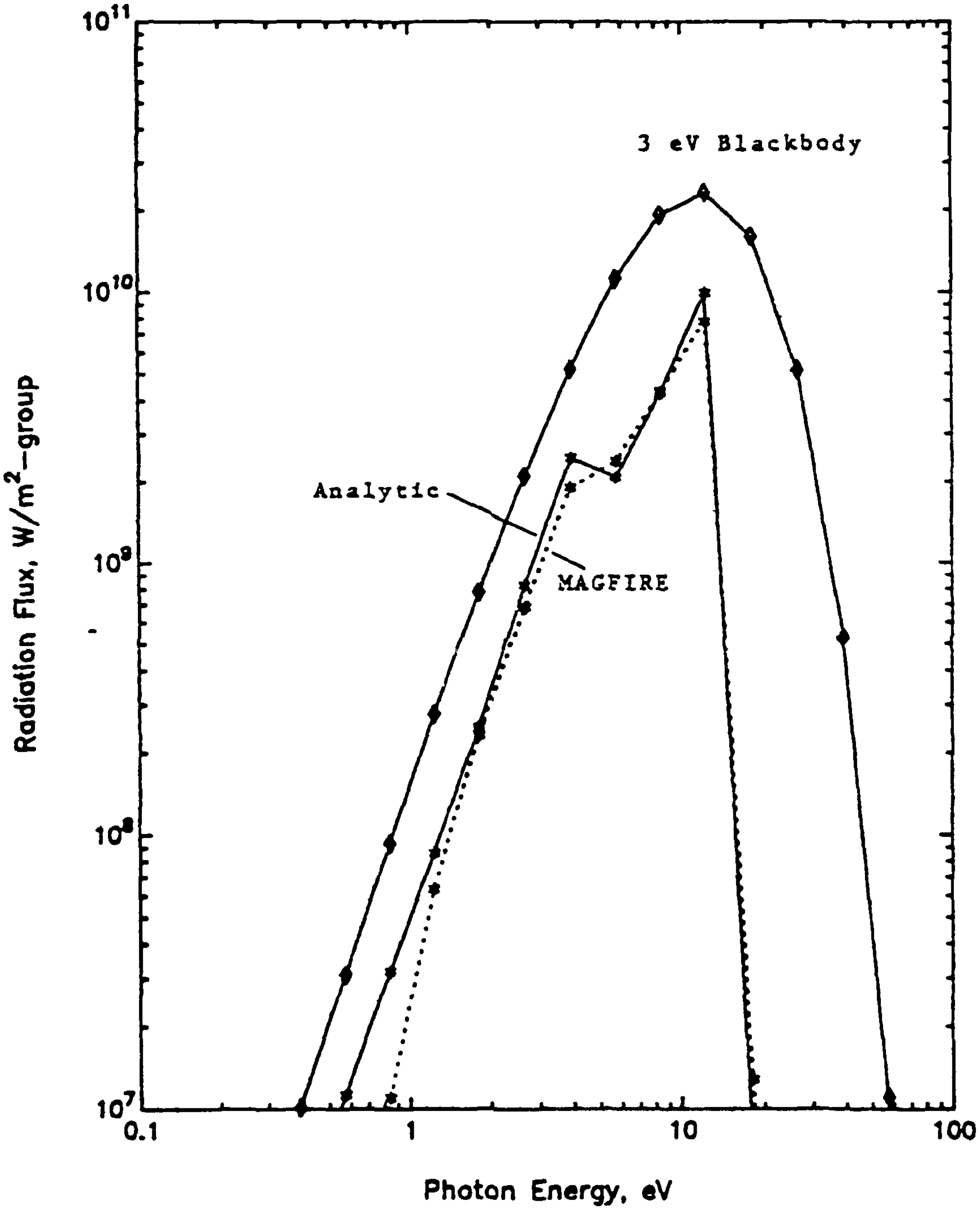


Fig. Radiation Flux at Iron Wall Surface Subjected to a 3 eV Blackbody Radiation (10 μs, Flux Limit = $(c/2)\ U_g$)

Continuity $\frac{\partial}{\partial x} \rho u + \frac{\partial}{\partial y} \rho v = 0$. (1)

Momentum (x component)

$$\rho \left(u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y}\right) = \frac{dP}{dx} + \frac{\partial}{\partial y} \left(\mu \frac{\partial u}{\partial y} - \sigma \overline{u'v'}\right) - \sigma u B_{yo}^2 \qquad (2)$$

Energy

$$\rho \left[u \frac{\partial c_p T}{\partial x}\right] + v \frac{\partial c_p T}{\partial y} = u \frac{dP}{dx} + \frac{\partial}{\partial y} \left(k \frac{\partial T}{\partial y}\right) + \mu \left(\frac{\partial u}{\partial y}\right)^2 + \sigma u^2 B_{yo}^2 \qquad (3)$$

$$+ \omega_p T - \omega_R E_R + \text{turbulent terms}$$

where u and v are the velocity components in the x and y directions respectively, $\overline{u'v'}$ is the perturbed (turbulent) correlation according to the usual Reynolds stresses, μ is the viscosity, σ is the conductivity, B_{yo} is the transverse applied magnetic field, ω_R is the Rosseland radiation absorption coefficient, E_R is the radiation density and ω_p is the radiation emission coefficient.

The equation-of-state will be calculated as a perfect gas with

$$P = \rho RT (1 + \bar{z}) \qquad (4)$$

where $\bar{z}$ is the average charge state determined from Saha equilibrium (found to be valid). The radiation transport equation is

$$\frac{\partial}{\partial y} \kappa_R \left(\frac{\partial E_R}{\partial y}\right) = \omega_R E_R - \omega_p T_p \qquad (5)$$

where κ_R is the radiation conductivity.

The equation for the turbulent kinetic energy $\underline{\bar{k}}$ has the Kitamura form

$$\sigma \epsilon_M \left(\frac{\partial u}{\partial y}\right)^2 + \frac{\epsilon_M}{\underline{\bar{k}}} \frac{\partial \underline{\bar{k}}}{\partial y} + \mu \frac{\partial^2 \underline{\bar{k}}}{\partial y^2} - 0.09 \frac{\underline{\bar{k}}^2}{\epsilon_M} - 0.5 \sigma B_{yo}^2 \underline{\bar{k}} = -\omega_R E_R \qquad (6)$$

where ϵ_M is the eddy diffusivity for momentum.

FINITE ELEMENT ANALYSIS OF ENGINEERING ELECTROMAGNETICS OF ETC GUNS

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ABSTRACT

Finite Element Electromagnetic Analysis has been used to determine the non-uniform current distribution and magnitude of electromagnetic forces associated with the large transient currents, such being used in ETC guns. A commercially available program, MSC/EMAS, which solves for the magnetic vector potential is currently being used to help in analyzing different configurations of conductors and interconnections and in the selection of different materials. Examples of work in progress, on a static solution for a two-dimensional model and a transient solution for a three-dimensional axisymmetric model are presented.

FINITE ELEMENT ANALYSIS OF ENGINEERING ELECTROMAGNETICS OF ETC GUNS

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LAND SYSTEMS DIVISION
WARREN, MICHIGAN

JANNAF WORKSHOP ON ELECTROTHERMAL CHEMICAL GUNS
JULY 9 - 11, 1991

FINITE ELEMENT ANALYSIS OF ENGINEERING ELECTROMAGNETICS OF ETC GUNS

OUTLINE

- THE ISSUES
- THE APPROACH
- ILLUSTRATIVE EXAMPLES

THE ISSUES

WITH LARGE TRANSIENT CURRENTS USED, THE ISSUES ARE SIMILAR TO THOSE IN RAIL GUNS.

SUCH AS

- NON-UNIFORM CURRENT DISTRIBUTION
- EDDY CURRENTS
- LARGE ELECTROMAGNETIC FORCES
- LOCALIZED HEATING

WHY WE NEED TO LOOK AT FIELD PROBLEMS

NON-UNIFORM CURRENT DISTRIBUTION

SKIN EFFECTS	(ISOLATED CONDUCTOR)
PROXIMITY EFFECT	(ADJACENT CONDUCTORS)
ELECTROMAGNETIC FORCES	(PROPORTIONAL TO I^2/d)
EDDY CURRENT EFFECTS	(SURROUNDING MEDUIM)

IN ETC

SUCH PROBLEMS ARISE IN

POWER SUPPLY FEEDS

AND INTERCONNECTIONS.

THE APPROACH:

- FINITE ELEMENT ANALYSIS
  - THE MAC-NEAL SCHWENDLER CORPORATION (MSC)
  - ELECTROMAGNETIC ANALYSIS (MSC/EMAS) ONLY
  - COUPLING TO STRUCTURAL/THERMAL ANALYSIS (MSC/NASTRAN)

ILLUSTRATIVE EXAMPLES:

- LINEAR MAGNETOSTATICS
- TRANSIENT ANALYSIS
- POWER LOSS - THERMAL ANALYSIS (COUPLING EMAS AND NASTRAN)

MAXWELL'S EQUATIONS:

AMPERE'S LAW	$\nabla \times \bar{H} = \bar{J} + \dot{\bar{D}}$
FARADAY'S LAW	$\nabla \times \bar{E} = - \dot{\bar{B}}$
FARADAY'S DEFINITION	$\nabla \cdot \bar{D} = \rho$
GAUSS' LAW	$\nabla \cdot \bar{B} = O$

SOLUTION APPROACHES

- CLOSED FORM
- APPROXIMATE METHODS
- NUMERICAL ALGORITHMS √

ALTERNATIVE

- CIRCUIT APPROXIMATION DERIVED FROM FIELD THEORY

USE OF NUMERICAL ALGORITHMS SPURRED BY

- DEVELOPMENTS OF INTERACTIVE GRAPHICS
- ADVANCES IN NUMERICAL ANALYSIS

NUMERICAL METHODS FOR SOLVING MAXWELL'S EQUATIONS

BOUNDARY ELEMENT

- EQUATIONS IN INTEGRAL FORM
- SOLUTION FOR SOURCES OF THE FIELD ON THE BOUNDARIES

FINITE ELEMENTS

- DIFFERENTIAL FORM
- SOLUTION FOR POTENTIALS AT GRID POINTS

FINITE DIFFERENCE

- DIFFERENTIAL FORM
- REGULAR MESH

FINITE ELEMENT METHODS

- ORIGINATED IN STRUCTURES
- FIRST APPLIED FOR ELECTROMAGNETICS IN 1969

NOW USED IN DIVERSE AREAS SUCH AS

- INTEGRATED CIRCUITS
- MICROWAVES
- OPTICS
- POWER CONVERSION
- MAGNETICS
- DIGITAL INTERCONNECTS

IN MSC/EMAS:

POTENTIAL SUBSTITUTIONS FOR FIELDS

$$\bar{B} = \nabla \times \bar{A}$$

$$\bar{E} = -\dot{\bar{A}} - \nabla \dot{\Psi}$$

$\bar{A}$ = MAGNETIC VECTOR POTENTIAL

Ψ = SCALAR POTENTIAL

CONVENTIONAL REPRESENTATION

$$\bar{E} = -\dot{\bar{A}} - \nabla \varnothing$$

$\varnothing$ = VOLTAGE

VECTOR POTENTIAL

$$\bar{U} = \begin{Bmatrix} \bar{A} \\ \Psi \end{Bmatrix}$$

IS DETERMINED AT EVERY NODE (GRID POINT)

FIELD QUANTITIES ARE RECOVERED.

PRE- AND POST- PROCESSING THRU MSC/XL.

GOVERNING MATRIX EQUATIONS

ELECTROMAGNETICS:

$$[\varepsilon][\ddot{\bar{U}}] + [\sigma][\dot{\bar{U}}] + [\tfrac{1}{\mu}][\bar{U}] = [\bar{J}]$$

PERMITTIVITY — CONDUCTIVITY — RELUCTIVITY — CURRENT

$[\bar{U}]$ = FUNCTION OF VECTOR AND SCALAR POTENTIALS

$\bar{U}$ IS SOLVED

STRUCTURES:

$$[M][\ddot{\bar{U}}] + [B][\dot{\bar{U}}] + [K][\bar{U}] = [\bar{P}]$$

MASS — DAMPING — STIFFNESS — FORCE (LOADS)

$[\bar{U}]$ = DISPLACEMENTS

[MSC/EMAS - MSC/NASTRAN: EXACT ONE-TO-ONE RELATIONSHIP]

MCS/EMAS

- A GENERAL PURPOSE ANALYSIS FOR SOLVING ELECTRIC AND MAGNETIC FIELD PROBLEMS
- FULLY THREE DIMENSIONAL PROGRAM
- CAPABILITY TO MIX 3-D, 2-D, 1-D AND SCALAR ELEMENTS
  - CAN INCLUDE CIRCUIT ANALYSIS
- INCLUDES INTEGRATED GRAPHICS
- SOLUTION SEQUENCES AVAILABLE FOR
  - LINEAR STATIC ANALYSIS
  - NONLINEAR STATIC ANALYSIS
  - FREQUENCY RESPONSE
  - REAL AND COMPLEX EIGENVALUE ANALYSIS
  - TRANSIENT ANALYSIS
- AVAILABLE ON SEVERAL COMPUTER PLATFORMS: WORKSTATIONS, MAINFRAMES
- CAPABILITY FOR COUPLING TO STRESS/THERMAL - MSC/NASTRAN

STEPS IN SOLUTION:

- **DESCRIBE PROBLEM**
  - **GEOMETRY**
  - **MESH GENERATION**
  - **MATERIALS**
    - CHARACTERISTICS (ρ, σ, ε, Linear/Non Linear)
  - **EXCITATIONS**
    - CURRENTS, CHARGES, PERMANENT MAGNETS
  - **BOUNDARY CONDITIONS**
- **CHOOSE SOLUTION TYPE**
- **SOLVE**
- **VIEW RESULTS**

MSC/NASTRAN TYPES OF ANALYSIS

- Linear Static Analysis
- Static Analysis with Geometric Nonlinearity
- Static Analysis with Material Nonlinearity
- Vibrational Analysis
- Buckling Analysis
- Direct and Modal Complex Eigenvalue Analysis
- Direct and Modal Frequency Analysis and Random Response

THREE DIMENSIONAL ANALYSIS OF AN ALUMINUM BRICK

DEVICE: RECTANGULAR ALUMINUM BLOCK WITH RECTANGULAR HOLE, SURROUNDED BY AIR

PURPOSE: TO DETERMINE EDDY CURRENTS AND POWER LOSSES IN THE BRICK.

(TEAM - TESTING ELECTROMAGNETIC ANALYSIS METHODS - PROBLEM)

TRANSIENT ANALYSIS

EXCITATION: A TANGENTIAL MAGNETIC FIELD, DECAYING EXPONENTIALLY WITH TIME IS APPLIED TO TWO PLANES FARTHEST FROM THE BRICK.

RESULTS: TOTAL POWER LOSS

ARROW PLOTS OF INDUCED CURRENTS AT DIFFERENT TIMES.

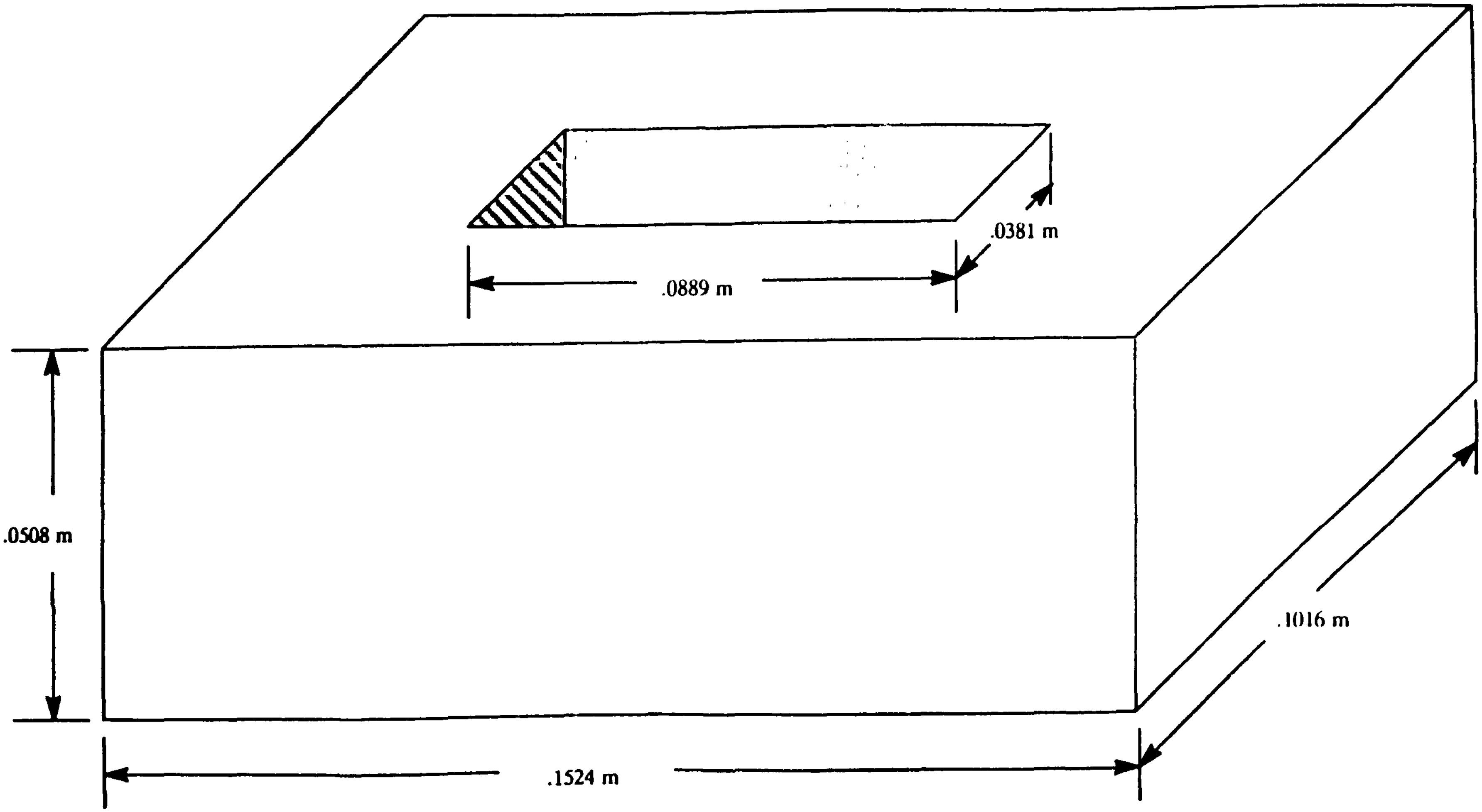


Figure 1. Dimensions of the "Felix Brick"

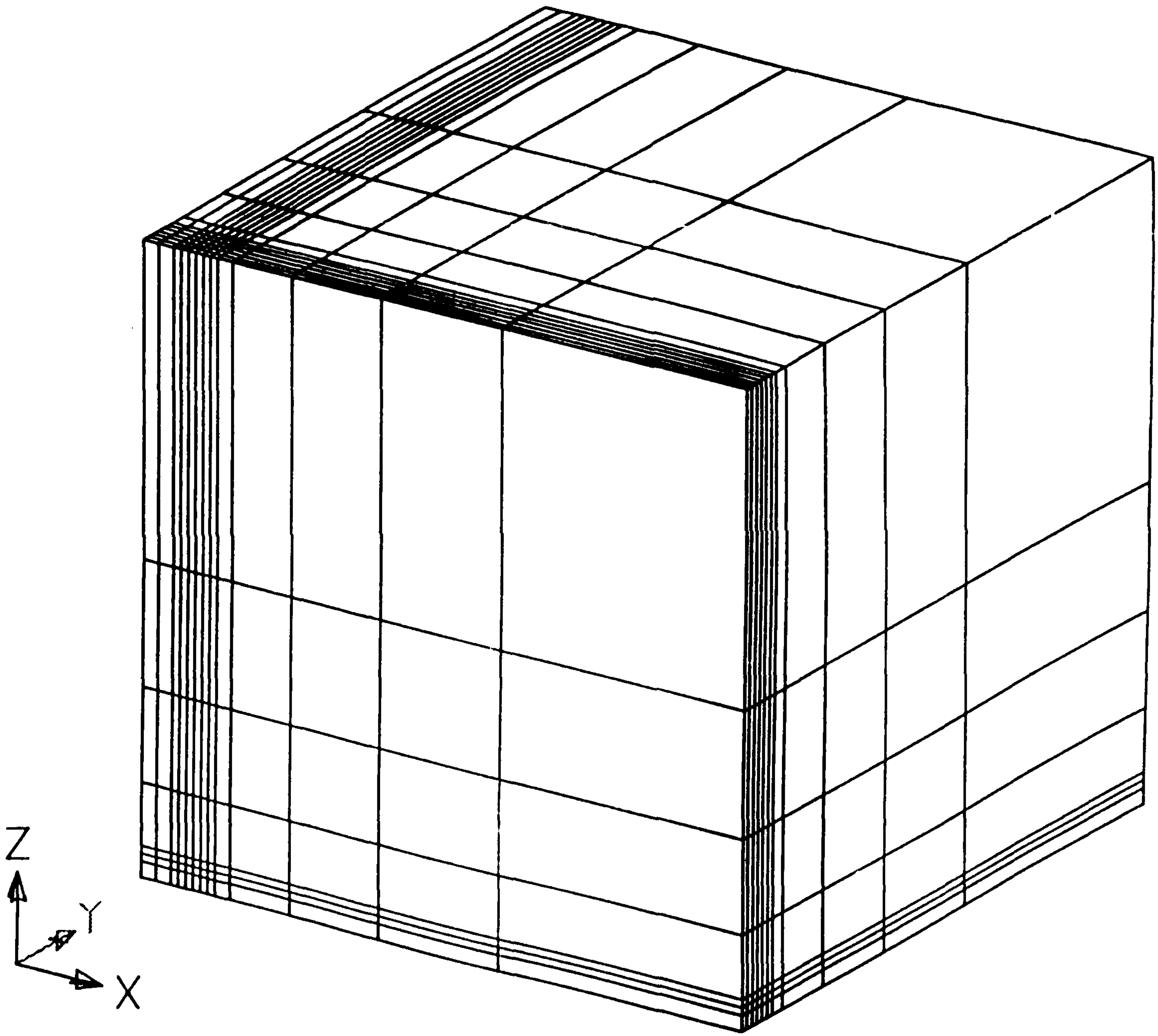


Figure 2. Entire Finite Element Mesh as defined by TEAM problem 4

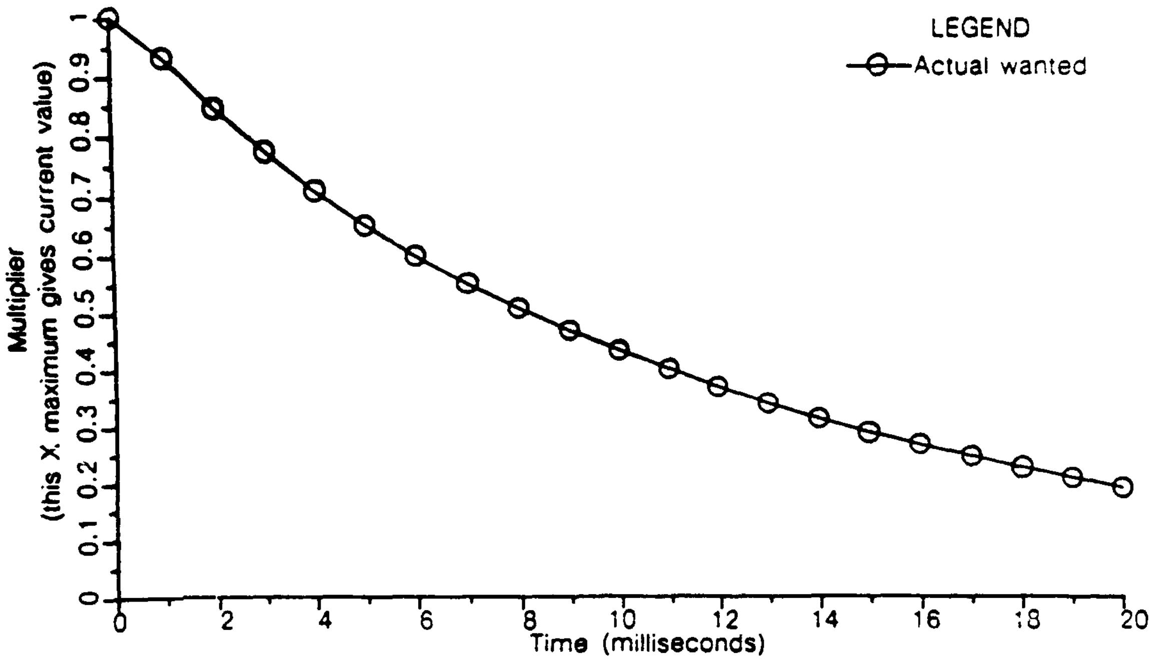


Figure 10. Transient excitation wanted

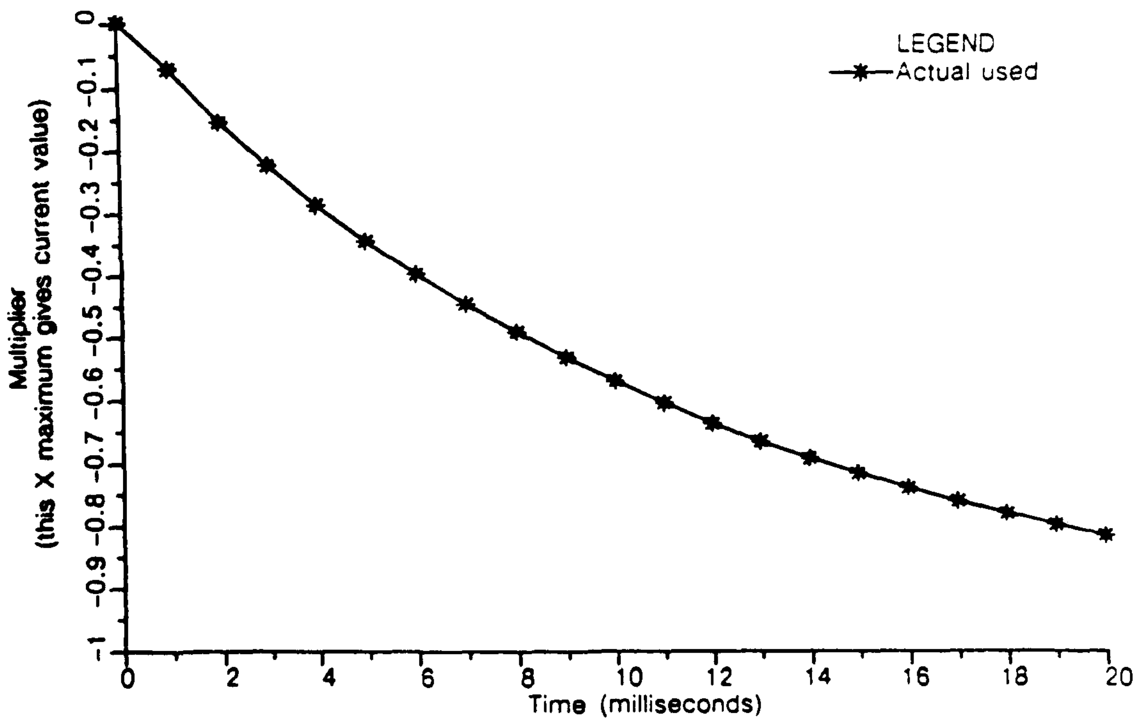


Figure 11. Transient excitation used

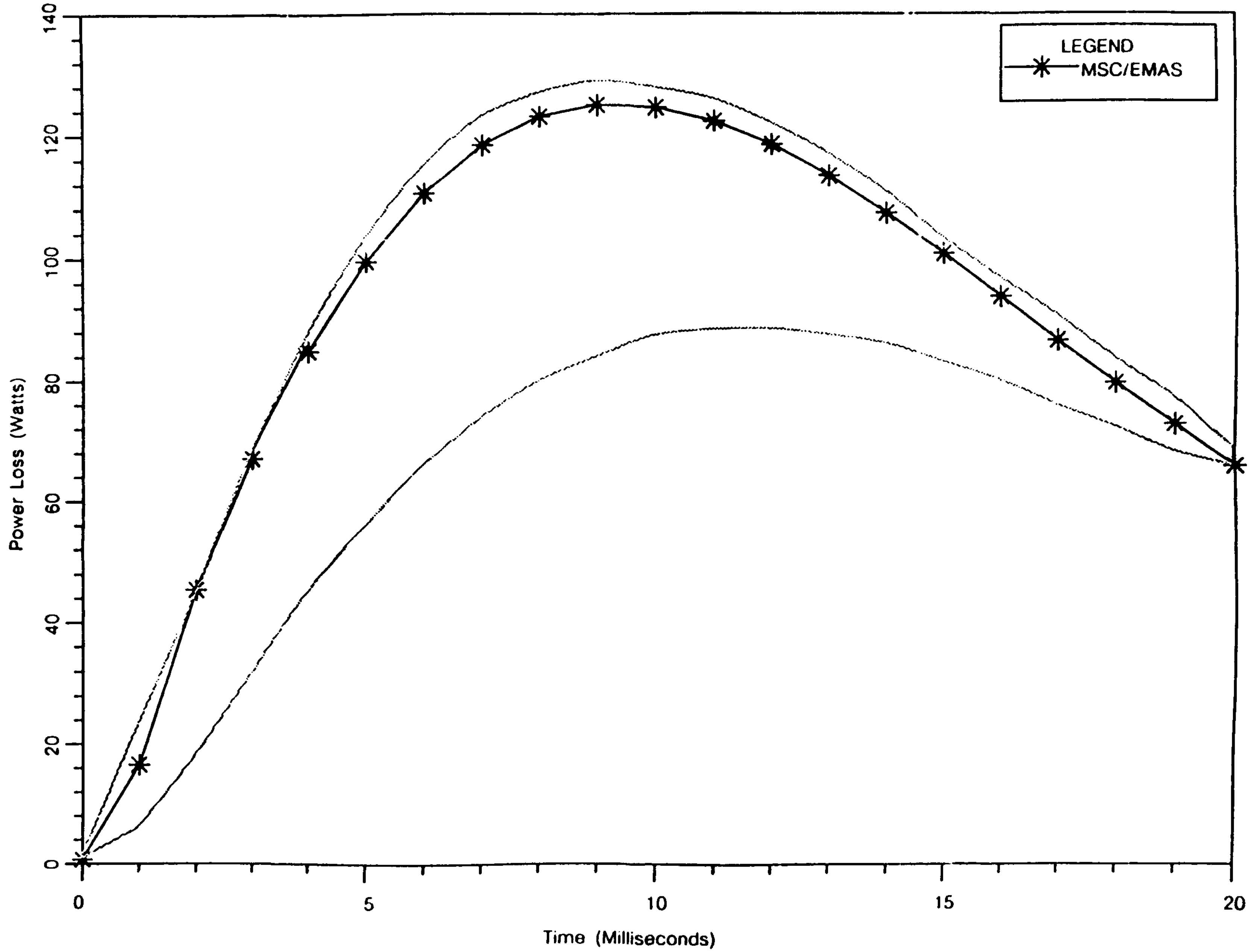


Figure 5. Emas results plotted with envelope of reported results

TRANSIENT EDDY CURRENT ANALYSIS OF SUPERCONDUCTING COIL

DEVICE:	TWO SUPERCONDUCTING SADDLE COILS - STAINLESS STEEL SUPPORT STRUCTURE
	END TURNS EXTEND OUT OF SUPPORT
	AIR FILLED BEAM TUBE
PURPOSE:	TO DETERMINE THE EFFECT OF EDDY CURRENTS ON THE MAGNETIC FIELD WITHIN THE BEAM TUBE.
	TRANSIENT ANALYSIS
MODEL:	ONE FOURTH OF DEVICE
MATERIALS:	REL. PERMEABILITY = 1.004
	J (STAINLESS STEEL) = 2E6 S/M
	J (COIL) = 6.25 E6 S/M (USED 1 S/M)
EXCITATION:	CURRENT DENSITY ON OUTER (+) AND INNER (-) COILS
	CURRENT RAMPED FROM 0 TO 720 KA IN 3 MINUTES
RESULTS:	INDUCED CURRENTS IN STAINLESS STEEL
	FLUX DENSITY ALONG TWO PATHS IN BEAM TUBE
	INDUCED CURRENTS - ARROW PLOTS

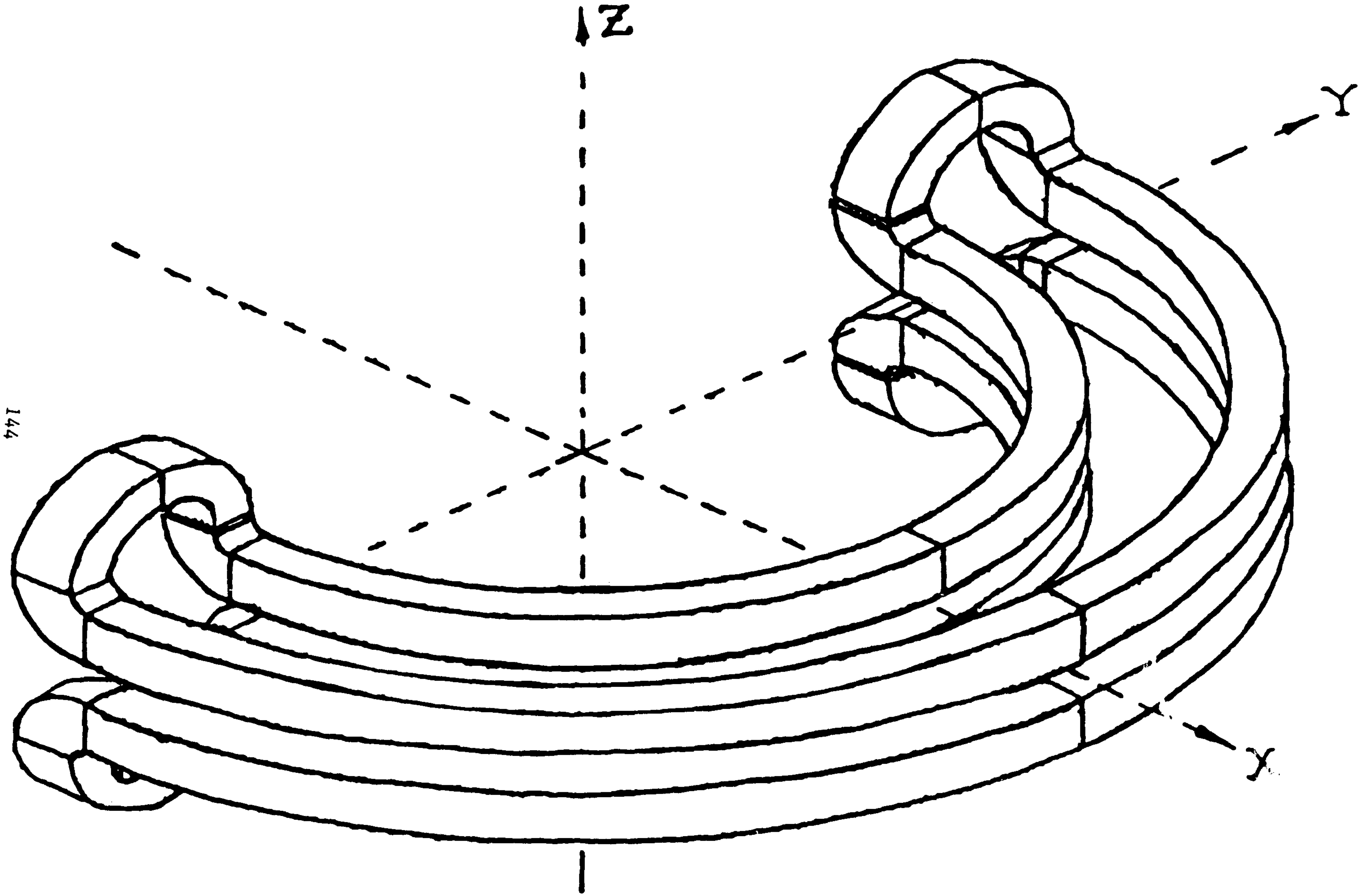


Figure 1. Saddle Coils

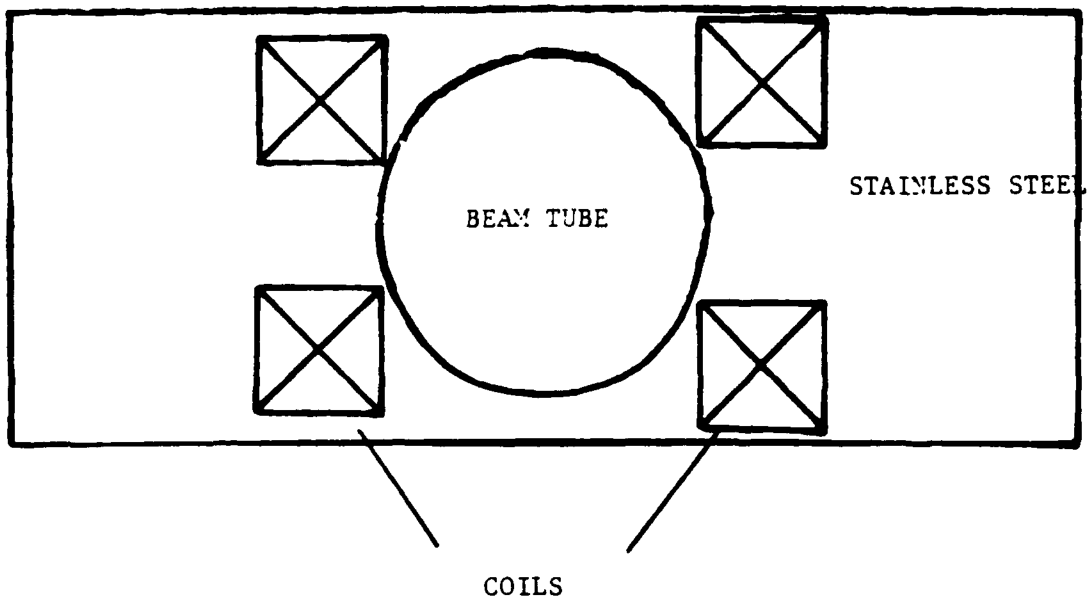


Figure 2. Cross Section View of Device

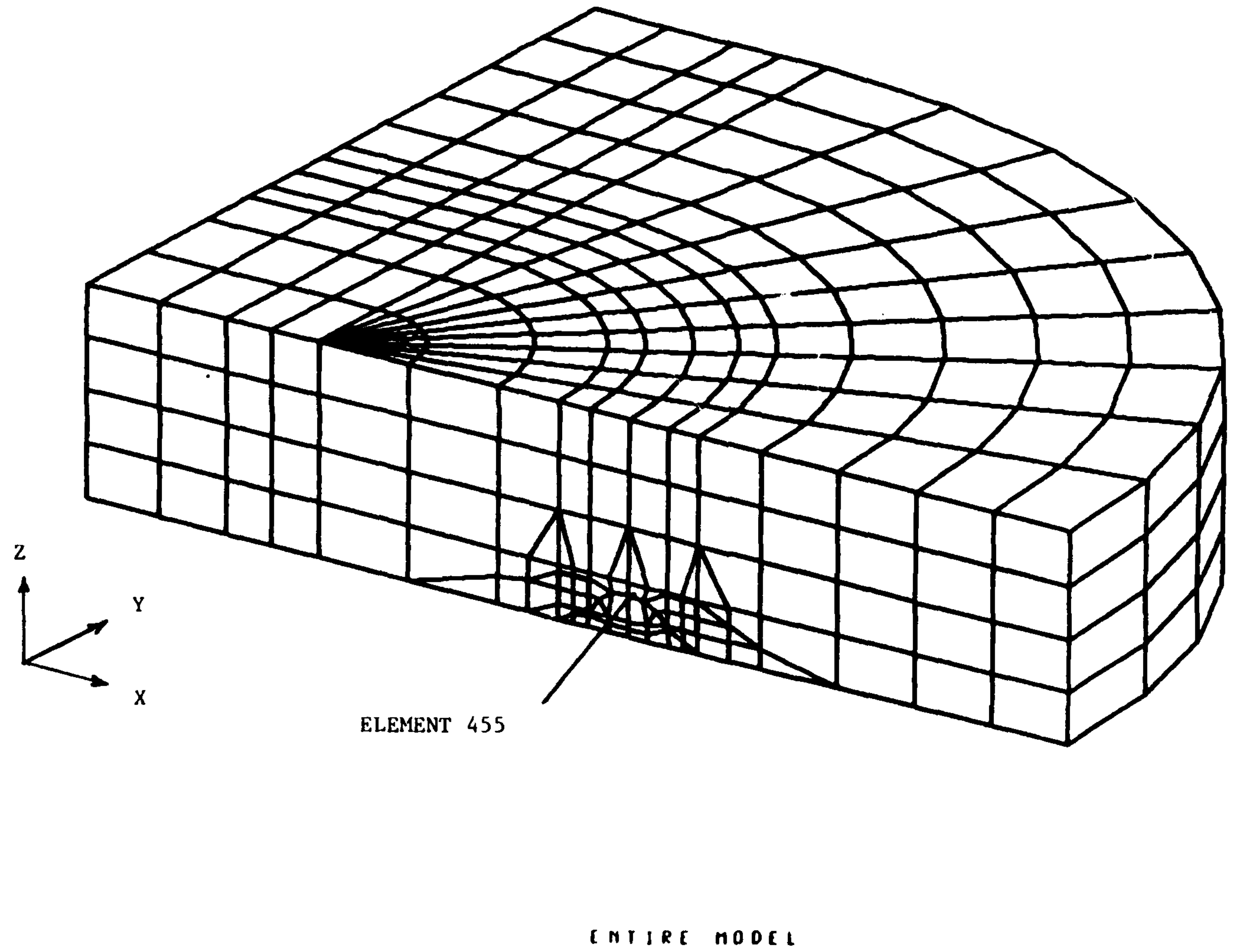


Figure 3. Finite Element Model

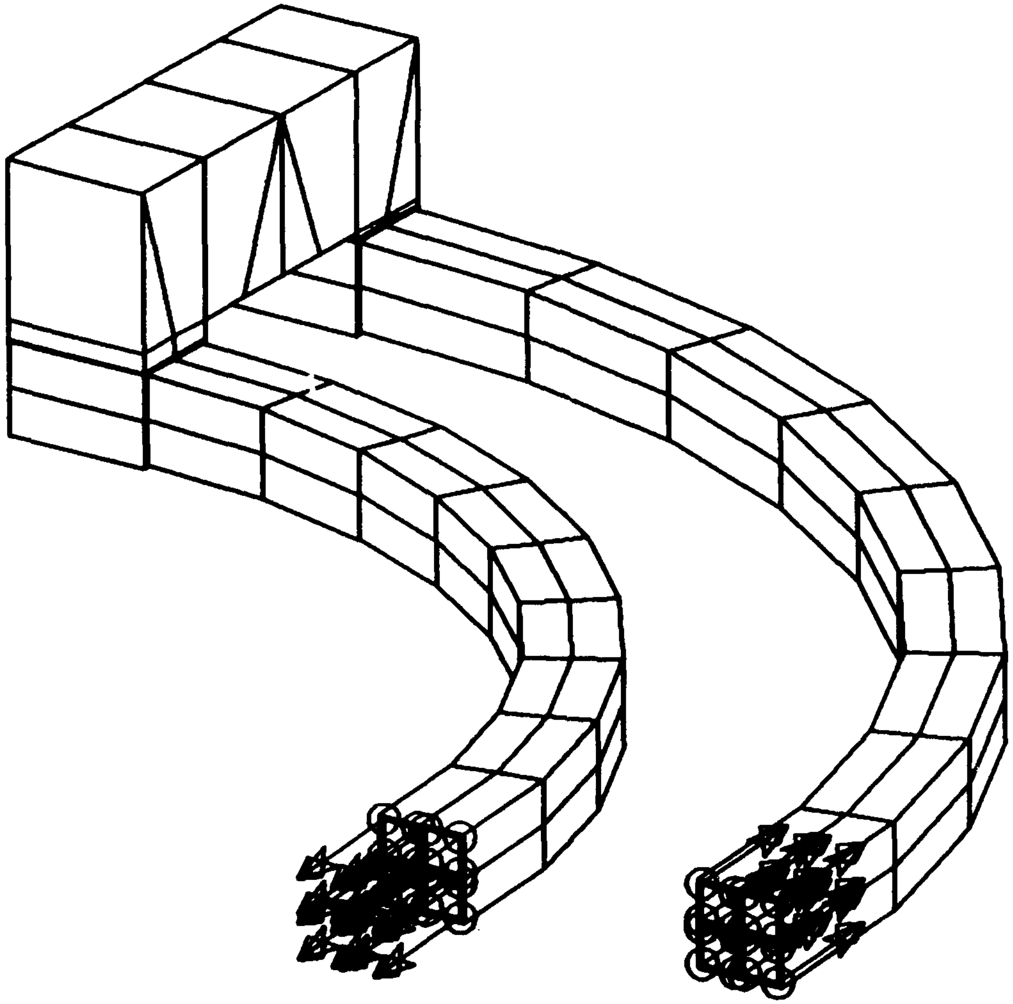


Figure 4. Coil

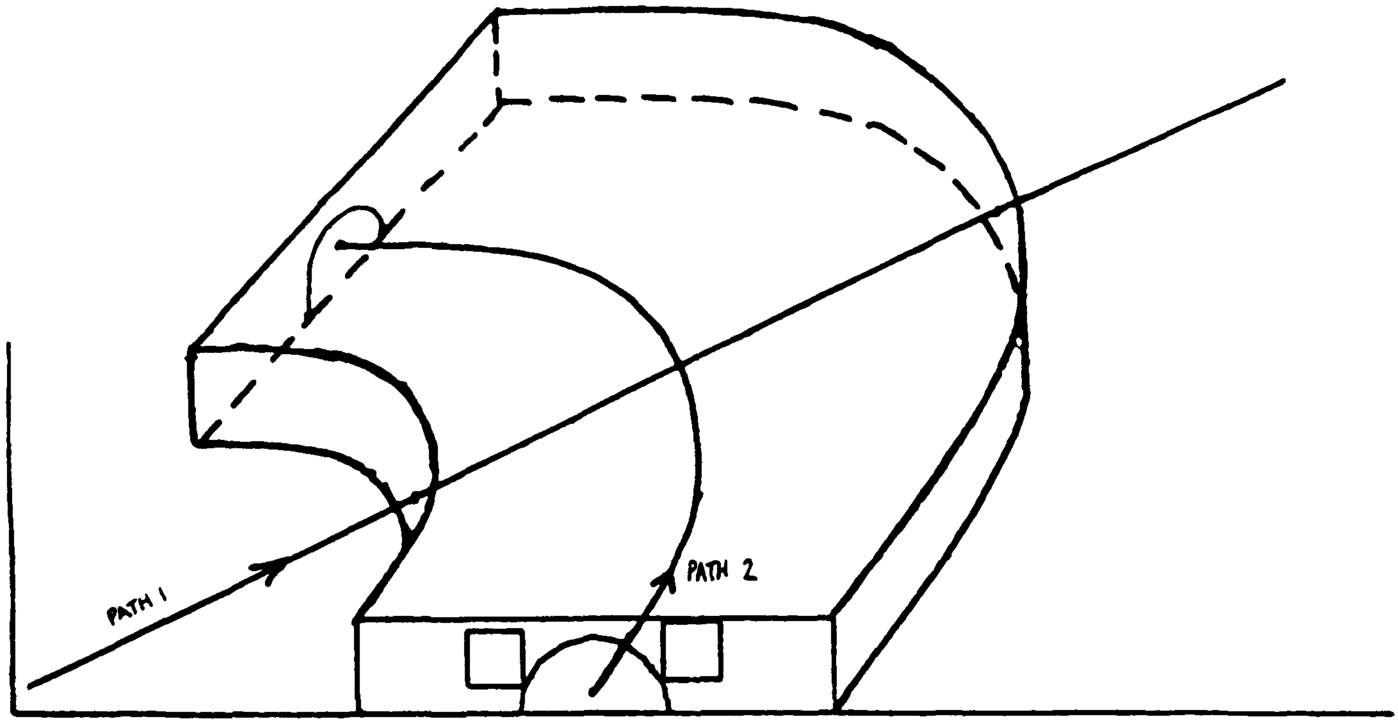


Figure 6. Sketch of Paths

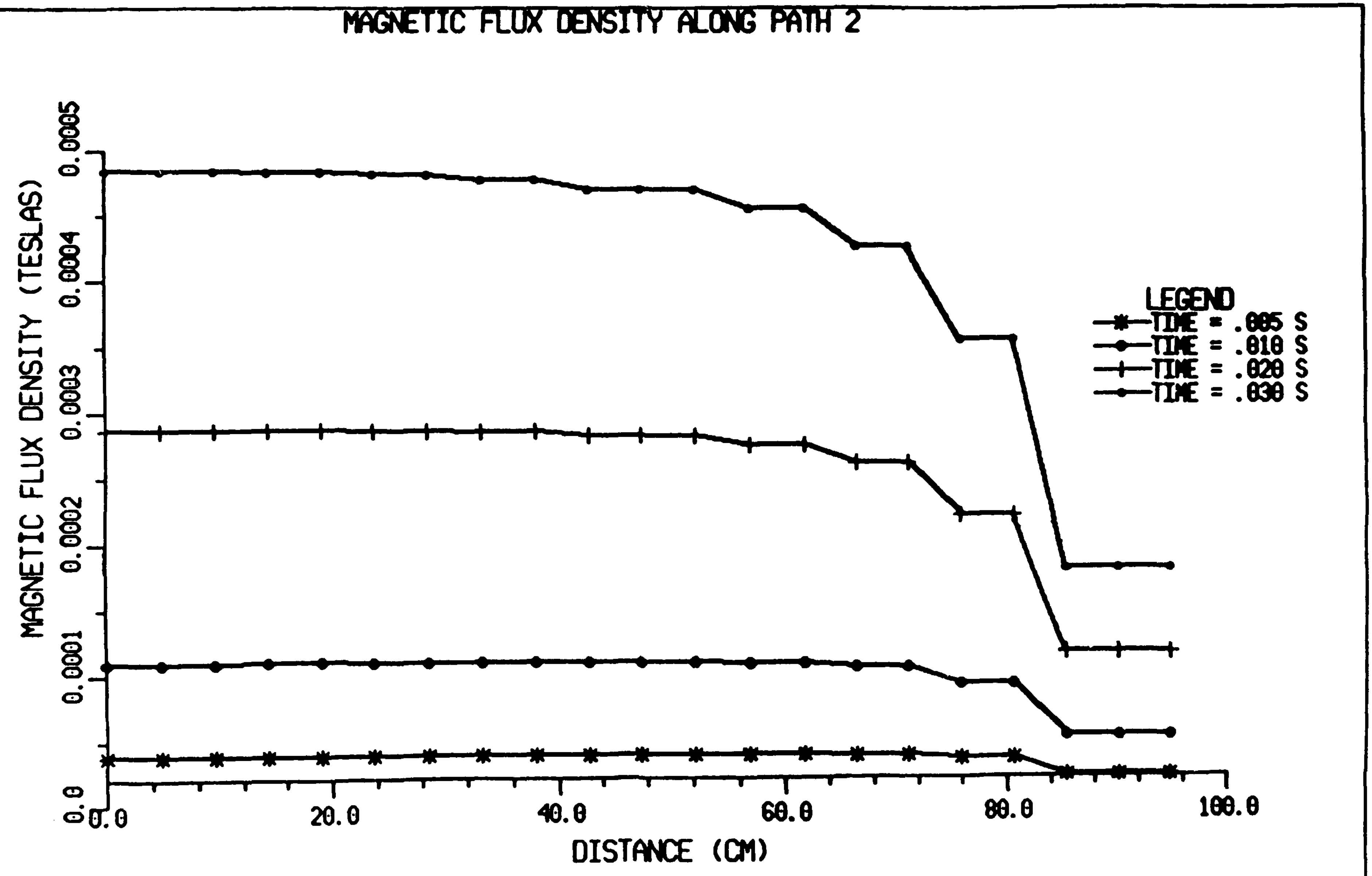


Figure 7. Magnetic Flux Density Along Center of Beam Tube

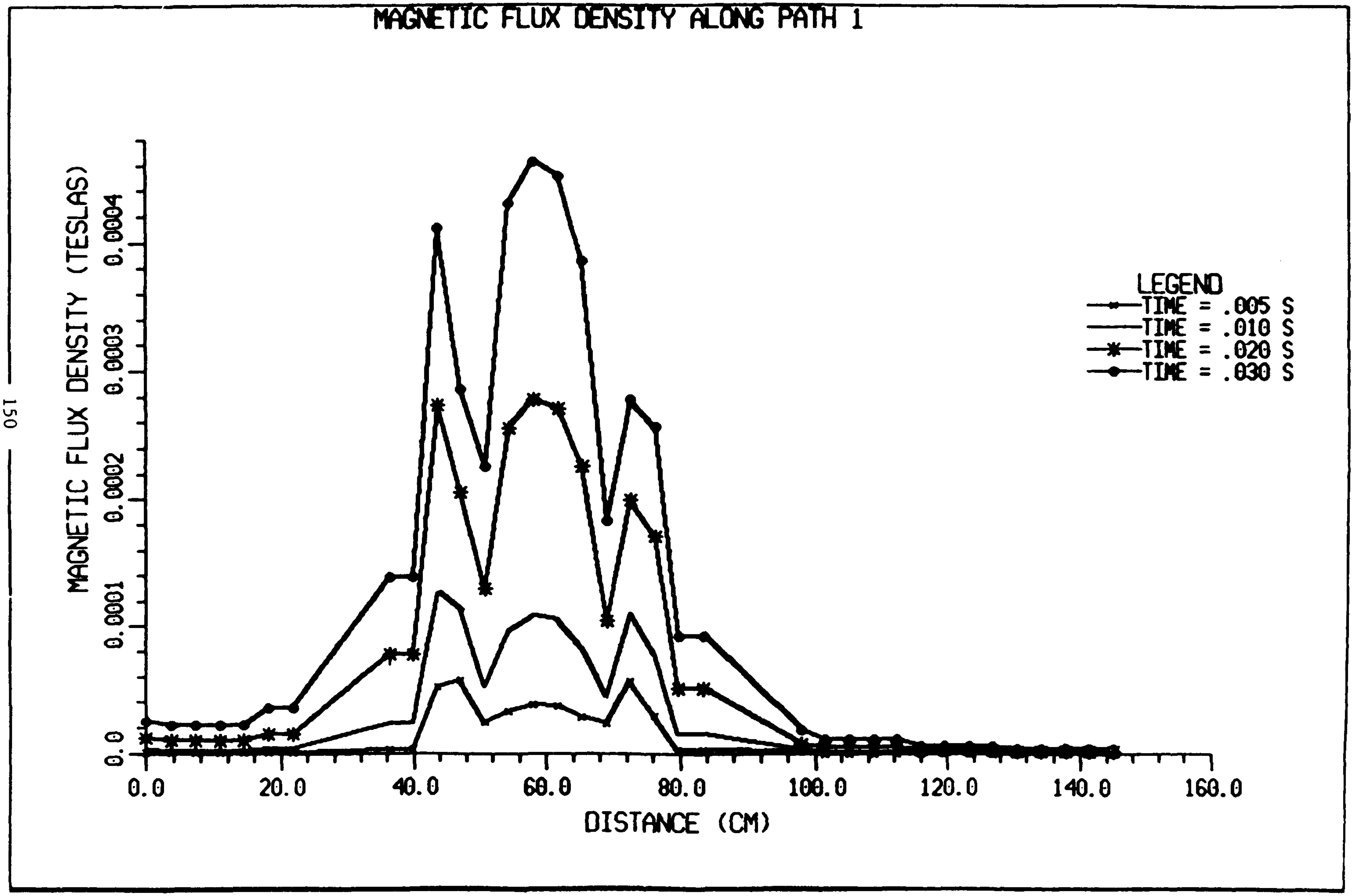


Figure 8. Magnetic Flux Density Along Radial Path

COUPLING OF MSC/EMAS POWER LOSSES TO MSC/NASTRAN THERMAL ANALYSIS

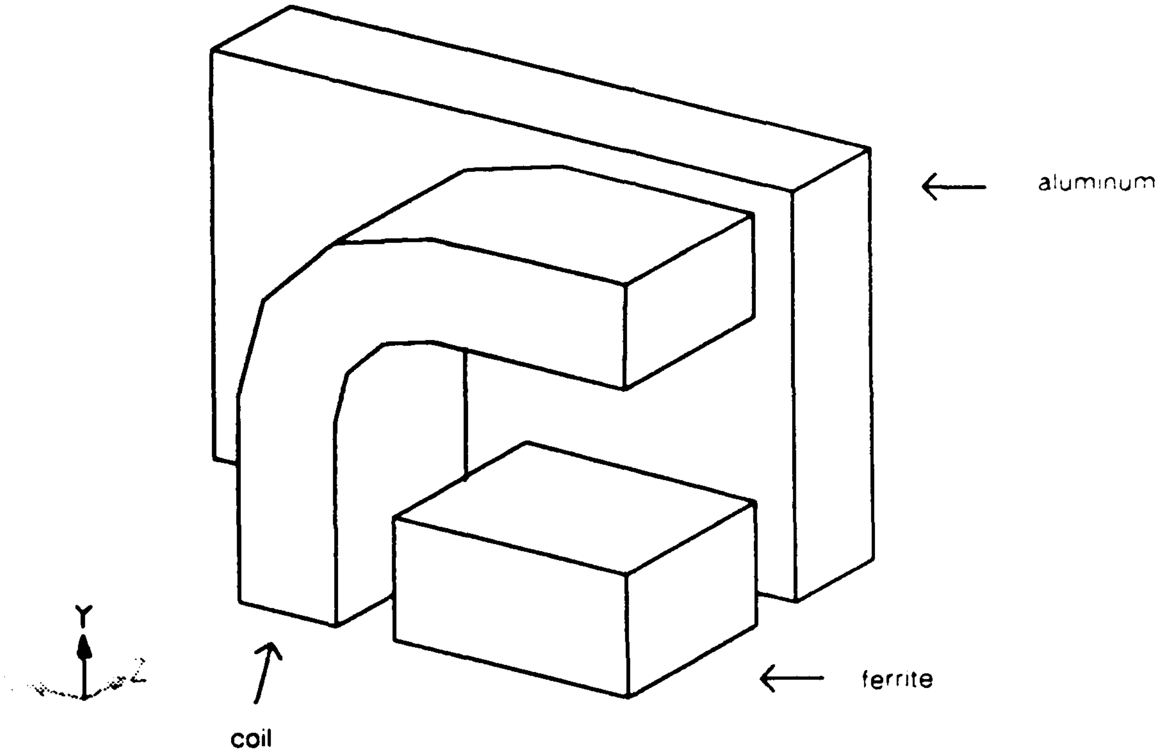
DEVICE: THREE-DIMENSIONAL REPRESENTATION OF FERRITE CORE SURROUNDED BY A COIL AND AN ALUMINUM PLATE

PURPOSE: TO DETERMINE POWER LOSS DENSITY AND TEMPERATURE DISTRIBUTION.

RESULTS:

POWER LOSS IN ALUMINUM PLATE	0.571 WATTS
MAXIMUM TEMPERATURE	47.3°C

RADIATION IS NOT A FACTOR



Outline Plot of 3-D Benchmark Model

ACKNOWLEDGEMENTS

THE MACNEAL - SCHWENDLER CORPORATION

E/EAD MILWAUKEE

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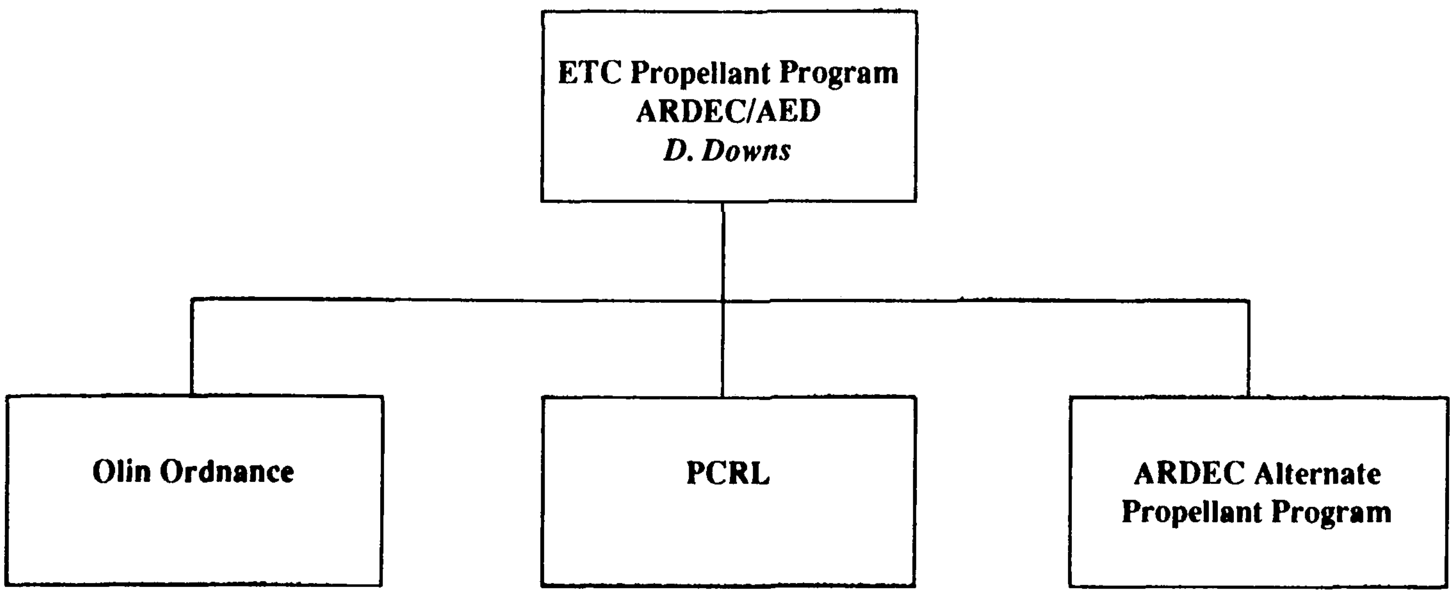
Army Alternate ETC Propellant Program

ARDEC

Army ETC Gun Propellant Development Program

ARMAMENT ENGINEERING DIRECTORATE

PROPULSION BRANCH



ARDEC

Army ETC Gun Propellant Development Program

ARMAMENT ENGINEERING DIRECTORATE

PROPULSION BRANCH

ARDEC :

- *Multi-year effort*
- *Identify alternate ETC propellants*
- *4 candidate propellants (gels, slurries) - Aug 91 - June 92*
- *Characterize candidate ETC-P developed in-house and by contractor*

Olin Inc. :

- *2 year contract*
- *Identify alternate ETC propellants*
- *2 - 5 candidate propellants (gels, solids or emulsions) - June 92*

PCRL :

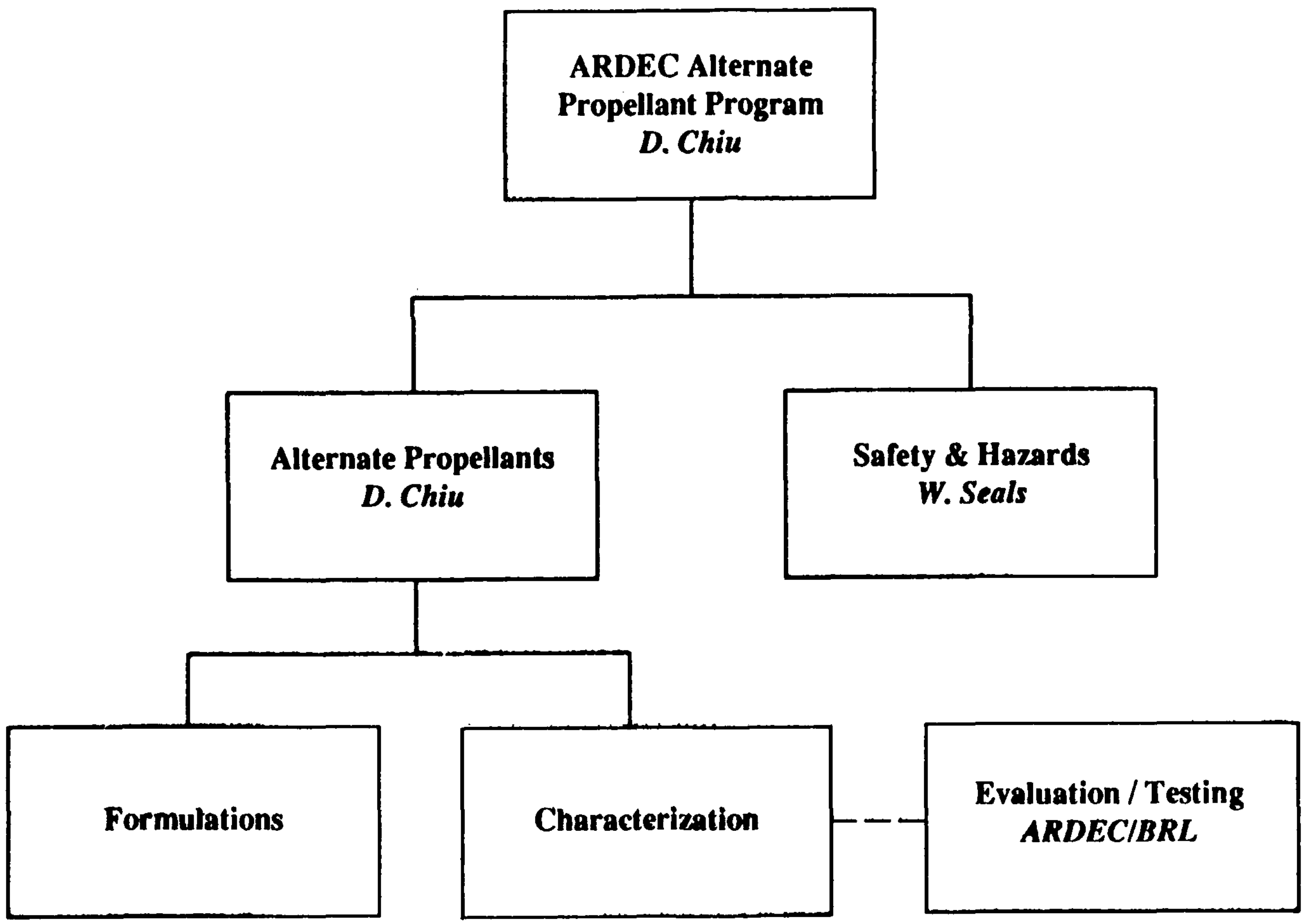
- *1 year contract*
- *Identify alternate ETC propellants*
- *2 candidate HAN-based energetic emulsions (propellants) - June 92*

ARDEC

Army ETC Gun Propellant Development Program

ARMAMENT ENGINEERING DIRECTORATE

PROPULSION BRANCH



ETC Alternate Working Fluid

Desired ETP Properties:

- *High specific energy density*
- *Low flame temperature*
- *Low molecular weight of combustion products*
- *Safe to handle*
- *Insensitive*
- *Long term stability*
- *Plasma energy provides control over ballistic cycle*

ETC Alternate Working Fluid

Advantages of Gel Propellant:

- *High Impetus*
- *Low Flame Temperature*
- *High Energy Density*
- *Ease of Processing*

ARDEC

ETC Alternate Working Fluid

ARMAMENT ENGINEERING DIRECTORATE

PROPULSION BRANCH

ETP evaluation methodology:

- thermochemical calculation
  - *with electrical energy input*
- review material safety data sheet (MSDS)
  - *sensitivity*
  - *safety*
  - *toxicity*
- small scale mix
  - *compatibility*
  - *processing parameters*
  - *gelling agents*
  - *physical stability*
- screening tests
  - *physical properties (density, viscosity, boiling pt., freezing pt.)*
  - *chemical properties (HOE, DSC)*
- large scale mix
  - *large scale processing parameters*
- Characterization
  - *IHC tests*

HAZARD CLASSIFICATION

Interim Hazard Classification (IHC) Tests:

1. *Thermal*
2. *Impact*
3. *Electrostatic*
4. *Card Gap*
5. *Detonation*
6. *Flash Point*
7. *Ignition and Unconfined Burning*

Additional Tests for System Safety Analysis:

1. *Adiabatic Compression Ignition*
2. *Critical Diameter*
3. *JANNAF Thermal Stability*
4. *Minimum Pressure for Vapor Phase Ignition*

Final Hazard Classification (Large Scale Tests):

(Conducted in approved DoD containers)

1. *Single Package Test*
2. *Stack Test*
3. *External Fire*

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ETC Alternate Working Fluid

Toxicity Test Program

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PROPULSION BRANCH

STATUS: ***Correspondence sent to the Surgeon Generals Office requesting a work effort for the ETC Working Fluid be conducted at Army Environmental Health Agency (AEHA).***

Toxicity Test Program:

I. Conduct literature search on each component of all working fluid composition candidates

II. Determine the following toxicity effects from selected candidate working fluid compositions:

1. *Skin Exposure*
   a. *Skin Irritation (15% exposure on Guinea Pigs)*
   b. *LD Value Determination*
2. *Oral Exposure*
   a. *Rats*
   b. *Dogs*
3. *Eye Irritation*

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ETC Alternate Working Fluid Program

10mm Plasma/WF Test Fixture

ARMAMENT ENGINEERING DIRECTORATE — PROPULSION BRANCH

Objective: *Evaluate the performance of candidate working fluid near actual ETC Gun condition.*

Approach:

- *Vented combustor nozzles were added at the plasma capillary and the combustion chamber exits to control the interactions between the hot plasma source and the working fluid.*
- *Measure pressure and thrust (basic methodology) as function of plasma parameters and working fluid.*

Accomplishments:

- ***Completed final design of the vented 10mm plasma/WF test fixture***
- ***Completed initial design of power supply and pulse forming network (PFN) for the fixture***
- ***Prepared SOP for the test fixture***

Planned Accomplishments:

- *Construct and install the 10mm plasma/WF test fixture*
- *Develop working fluid performance evaluation methodology*
- *Performance studies of working fluids from ARDEC and other contractors*

ETC Alternate Working Fluid

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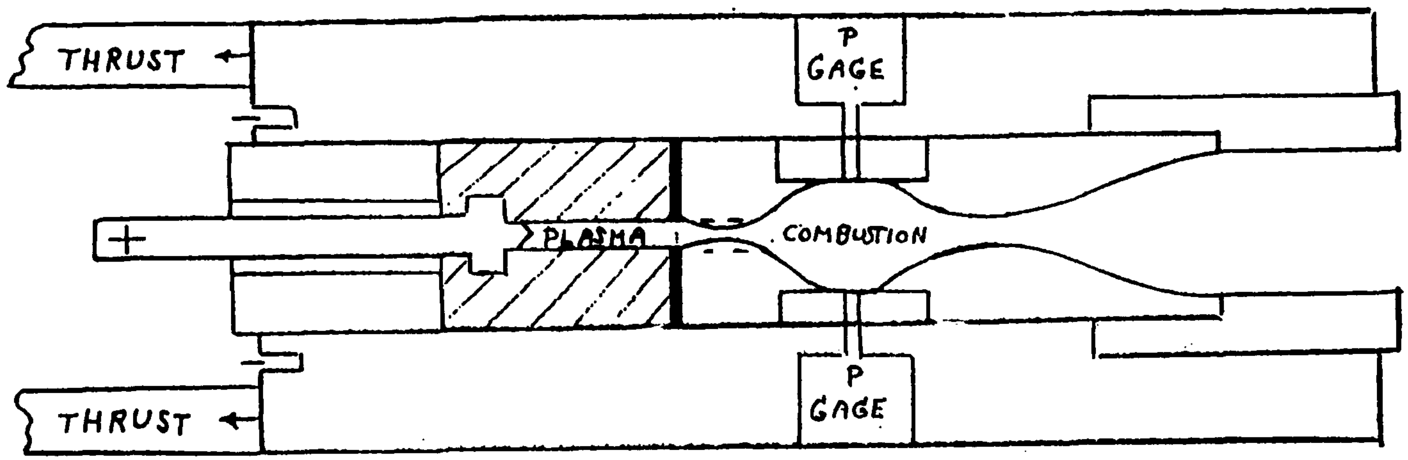
PROPULSION BRANCH



Army ETC Gun Propellant Development Program

Lot #	7655	7665	7669	Future
TMETN	-	80%	27%	20%
DEGDN	90%	-	-	-
RDX	-	-	58%	70%
EGLY	10%	20%	-	10%
PGLY	-	-	15%	-
Gelling Agent (added)				
Klucel H	-	0.5%	1%	1%
NC12.6	5%	1%	-	-
EC	0.05%	0.01%	-	-
Flame Temp, K	2587	2373	2746	3348
Impetus, J/g	1052	998	1125	1255
Gamma	1.261	1.269	1.269	1.254
Mol. Wt.	20.46	19.78	20.29	22.18
Calc. Density, g/cc	1.37	1.38	1.54	1.63
Vol. Energy, MJ/L	5.52	5.12	6.44	8.05

Safety Tests

- Impact
  - *ARDEC*

    30 mg sample on sandpaper

    2.5 Kg drop wt.
- Electrostatic discharge
- Sliding friction

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Impact Tests

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Sample	cm
RDX	24.0
HELOVA II	44.8
M30	16.2
JA-2	< 12.0
7655	68.8
7665	> 100.0

Electrostatic & Friction Tests

Sample	Electrostatic	Friction
7655	no reaction	no reaction
7665	no reaction	no reaction

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ETC Alternate Working Fluid

ARMAMENT ENGINEERING DIRECTORATE

PROPULSION BRANCH

Rationale for ETP Selection:

- *Availability of Ingredients*
- *Compatibility*
- *Producibility*
- *Low Sensitivity*
- *Environmental Safety*

OVERVIEW OF SOLID PROPELLANT ETC GUNS

AA JUHASZ
USABRL

JANNAF WORKSHOP ON

ETC MODELING & DIAGNOSTICS

9-11 JULY, 1991

ABERDEEN PROVING GROUND, MD

SOLID PROPELLANTS

ADVANTAGES:

- SUCCESSFUL HISTORY/ FAMILIAR
- PROVEN PERFORMANCE
- ~5 KJ/g ENERGY LEVEL
- ~ > 1KJ/g MASS IMPETUS
- KNOWN/ PREDICTABLE COMBUSTION PROPERTIES
- PROGRESSIVITY BUILT IN via GEOMETRY OR CHEMISTRY
- ACCEPTABLE HAZARDS

DISADVANTAGES:

- "MATURE TECHNOLOGY"
- GRANULATION LIMITS VOLUMETRIC ENERGY DENSITY & IMPETUS
- MANUFACTURING TOLERANCES, GRAIN SIZE LIMIT PROGRESSIVITY ATTAINABLE

POTENTIAL FOR SOLID PROPELLANTS IN ETC GUNS

- FIXED GEOMETRY AND LAMINAR COMBUSTION PROPERTIES REDUCE BALLISTIC RISKS
- PLASMA CAN BE USED TO INCREASE THE ENERGY PER UNIT VOLUME IN CHARGE
- PLASMA MAY PROVIDE CONTROLLED, AUGMENTED BURNING, PERMITTING:

    LARGER WEB GRAINS
    COMPACTED/CONSOLIDATED OR
    MULTIMODAL CHARGES
    MONOLITHIC CHARGES

- PLASMA IGNITION COULD PERMIT ELIMINATION OF BALLISTIC TEMPERATURE SENSITIVITY OF CONVENTIONAL CHARGES

UNKNOWNS

- EFFECT OF PLASMA ENERGY, DURATION AND MODE OF INJECTION ON THE BURNING OF SOLID PROPELLANT GRAINS
- POTENTIAL OF PLASMA TO BREAK UP CONSOLIDATED/ COMPACTED CHARGES
- EXTENT OF IGNITION & COMBUSTION CONTROL POSSIBLE WITH PLASMA

KNOWN SOLID PROPELLANT & RELATED ETC EFFORTS

- **SOREQ - SDC/SDIO**
- **SOREQ - BRL**
- **OLIN - BRL**
- **OLIN IR&D**
- **SANDIA**
- **BRL LOVA IGNITION**

SOREQ-SDC/SDIO

SOREQ - BRL

OBJECTIVE:

SDC/SDIO - SOREQ, 1KG @ 2500 M/S

BRL - SOREQ, 1.35 KG @ min 1812 M/S
(min 25% KE over Optim Conv)

APPROACH:

- SINGLE AXIAL PLASMA INJECTOR
- M30 PROPELLANT (7P)
- UP TO 3 MJ PLASMA ENERGY
- STEPWISE INJECTION WITH MAXIMIZED POST-PMAX ENERGY
- 60-mm GUN FIRINGS (BRL)
- 60- & 105-MM GUN FIRINGS (SDC/SDIO)
- PLASMA-AUGMENTED CLOSED BOMB COMBUSTION STUDIES

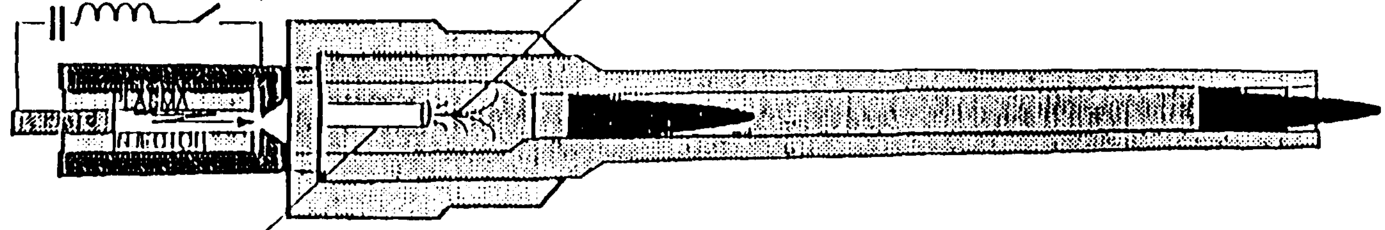
STATUS:

- HAVE LAUNCHED 1 KG @ 1850 M/S
- HAVE ACHIEVED SMOOTH P-T RECORDS, i.e. BALLISTIC CONTROL
- HAVE ACHIEVED ~1% IMPROVEMENT OVER OPTIMIZED CONVENTIONAL IN 60-MM
- PLASMA INJECTION STILL LIMITED TO 1.6 MJ

IMPLICATIONS:

- IF INJECTOR ENERGY CAN BE INCREASED, SHOULD ACHIEVE BRL & SDC GOALS, MAY OPEN DOOR TO FIRST TACTICAL AND STRATEGIC USES OF ETC

ET-Boosted Solid Propellant Gun



- Gun Parameters

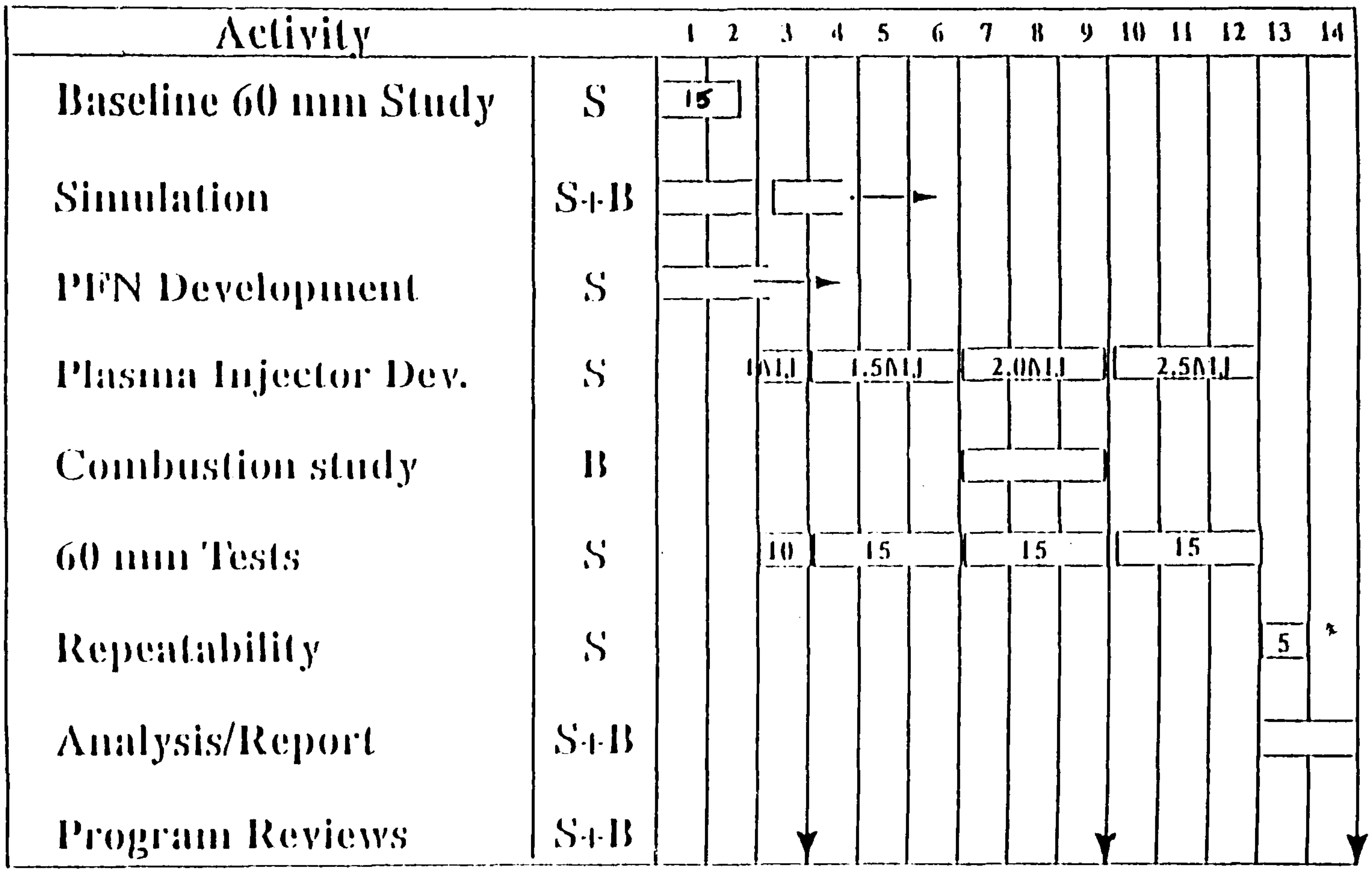
Caliber:	60 mm
Travel:	400 cm
Chamber Volume:	2200 cm^3
Propellant:	M30, 7 perf
Projectile Mass:	1.35 kg - 2.0 kg
Elec. Energy Input:	3 MJ (maximum)

- Baseline case, solid propellant only

Propellant Mass:	2.25 kg
Projectile Mass:	1.35 kg
Velocity:	1620 m/s
Muzzle KE:	1.77 MJ

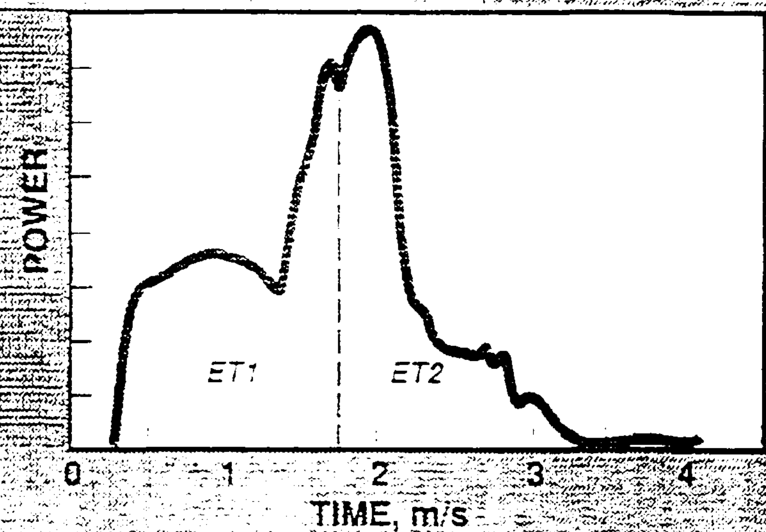
ET-BOOSTED CONVENTIONAL GUN PROGRAM

US ARMY LABORATORY COMMAND

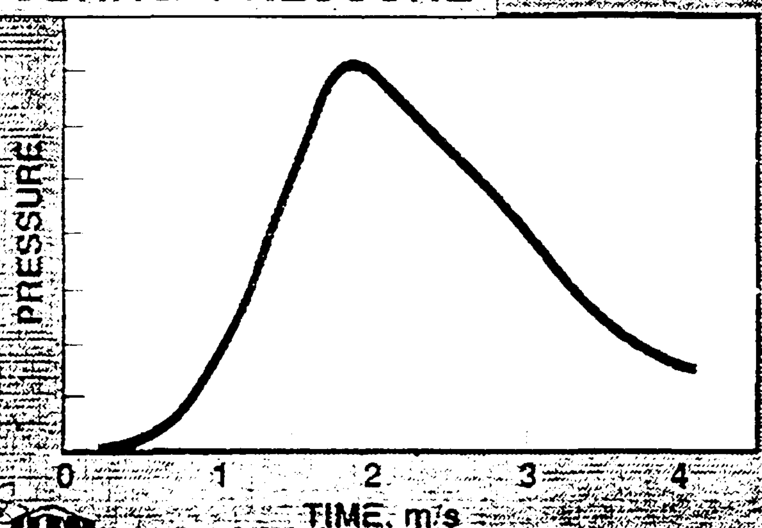


TYPICAL ET BOOSTED SHOT WITH A DOUBLE PULSE

INJECTED ET ENERGY



RESULTING PRESSURE



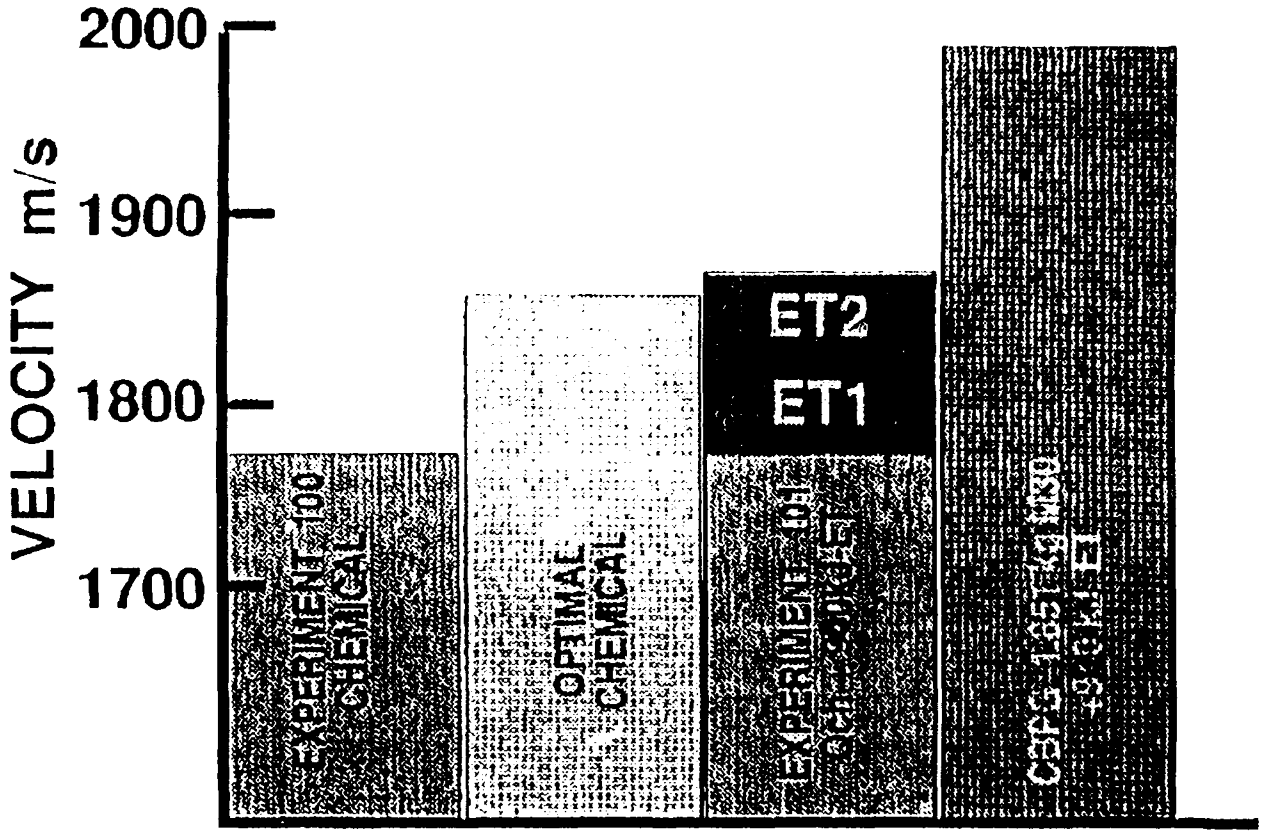
Soreq NRC

ANALYSIS OF EXPERIMENT 101.

Projectile mass	kg	1.0
Charge weight	kg	1.851
Chemical energy	kJ	8238
ET-energy	kJ	899
P_{max}-Exper.	bar	5100
P_{max}-Calcul.	bar	5104
Muzzle velocity	m/s	1850
Calculated velocity	m/s	1849
Optimal velocity	m/s	1844
CBPG (Q+ET) velocity	m/s	1976
Adjusted P_{start}	bar	170
Adjusted Erosion const.	s/m	7E-5
Kinetic Energy (Con)	kJ	1473
Kinetic Energy (ET)	kJ	1709
Δ EK	kJ	236
	%	16
ET1	kJ	494
ET2	kJ	405
$\Delta EK = EK_{ET} - EK_{ET1}$	kJ	98
	%	6.08

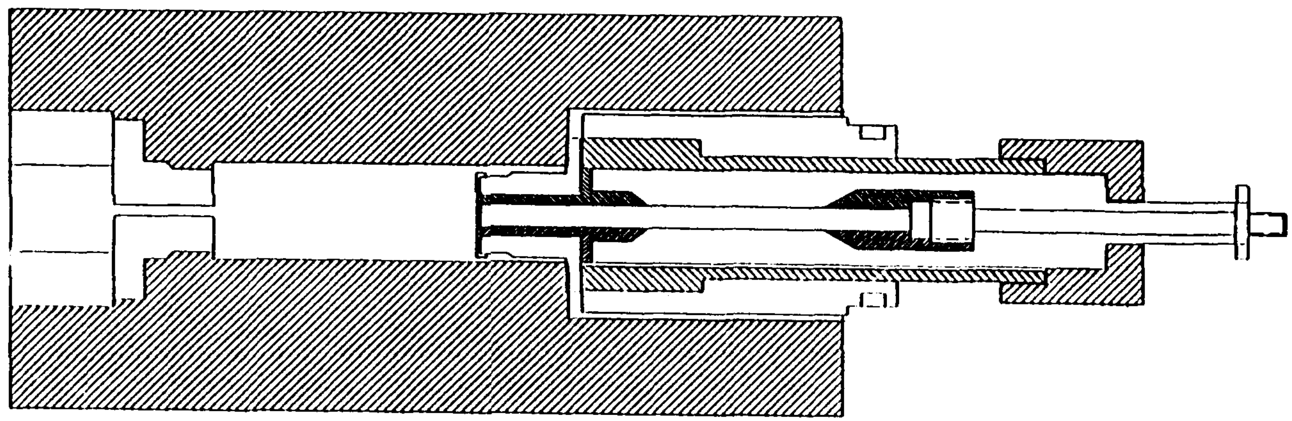
DSNP-ET-180

COMPARING ET BOOSTED SHOT 101 TO OPTIMAL AND CBPG SHOTS



Soreq NRC

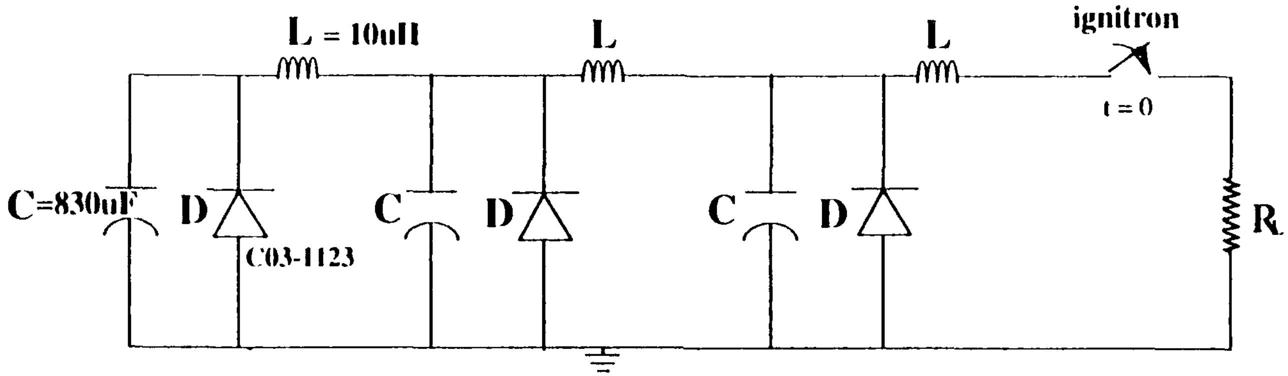
BRL SOLID PROPELLANT ETC
CLOSED BOMB FIXTURE



BALLISTIC RESEARCH LABORATORY

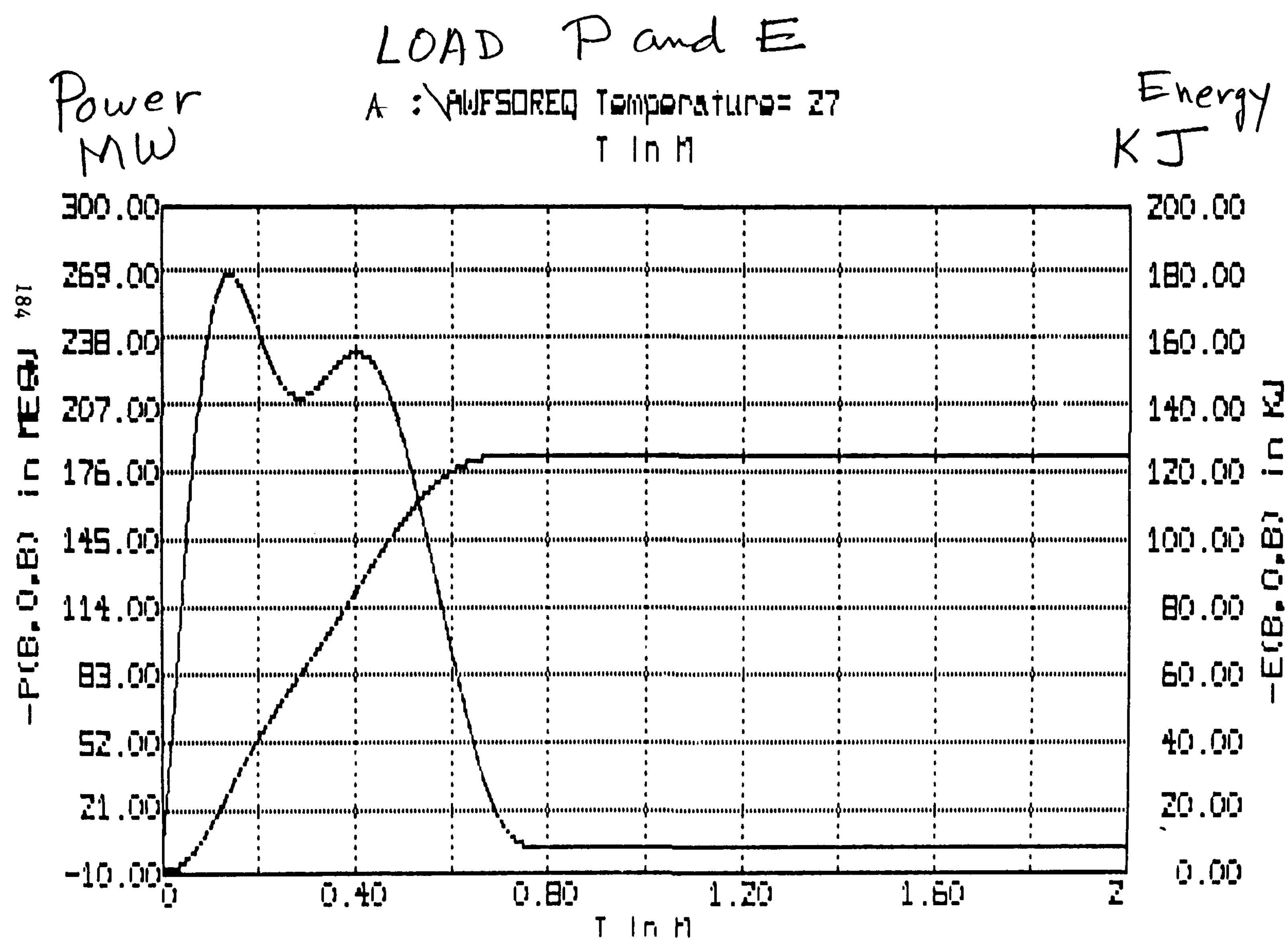
US ARMY LABORATORY COMMAND

PULSE FORMING NETWORK STATUS



- Design is based on BRL and Soreq plasma resistance characteristics
- 50kJ capacitor units (compact)
- Diode protection from voltage reversal (capacitor/power supply lifetime)
- Single closing switch/triggering signal/electronics (increased reliability/decreased maintenance)
- Limited flexibility on power-pulse shape

DESIGN: Completed 2/7/91
CONSTRUCTION: Began 2/10/91



LOAD P and E
A :\AWFSOREQ Temperature= 27
T In M
Power
MW
Energy
KJ
300.00
269.00
238.00
207.00
176.00
145.00
114.00
83.00
52.00
21.00
-10.00
-P(B.O.B) in MEGW
200.00
180.00
160.00
140.00
120.00
100.00
80.00
60.00
40.00
20.00
0.00
-E(B.O.B) in KJ
0
0.40
0.80
1.20
1.60
2
T In M

OLIN - BRL

BALL PROPELLANT ETC

OBJECTIVE:
PROOF OF PRINCIPLE FOR INFLUENCING INTERIOR BALLISTIC PERFORMANCE OF BALL PROPELLANT via PLASMA INJECTION

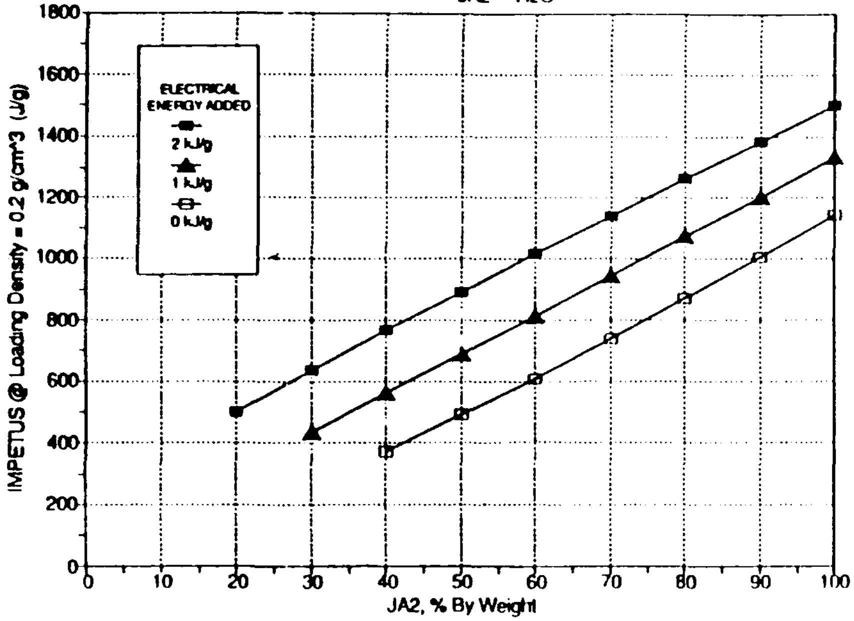
APPROACH:
WC 891 PROPELLANT TO BE FIRED IN GFE 30-MM ETC GUN AT GTD USING AXIAL PLASMA INJECTION

BALLISTIC PERFORMANCE & P-T BEHAVIOR TO BE COMPARED WITH BASELINE WC 891

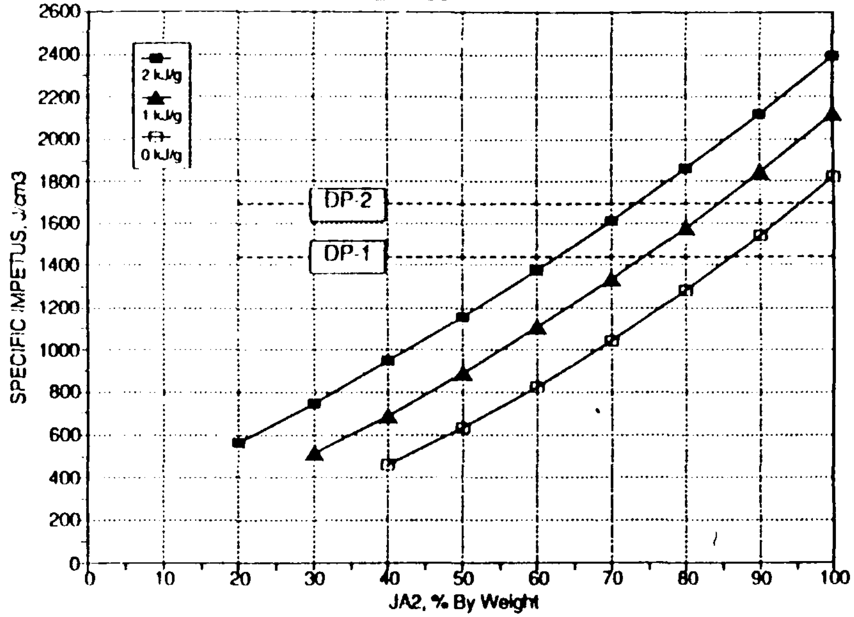
STATUS:
INSTRUMENTATION COMPLETE, BASELINE FIRINGS UNDER WAY, ETC FIRINGS SUMMER 91

IMPLICATIONS:
IF SUCCESSFUL, OPENS WAY TO NEAR-TERM ETC CONTROL & MODEST PERFORMANCE GAINS; POSSIBILITY OF MULTIMODAL & CONSOLIDATED CHARGES

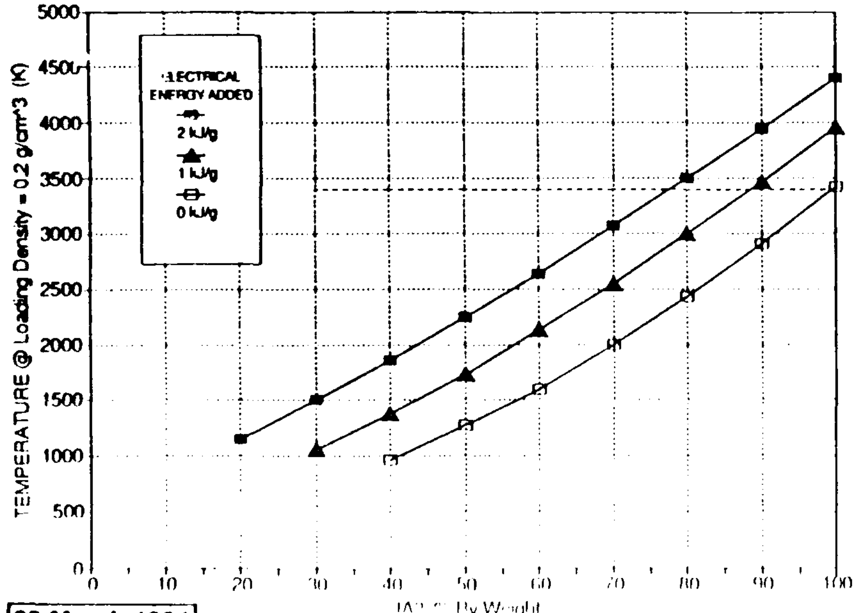
THEORETICAL IMPETUS of ET-C GUN PROPELLANTS
JA2 - H2O



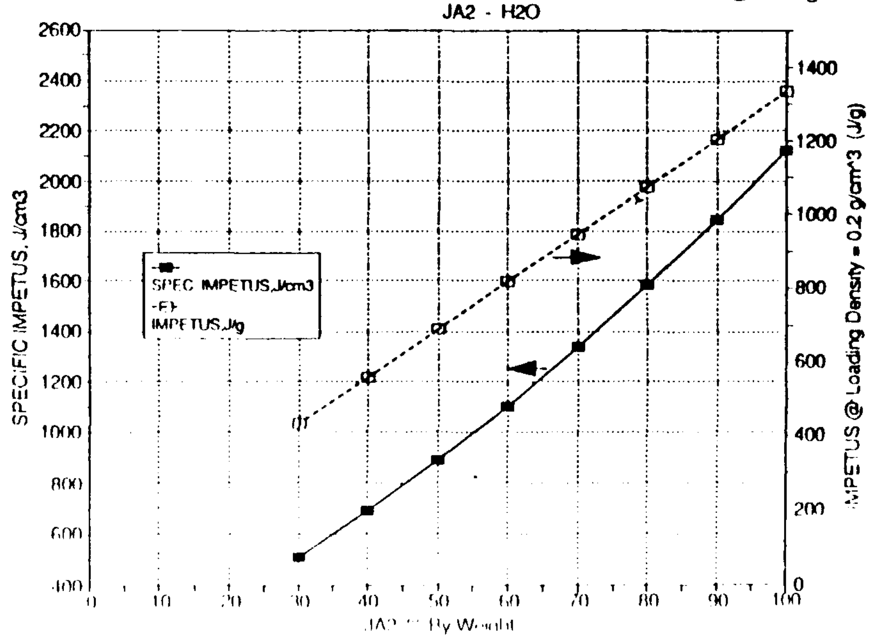
THEORETICAL SPECIFIC IMPETUS
JA2 - H2O



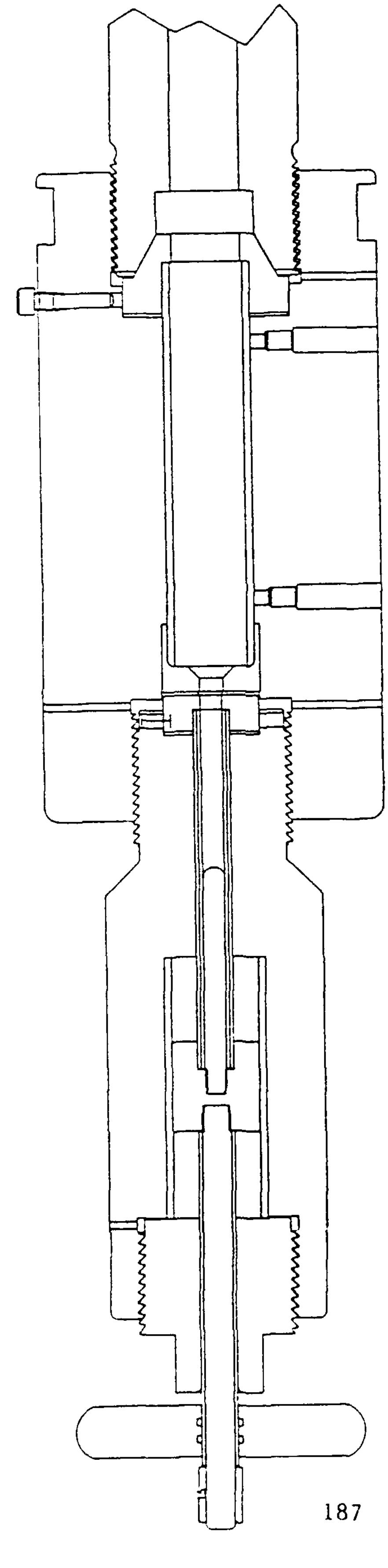
THEORETICAL TEMPERATURE of ET-C GUN PROPELLANTS
JA2 - H2O



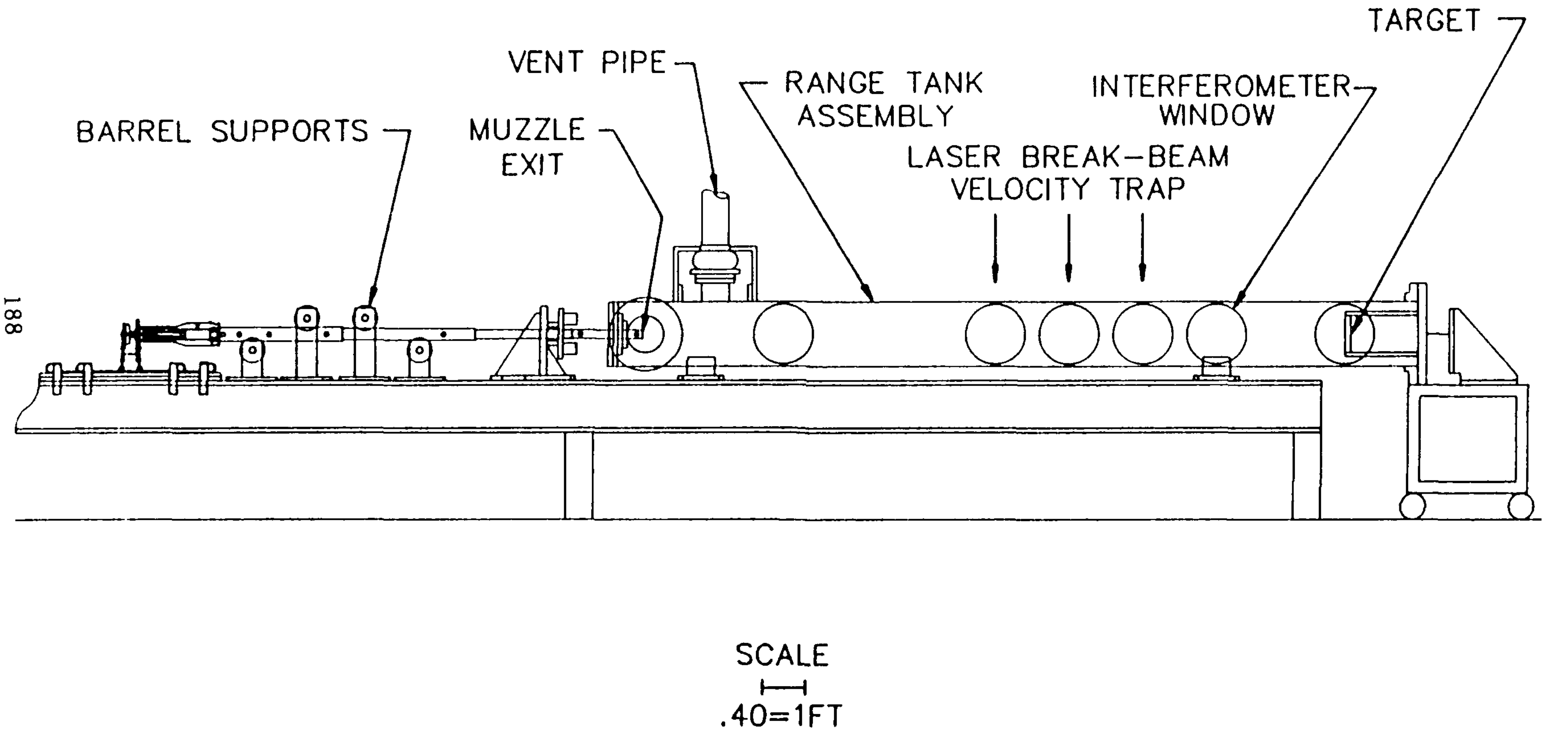
THEORETICAL IMPETUS AND SPECIFIC IMPETUS @ 1 kJ/g
JA2 - H2O



30 March 1991



30mm GUN AND RANGE



21A6112

SANDIA PLASMA LINER

OBJECTIVE:

INCREASE THE MASS FLOW FROM THE PLASMA CARTRIDGE BY TAILORING LINER CHEMISTRY

USE INCREASED MASS FLOW FROM PLASMA CARTRIDGE TO PROMOTE MIXING IN GUN CHAMBER

APPROACH:

STARTING WITH POLYETHYLENE/ POLYVINYL ALCOHOL COPOLYMER, NITRATE TO FORM POLYMER WITH LIMITED OXIDIZER FUNCTIONALITY

EXOTHERMIC DECOMPOSITION OF NITRATED POLYMER AIDS IN 'UNZIPPING' LINER, INCREASING THE RATE OF DECOMPOSITION AND MASS GENERATION BY THE LINER

PERFORM PLASMA LINER ABLATION TESTS FOR QUANTITATIVE DETERMINATION OF PLASMA EFFECTS ON LINER DECOMPOSITION

STATUS:

MATERIALS OF VARYING NITRATE CONTENT SYNTHESIZED
TESTS USING PLASMA DISCHARGE INDICATE MUCH FASTER DECOMPOSITION OF NITRATED MATERIAL

IMPLICATIONS:

RESULTS MAY HELP IN UNDERSTANDING LEVELS OF AUGMENTATION POSSIBLE IN INCREASING GAS GENERATION RATES FROM REACTIVE MATERIALS BY PLASMAS

BRL LOVA PLASMA IGNITION

OBJECTIVE:

TAILOR PLASMA IGNITION FOR LOVA PROPELLANTS TO CONTROL IGNITION DELAY & REDUCE TEMPERATURE SENSITIVITY OF BALLISTICS

APPROACH:

TAILOR PLASMA ENERGY, DURATION & DECOMPOSITION PRODUCTS OF IGNITER TUBE FOR ENHANCED REACTION KINETICS WITH NITRAMINE/INERT BINDER PROPELLANT PYROLISIS PRODUCTS

DETERMINE ENERGY ADDITION NEEDED TO ELEVATE LOW & AMBIENT BURNING RATES TO ELIMINATE/REDUCE BALLISTIC TEMPERATURE COOEFFICIENT

STATUS:

UNFUNDED; CONCEPTS, PROJECT PLANS DEVELOPED EXECUTION SECOND TO ALTERNATE WORKING FLUID CHARACTERIZATION TESTS

IMPLICATIONS:

FIRST POTENTIAL PAYOFF FOR ET COULD BE PERFORMANCE ENHANCEMENTS BASED ON IMPROVED IGNITION AND COMBUSTION IN THE CONVENTIONAL MODE

CONCLUSIONS

- REASONABLE POSSIBILITY OF SUCCESS WITH SOLID PROPELLANT ETC
- CONTROLLED BALLISTIC PT RECODS ACHIEVED EQUALLING/ SLIGHTLY EXCEEDING OPTIMUM CONVENTIONAL PERFORMANCE
- CONVENTIONAL SOLID LOADING DENSITIES PERMIT ~ 0.9 G/CC, BUT CONSOLIDATION, COMPACTION CAN RAISE THIS TO ~ 1.3 G/CC; MONOLITHIC CHARGES EVEN HIGHER
- UNDER CERTAIN CIRCUMSTANCES, THEREFORE, SOLID PROPELLANT ETC MAY APPROACH THE OPERATIONAL ENERGY DENSITIES OF LIQUIDS/GELS
- AT THE MINIMUM, ET TYPE PLASMA INJECTORS COULD BE USED TO OPTIMIZE THE PERFORMANCE OF CONVENTIONAL SYSTEMS, ELIMINATING PERFORMANCE LIMITATIONS BASED ON BALLISTIC TEMPERATURE SENSITIVITY

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OVERVIEW OF GEL/SLURRY PROPELLANTS

A. J. Bracuti and D. S. Chiu
US Army Armament Research, and Development & Engineering Center
Picatinny Arsenal, NJ 07806-5000

ABSTRACT

Gel/slurry propellants have been formulated and fabricated at ARDEC as part of the liquid propellant program because they have been considered potential candidates for both spray injected and bulk-loaded gun systems. The rationale for this was based on a combination of properties unique to the gel/slurry propellant system. These properties are high/energy density and non-Newetonian liquid behavior. This paper discusses a few representative formulations and their associated properties.

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PROPULSION BRANCH

Overview of Gel / Slurry Propellant

A. J. Bracuti
D. S. Chiu

ARDEC
Picatinny Arsenal, NJ

July 9-11, 1991
JANNAF Workshop on ETC Modeling and Diagnostics

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OUTLINE

ARMAMENT ENGINEERING DIRECTORATE

PROPULSION BRANCH

- Background
- Formulation
- Safety Tests
- Burning Rates
- 20mm Gun Test
- Summary

BACKGROUND

Gel / Slurry Propellants

- Initial Concept
  - Bulk Loaded LP Gun
- Advantage
  - High Energy LP
  - Max Packing Density
  - "Simple" Concept
- Bulk Loaded
  - Small Caliber
    erratic Velocities
    Non-reproducible p-t traces
  - Large Caliber
    BOOM!

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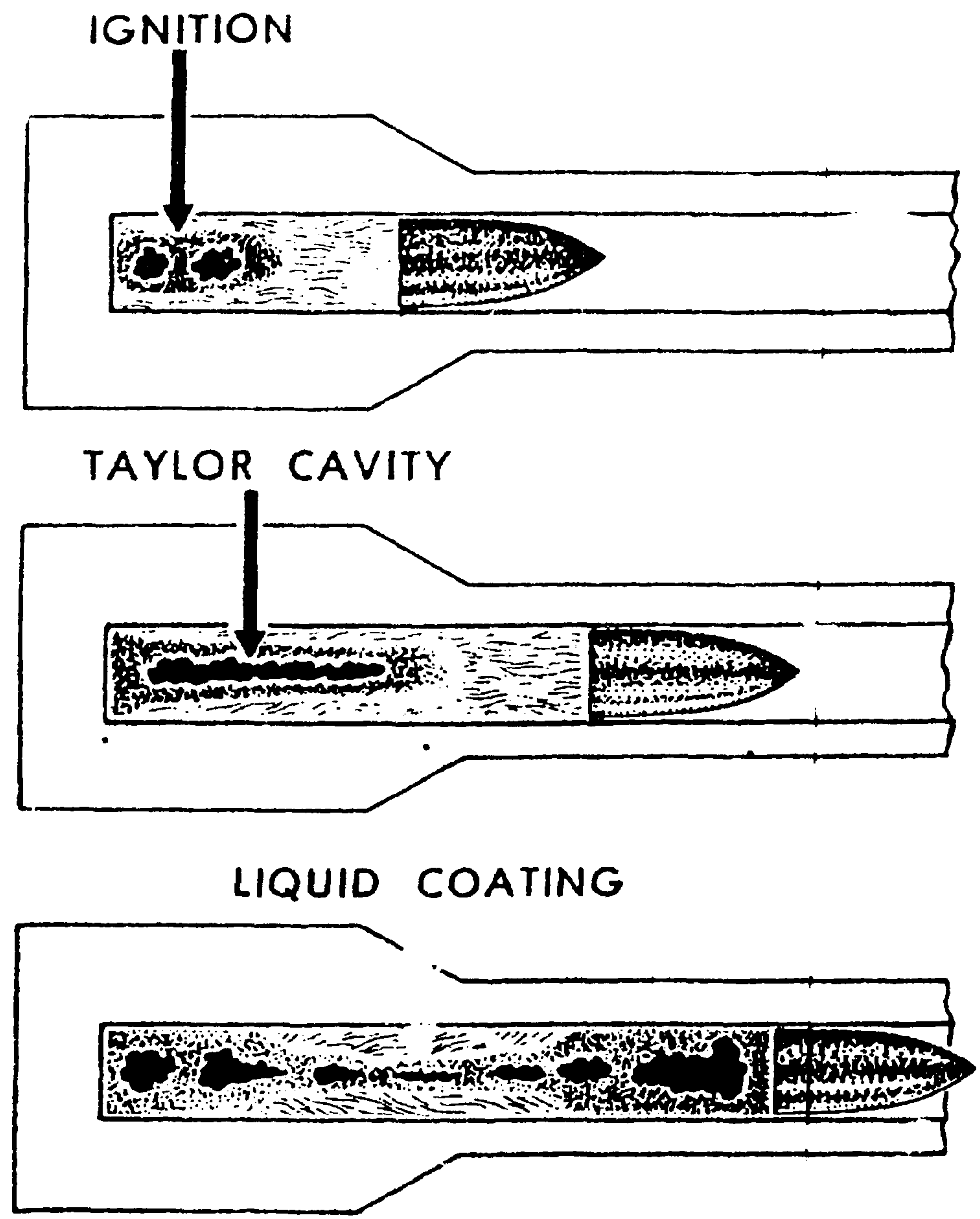
PROPULSION BRANCH

BULK LOADED STATUS

- DARPA Workshop Conclusions
  - LP not good for large caliber guns
  - Viscous LP potential candidate
    Non-Newtonian Liquids

- ARDEC Conclusions
  - In-House modeling
  - Supports DARPA views
  - Several 'Non-Newtonian' candidate made
  - Best near-term bet
    Direct fire systems



BULK-LOADED IGNITION & COMBUSTION

PROPELLANT PARAMETERS

- **Flame temperature**
  - Thermochemical code (MCVECE)
- **Mass Impetus of propellant (J/g)**
  - Thermochemical code (MCVECE)
- **Volumetric Impetus of propellant (J/cc)**
  - Mass impetus (J/g) x density (g/cc)
- **Charge loading fraction**
  - LP is 1.0
  - Solid charge (M30) is 0.7
- **Effective vol. Impetus of charge**
  - vol. impetus x loading fraction
- **Propellant Energy**
  - Impetus/(Gamma-1)
    (Gamma is the ratio of Specific Heats)

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GEL / SLURRY OBJECTIVES

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1. **Gravimetric Impetus**
   1070 - 1200 J/g
2. **Volumetric Impetus**
   1800 - 2000 J/g
3. **Flame Temperature**
   2600 - 3100 K
4. **Vulnerability**
   Comparable to LOVA
5. **Density**
   1.5 or Greater

FORMULATIONS

- Solid Oxidizers
  - *RDX (0 - 65%)*
  - *TAGN (0 - 65%)*
- Liquid Fuel
  - *TAE (35 - 50%)*
- Gelling Agent
  - *Cellulosic (0.5 - 1%)*

THERMAL PARAMETERS

Sample	I (J/g)	I (J/cc)	T (K)
M30	1070	1070	3030
WC870	1183	1139	2830
7178	1295	2295	3176
7089	1095	1789	2368
7117	1165	1966	2602
7150	1223	2117	2845
7176	1227	2124	2863
7173B	1250	2184	2942
7136	1185	2038	2707
7121	1205	2015	2774
LP1846	899	1294	2600

SAFETY TESTS

- Impact
  - *ARDEC*

    30 mg sample on sandpaper

    2.5 Kg drop wt.
  - *NOS*

    20 mg sample on sandpaper

    5.0 Kg drop wt.
  - *NOS Safety Cavity*

    0.3 ml in cup

    2.0 Kg drop wt.
- Electrostatic discharge
- Sliding friction
- Hot fragment conductive ignition

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SAFETY TEST

Formulations

	7117	7117A	7121A	7136	7137
% TAGN	20.0	30.0	23.3	10.0	10.0
% RDX	40.0	30.0	45.6	50.0	55.0
% TAE	40.0	40.0	31.1	40.0	35.0
I_m (J/g)	1165	1129	1205	1185	1229
T_f (K)	2602	2479	2774	2707	2854

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IMPACT TESTS

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PROPULSION BRANCH

Sample	ARDEC 2.5 Kg (cm)	NOS 5.0 Kg (cm)	NOS Cavity 2.0 Kg (cm)
RDX	23.0	15.0	-----
HELOVA II	44.8	30.0	-----
OTTO Fuel	-----	-----	10.5
7717	80.7	-----	-----
7117A	78.0	-----	-----
7136	-----	60.0	23.9
7137	-----	> 60.0	30.4

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ELECTROSTATIC DISCHARGE

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PROPULSION BRANCH

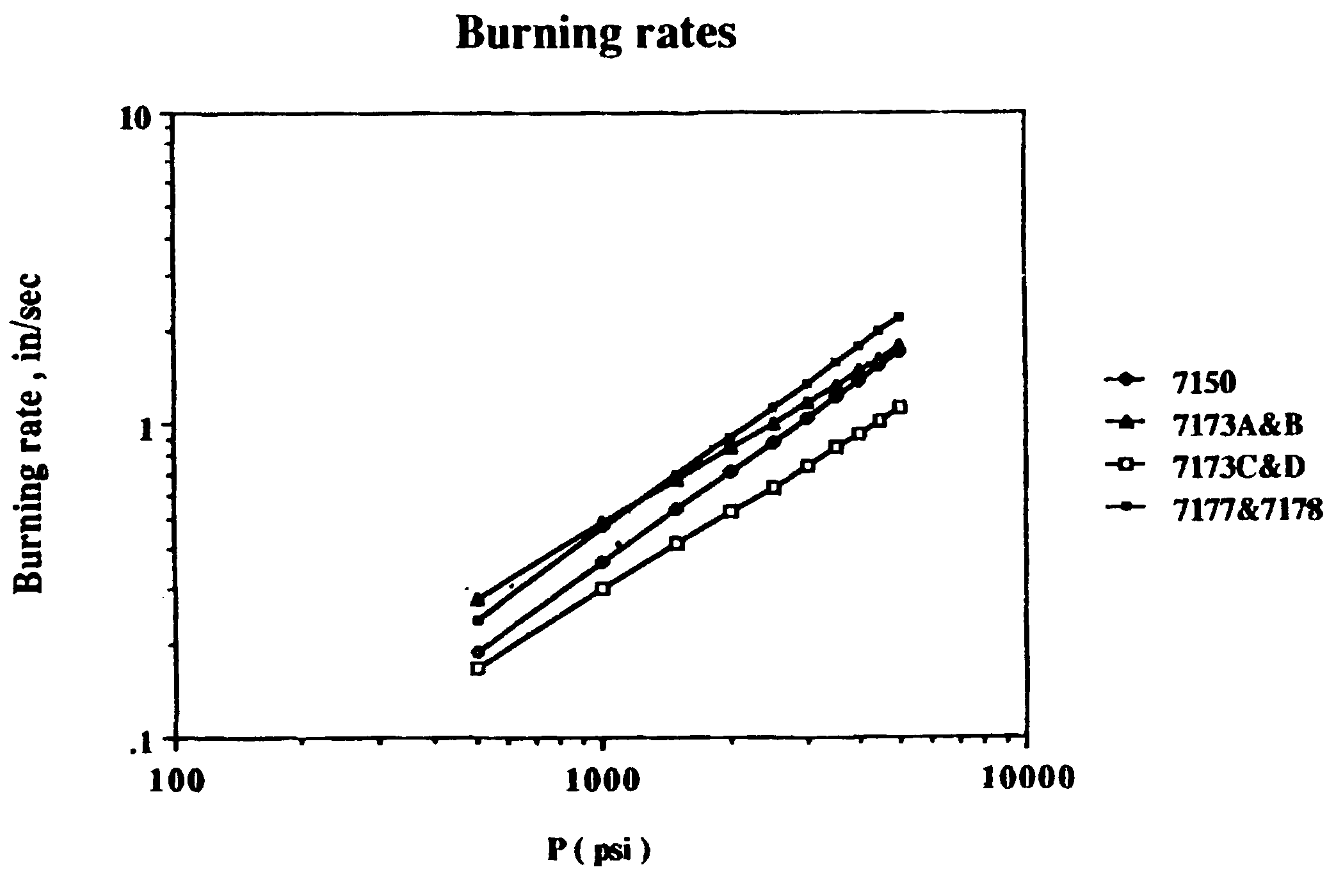
TESTS @ 5KV

Sample	Discharge Energy, J	Sensitivity
7136	8.75	Low
7137	6.25	Low

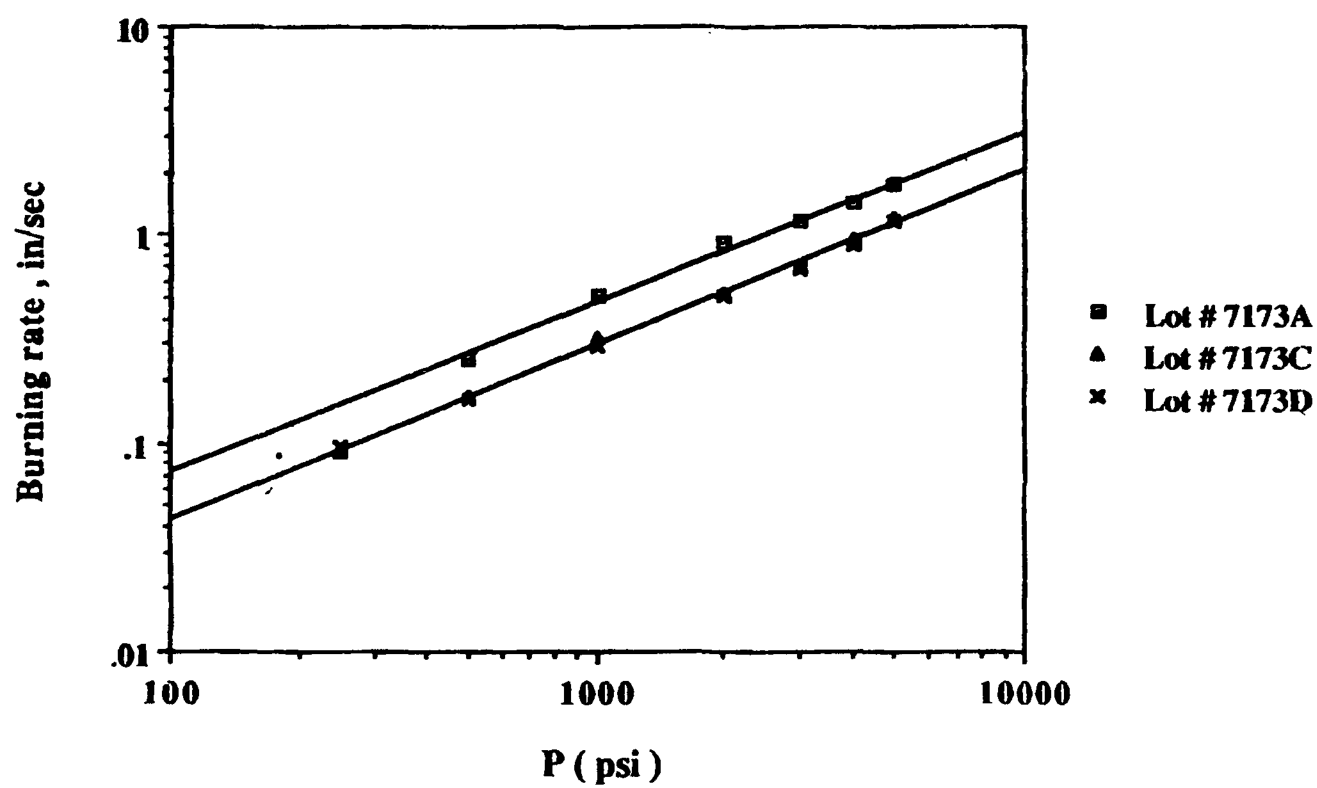
SLIDING FRICTION TESTS

LOT	SLIDING FRICTION	SENSITIVITY
7136	>980	LOW
7137	>980	LOW

	FRAGMENT WEIGHT (g)			
	0.43	1.03	2.03	3.50
LOT	IGNITION TEMPERATURE (c)			
M30	363	338	313	288
LOVA STD	788	663	563	463
7117	488	463	388	363
7117A	538	488	438	413
7121A	>800	713	488	438
7136	>800	788	638	588
7137	>800	738	538	488


Burning rates
Burning rate , in/sec
10
1
.1
100
1000
10000
P (psi)
7150
7173A&B
7173C&D
7177&7178

STRAND DATA 21C



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STRAND BURNER RESULTS TO 5 KPSI

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PROPULSION BRANCH

Particle Size Effect

- Sample Lots 7173 A, B, C & D
  - *5% TAGN, 60% RDX & 35% TAE*
  - *I = 1245, T = 2938*
  - *Constant TAGN particle size*
  - *Varied RDX particle size*
- 7173C 15μ RDX & 7173D 5μ RDX
  - *Burning Rate (BR) identical*
- 7173A & 7173B 50μ RDX
  - *Different gel agent concentration*
  - *Identical BR*
  - *Same BR curve slope*
  - *Higher BR than 5-15μ RDX*

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STRAND BURNER RESULTS TO 5 KPSI

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TAGN Concentration Effect

- **Sample lots 7150**
  - *10% TAGN, 55% RDX & 35% TAE*
  - *I = 1223, T = 2845*
  - *RDX particle size 15μ*
- **Increase in TAGN concentrations, increase slope of BR curve**
  - *BR close to 15μ RDX BR at low pressure limit*
  - *BR close to 50μ RDX BR at 5000 psi*

STRAND BURNER RESULTS TO 5 KPSI

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RDX Concentration Effect

- Sample lots 7177
  - *65% RDX & 35% TAE*
  - *I = 1262, T = 3016*
- Sample lots 7178
  - *70% RDX & 30% TAE*
  - *I = 1295, T = 3176*
- 50μ RDX
- Same burning rates
- BR curve slope increases similar to increase exhibited with higher TAGN concentration

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STRAND BURNER RESULTS TO 35 KPSI

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Sample	7136	7137
% TAGN	10	10
% RDX (*15μ*)	50	55
% TAE	40	35
Impetus, J/g	1185	1223
Flame Temp, K	2707	2854
Calc. Density, g/cc	1.72	1.73
BR Coef, A	1.2E-3	1.9E-3
Exponent, N	0.87	0.83

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PROPELLANTS - 20 mm Ballistic Tests

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PROPULSION BRANCH

Type	Solid	Gel/Slurry	Gel/Slurry	Gel/Slurry
Lot #	WC870	7136	7121A	7150
Temp, K	2830	2707	2774	2854
Im, J/g	1183	1185	1205	1223
Iv, J/cc	1136	2074	1976	2116
ρ, g/cc	0.96	1.72	1.67	1.73

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20mm GUN TEST

ARMAMENT ENGINEERING DIRECTORATE PROPULSION BRANCH

WC870 vs 7136

Sample	% case loaded	Charge (gm)	Velocity (ft/sec)	Pressure (psi)
7136	55	37.7	3409	83840
7136	55	38.5	3607	72760
7136	55	38.9	3140	60920
7136	72	50.3	4184	55680
7136	72	50.2	3591	61600
7136	72	51.0	3655	46720
7136	72	51.0	3683	49640
7136	82	55.9	3571	40400
7136	82	56.0	3628	42640
7136	82	55.7	4275	> 100000
7136	82	56.2	4056	69160
7136	82	56.2	3688	44480

* Ref round M55a2 with 40g WC870 - 3380 ft/sec @ 60 Kpsi

20mm GUN TEST

WC870 vs 7121A

Sample	% case loaded	Charge (gm)	Velocity (ft/sec)	Pressure (psi)
7121A	72	50.6	3802	67000
7121A	82	56.8	4170	76000
7121A	82	56.8	3894	70880
7150	82	56.8	3799	58520
7150	82	57.0	4356	87560
7150	82	57.4	4283	76440

* Ref round M55a2 with 40g WC870 - 3380 ft/sec @ 60 Kpsi

SUMMARY

GEL / SLURRY PROPELLANTS

- High / energy density candidates easily made
- Can be LOVA like
- Burning rate can be tailored
- Can be pumped
- Bulk LP ignition & combustion systems must be modified for success

ELECTROTHERMAL-CHEMICAL (ET-C) ALTERNATE PROPELLANT SYSTEMS INVESTIGATION AND STUDY EFFORT

Hugh McElroy, Olin Ordnance
and
Gene Rothgery, Olin Chemicals
and
Eckard Schmidt, Olin Rocket Research

ABSTRACT

1) A report on the status of work performed under Contract DAAA05-90-C-1061 during the first 3 quarters.

2) A brief outline of the future direction of the program.

ELECTROTHERMAL-CHEMICAL (ET-C) ALTERNATE PROPELLANT SYSTEMS INVESTIGATION AND STUDY EFFORT

CONTRACT DAAA15-90-C-1061

JANNAF WORKSHOP
ET-C MODELING & DIAGNOSTICS

JULY 9 – 11, 1991

ABERDEEN PROVING GROUND, MD

Olin ORDNANCE

VG198 7/91 7423

CONTRACT OBJECTIVES

TO EXAMINE THE VARIOUS CHEMISTRIES AVAILABLE FOR ALTERNATE ETC PROPELLANTS

TO DEVELOP VIABLE ALTERNATE PROPELLANT CANDIDATES FOR ETC

ATTEMPT POSITIVE IMPACT ON ETC COMMUNITY BY TIMELY SHARING OF CONTRACT DATA

CONTRACT TASKS

TASK 1. THEORETICAL APPROACH & PERFORMANCE CALCULATIONS

TASK 2. INGREDIENT COMPATIBILITY & STABILITY

TASK 3. PROPELLANT FORMULATION STUDIES

TASK 4. PROPELLANT SAFETY

TASK 5. PRELIMINARY DESIGN

TASK 6. ETC GUN TEST OF ALTERNATE WORKING FLUIDS

TASK 7. REPORTING

TASK 8. SAMPLE DELIVERY TO BRL

NOTE TO INVITED GUESTS

* OLIN & ARMY ARE WORKING HARD TO MAKE THIS THE BEST POSSIBLE PROGRAM
* SOME EXCITING CHEMISTRIES HAVE EMERGED AS A RESULT OF THE EFFORT
* WE WANT TO MAKE INFORMATION AS ACCESSIBLE AS POSSIBLE
* YOUR TECHNICAL INPUT AND SUGGESTIONS FOR SHARING THE DATA ARE WELCOME

TASK 1

Dr. Eckart W. Schmidt
Olin Rocket Research Company

Dr. Eugene F. Rothgery
Olin Chemicals

Hugh A. McElroy
Olin Ordnance

Olin ORDNANCE

TASK 1
THEORETICAL AND THERMOCHEMICAL STUDIES
STATUS (JULY 2, 1991)

- IDENTIFIED INGREDIENTS FOR STUDY
- THERMOCHEMICAL CALCULATIONS FOR INGREDIENTS AND MIXTURES
  - WITH AND WITHOUT PLASMA ENERGY
  - DATA BASE TABULATION
  - 4-PLOT SUMMARY
- HANDOUTS OF THERMOCHEM DATA BASE
- HANDOUTS OF THERMOCHEM PLOTS
- COMPILED STRAWMAN CANDIDATE LIST FOR ETC
  - ROCKET RESEARCH
  - OLIN CHEMICALS
  - OLIN ORDNANCE
- TASK LARGELY COMPLETED, FUTURE EFFORTS UNDER TASK 5

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CRITERIA FOR CANDIDATE RANKING

* FIGURES OF MERIT

* ENERGY (J/g)
* SPECIFIC ENERGY (J/cc)
* IMPETUS (J/g)
* SPECIFIC IMPETUS (J/cc)
* FLAME TEMP deg K

* BROAD ARMY GUIDANCE

* 18 MJ KE @ MUZZLE
* 10 ~ 11 KJ/cc (CE + EE) @ 0.5 KJ/g EE AUGMENTATION
* FT < 3400 °K

* DAAA15-90-C-1061

* 18 MJ KE @ MUZZLE
* > ~ 2 KJ/CC SPECIFIC IMPETUS @ 0.5 KJ/g EE AUGMENTATION
* FT OF 3400 °K NOT A HARD LIMIT

ASSUMPTIONS: 572 MPa MAX CHAMBER PRESS
120 mm GUN M256, 4.75 M TRAVEL
SPECIFIC IMPETUS (J/cc) ≅ SPECIFIC ENERGY (J/cc) * (γ-1)

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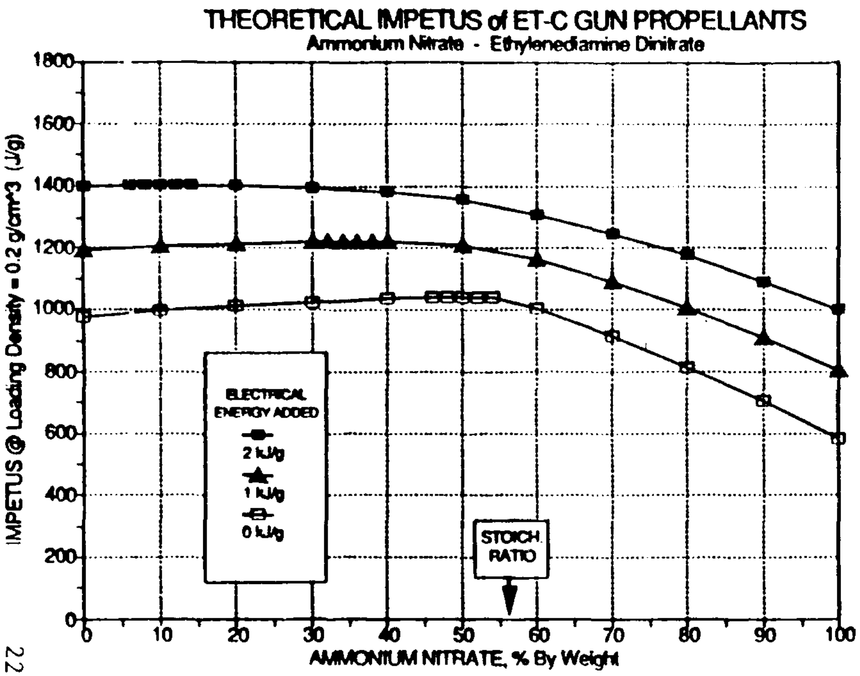
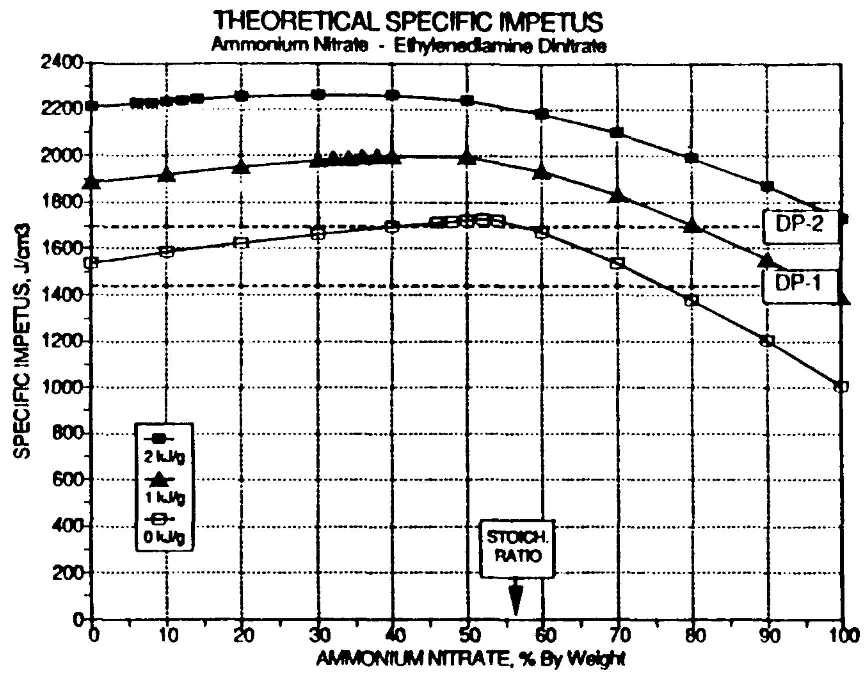
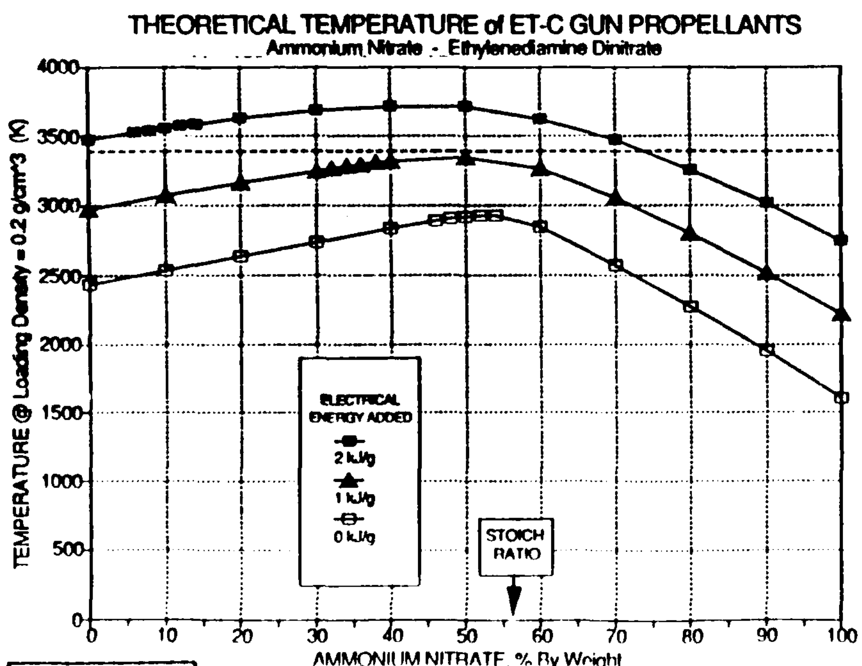
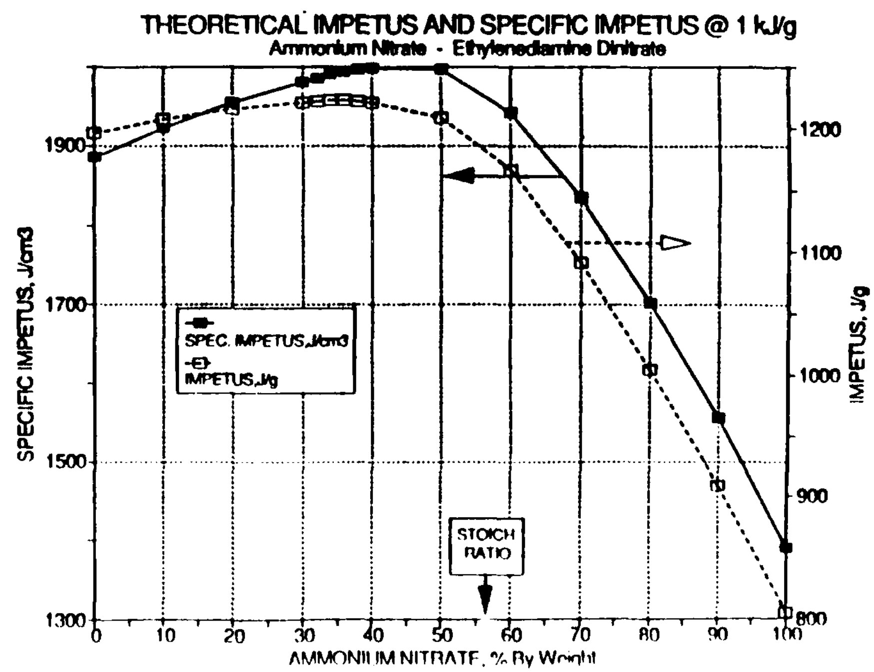


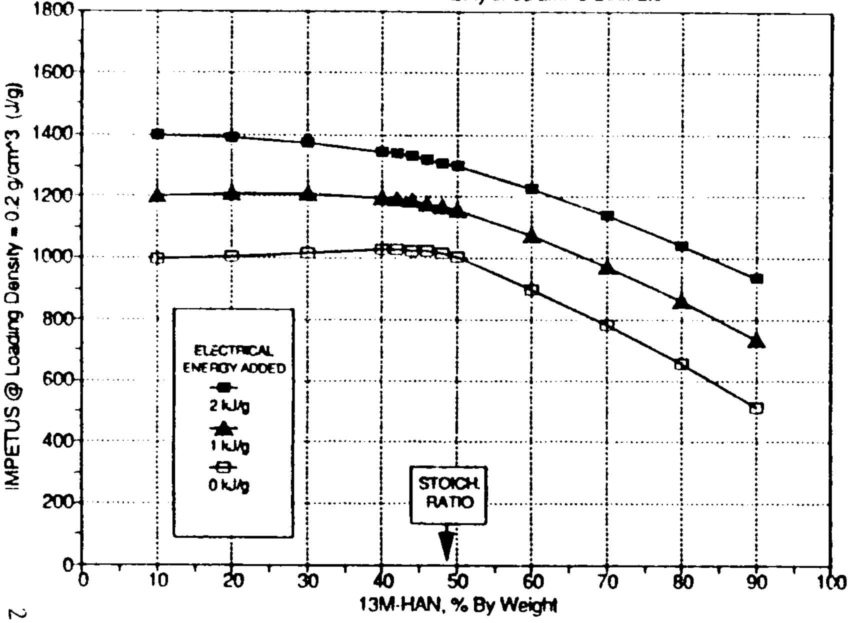




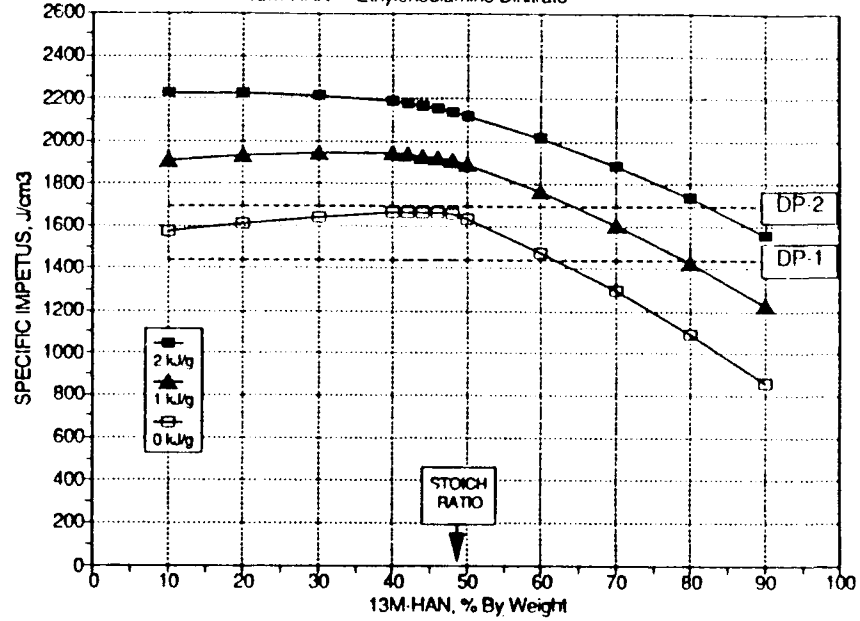


30 March 1991

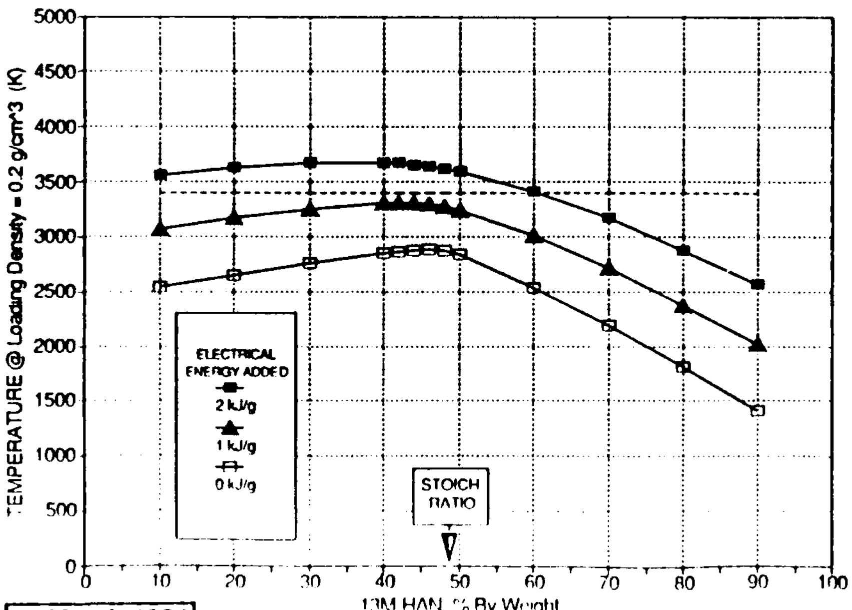
THEORETICAL IMPETUS of ET-C GUN PROPELLANTS
13M-HAN - Ethylenediamine Dinitrate



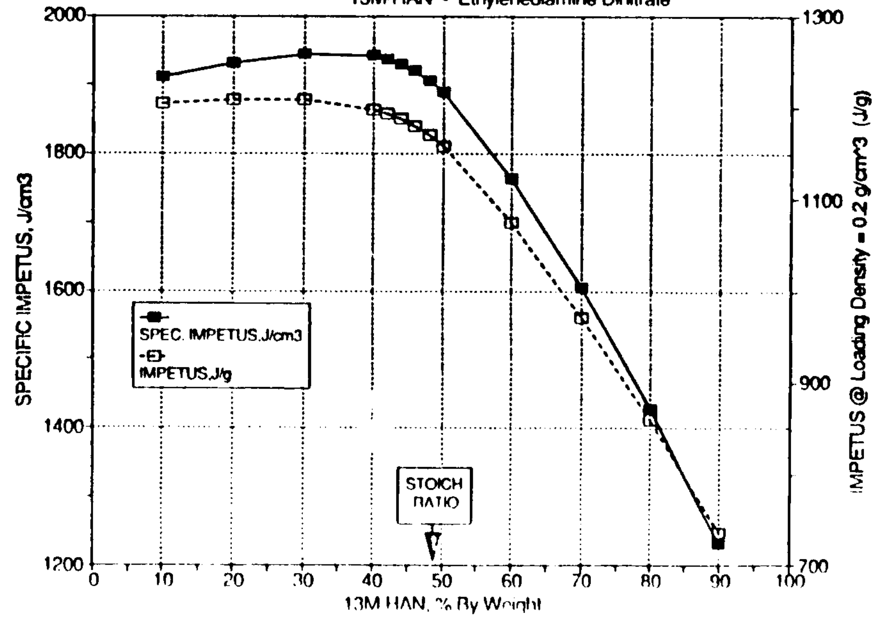
THEORETICAL SPECIFIC IMPETUS
13M-HAN - Ethylenediamine Dinitrate



THEORETICAL TEMPERATURE of ET-C GUN PROPELLANTS
13M-HAN - Ethylenediamine Dinitrate



THEORETICAL IMPETUS AND SPECIFIC IMPETUS @ 1 kJ/g
13M-HAN - Ethylenediamine Dinitrate



30 March 1991

ET-C CANDIDATE AND REFERENCE SYSTEMS - SPECIFIC IMPETUS (J/cc) SORT

30-Jun-91

	FORMULA NAME OR ID #	IMPETUS (J/g)	DENSITY (g/cc)	SPEC IMP (J/cc)	SPECIFIC IMPETUS SELECT	COVOLUME (cm3/g)	GAMMA ---	FL TEMP (DEG K)	(CHEMICAL + ELECTRICAL) ENRGY (J/g)	ENERGY (J/cc)	ENERGY SELECT	GMW ---	COMP1 ---	PERCENT ---	COMP2 ---	PERCENT ---	COMP3 ---	PERCI ---
	#H2GASKJ33H#	14068	0.200	2814	MARKER	3.8200*	1.2820*	3406	49887	9977	MARKER	2.01	H2 GAS	100.00	ELECTRONS	33.5 KJ/g FOR REFERE!		
	#H2GASKJ40B#	14032	0.200	2806	MARKER	3.6950*	1.4339*	3401	32339	6468	MARKER	2.01	H2 GAS	100.00	ELECTRONS	39.7 KJ/g FOR REFERE!		
	ET270KJ1	1657	1.689	2799	1	1.0210	1.2201	4290	7528	12715	1	21.52	HNF	80.00	AH	20.00		
	ET264KJ1	1725	1.603	2765	2	1.0930	1.2282	4019	7559	12117	2	19.36	HNF	70.00	AH	30.00		
	ET906KJ1	1491	1.840	2743	3	0.9940	1.2320	5000	6425	11821	3	27.89	TNAZ	100.00				
	ET905KJ1	1478	1.820	2690	4	0.9960	1.2295	4921	6439	11719	4	27.69	TNAZ	89.99	NC1300	10.01		
	ET265KJ1	1732	1.518	2629	5	1.1790	1.2390	3638	7247	11001	14	17.47	HNF	60.00	AH	40.00		
	ET904KJ1	1464	1.790	2621	6	0.9970	1.2272	4839	6445	11537	5	27.47	TNAZ	80.01	NC1300	20.00		
	ET764KJ1	1503	1.740	2615	7	1.1370	1.2492	3861	6030	10492	40	21.36	RDX	89.99	NMP	10.02		
	ET864KJ1	1499	1.730	2594	9	1.0670	1.2348	4145	6385	11046	11	22.99	NC1300	0.00	DNPN	100.00		
	ET833KJ1	1557	1.650	2570	8	1.0870	1.2358	4089	6605	10898	19	21.83	RDX	40.02	MENENA	59.99		
	ET824KJ1	1557	1.650	2570	10	1.0870	1.2358	4089	6605	10898	18	21.83	RDX	40.02	MENENA	59.99		
**	ET903KJ1	1450	1.770	2567	11	0.9980	1.2253	4753	6437	11394	7	27.25	TNAZ	69.97	NC1300	30.03		
**	ET835KJ1	1549	1.640	2540	12	1.0790	1.2346	4111	6601	10826	21	22.07	RDX	39.98	MENENA	50.02	TMETN	10.
	ET865KJ1	1476	1.720	2539	13	1.0610	1.2339	4116	6312	10856	20	23.18	NC1300	10.00	DNPN	90.00		
	ET400KJ0	1391	1.820	2532	14	1.0400	1.2300	4072	6048	11007	13	24.34	RDX	100.00				
	ET853KJ1	1515	1.670	2530	15	1.0240	1.2234	4277	6782	11326	8	23.47	NC1300	0.00	DINA	100.00		
	ET270KJ0	1495	1.689	2525	16	1.0010	1.2195	3937	6811	11502	6	21.89	HNF	80.00	AH	20.00		
**	ET829KJ1	1540	1.630	2511	17	1.0710	1.2332	4134	6605	10766	25	22.32	RDX	40.01	MENENA	39.98	TMETN	20.
	ET902KJ1	1435	1.740	2496	18	0.9990	1.2237	4661	6414	11159	9	27.01	TNAZ	60.02	NC1300	39.98		
	ET854KJ1	1492	1.660	2476	19	1.0220	1.2234	4238	6677	11084	10	23.62	NC1300	10.00	DINA	90.00		
	ET906KJ0	1344	1.840	2472	20	0.9830	1.2244	4657	5987	11016	12	28.82	TNAZ	100.00				
	ET866KJ1	1454	1.700	2471	22	1.0550	1.2330	4086	6238	10605	35	23.37	NC1300	20.02	DNPN	79.98		
**	ET831KJ1	1542	1.590	2452	21	1.1010	1.2382	3927	6474	10294	49	21.17	RDX	19.98	MENENA	80.02		
						*		*				*						
**	#JA2 KJ0B#	1141	1.590	1814	MARKER	0.9930	1.2258	3412				24.86	ACTUAL SPECIFIC IMPETUS LIMITED TO 1255 J/cc DUE TO LOAD DEN <1.1 g/cc					
						*		*				*						
**	#JA2NomLDen#	1141	0.880	1004	MARKER	0.9930	1.2258	3412				24.86	JA2 TYPICAL OR NOMINAL ACTUAL LOAD DENSITY WHICH IS <1.1 g/cc					

ET-C CANDIDATE AND REFERENCE SYSTEMS - SPECIFIC (J/cc) SORT

30-Jun-91 FORMULA NAME OR ID #	IMPETUS (J/g)	DENSITY (g/cc)	SPEC IMP (J/cc)	SPECIFIC IMPETUS SELECT	COVOLUME (cm3/g)	GAMMA ---	FL TEMP (DEG K)	(CHEMICAL + ELECTRICAL) ENRGY (J/g)	ENERGY (J/cc)	ENERGY SELECT	GMW ---	COMP1 ---	PERCENT ---	COMP2 ---	PERCENT ---	COMP3 ---	PERCI ---
ET270KJ1	1657	1.689	2799	1	1.0210	1.2201	4290	7528	12715	1	21.52	HNF	80.00	AH	20.00		

VOLUME-SPECIFIC CHEMICAL + ELECTRICAL ENERGY
= I / (GAMMA-1) * RHO, (J/CC)

CHEMICAL + ELECTRICAL ENERGY
= I / (GAMMA-1), (J/G)

VOLUME-SPECIFIC IMPETUS
= I * RHO, (J/CC)
SPECIFIC IMPETUS (J/CC) ≅ SPECIFIC ENERGY (J/CC)*(γ-1)

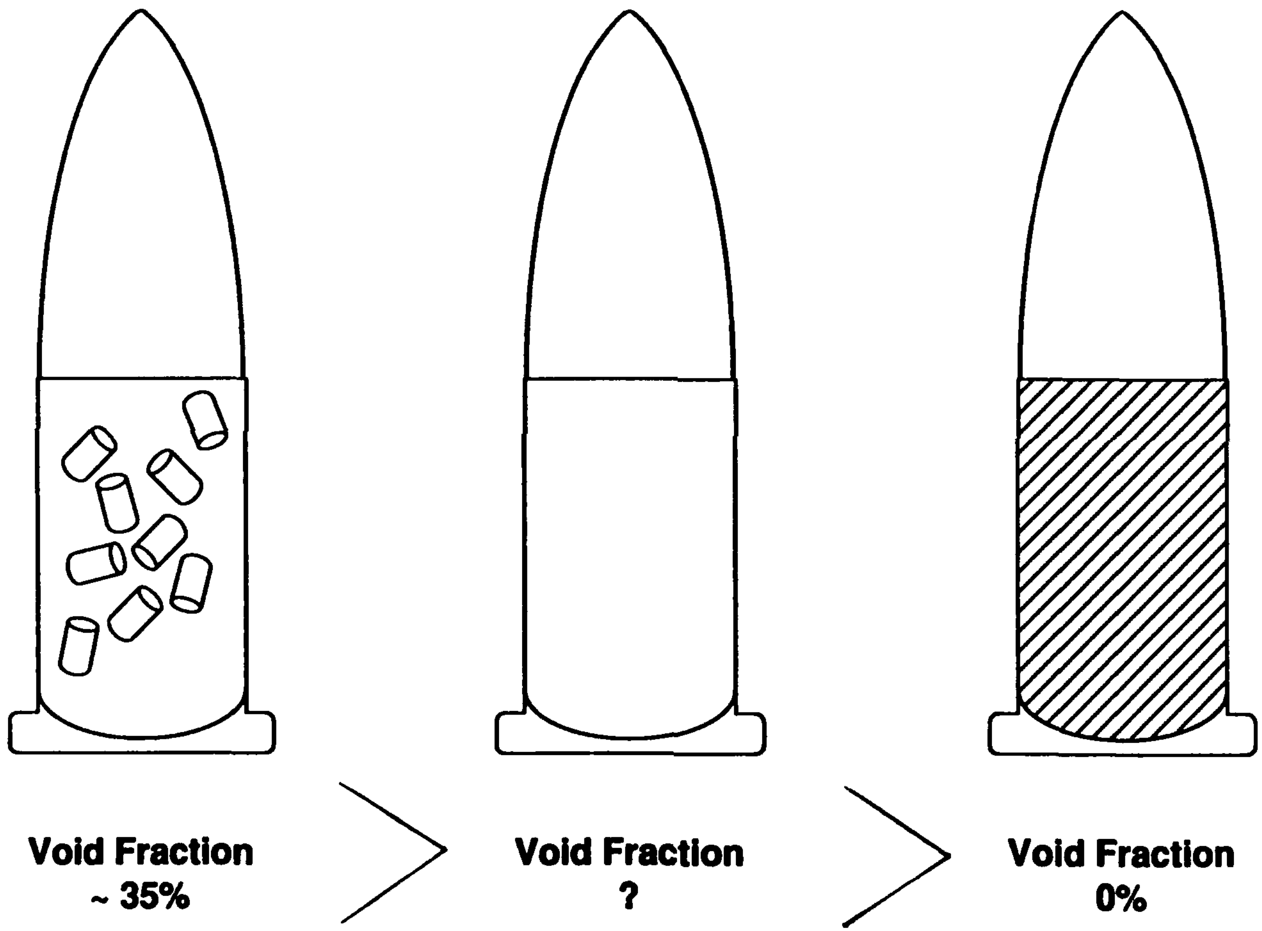
IMPETUS
I = R * T / M, (J/G), WHERE R = UNIVERSAL GAS CONSTANT

FORMULA NAME OR ID, WHERE : ET270KJ1
ELEC ENERGY AUGMENTATION LEVEL
FORMULA NAME OR ID SERIAL NUMBER

Olin ORDNANCE

C33031-53

Packaging



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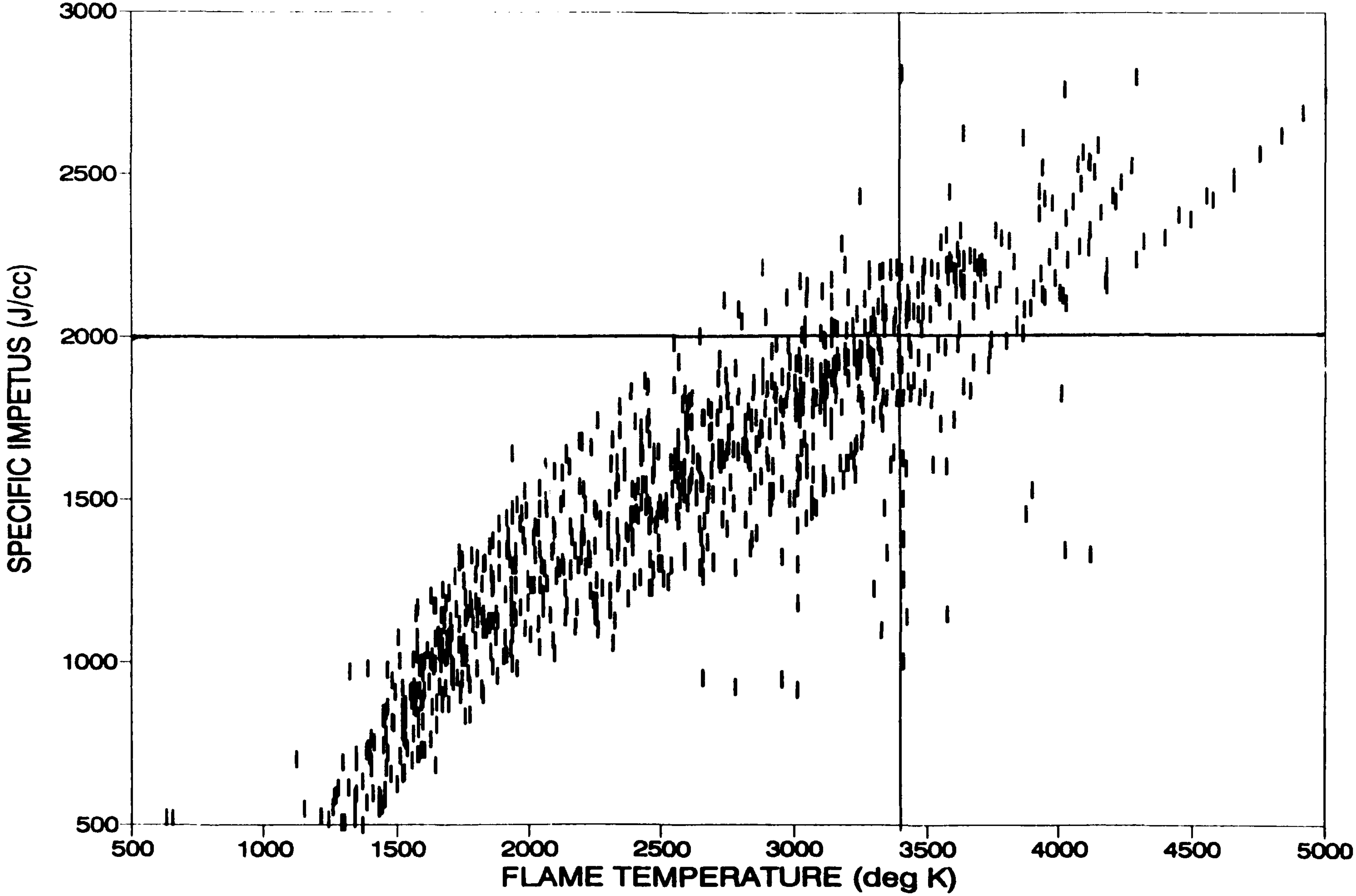
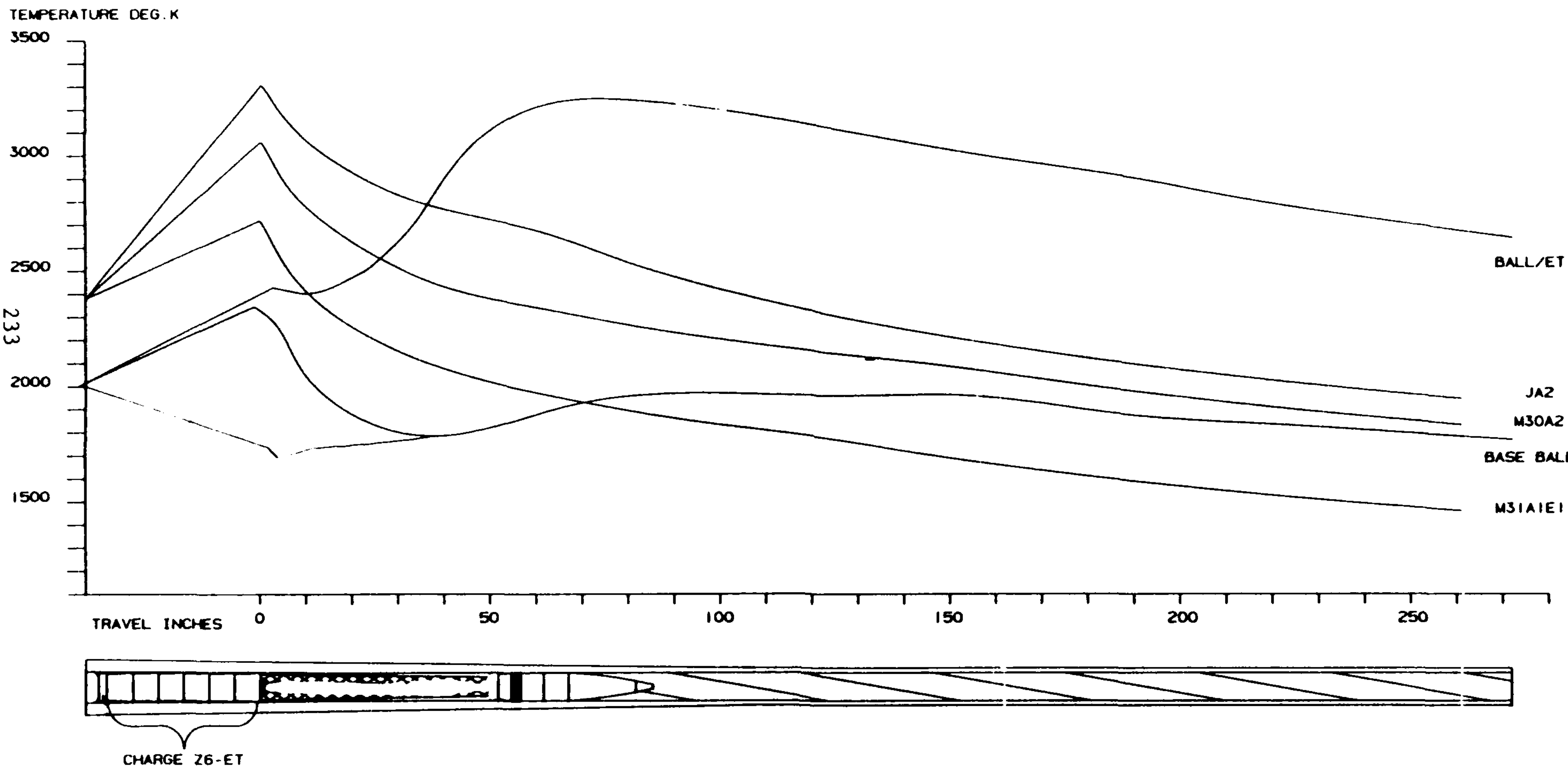
FLAME TEMPERATURE vs SPECIFIC IMPETUS
0 KJ/g and 1 KJ/g





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GENERAL APPROACH

TASK 1

- CONVENTIONAL PROPELLANTS
- CONVENTIONAL INGREDIENTS
  UNCONVENTIONAL FORMULATIONS
- NEW INGREDIENTS

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CANDIDATE SELECTION

- HAN/DEG HAN/NMP — Solvent is also fuel component yet less endothermic than water.
- HAN/MMHN HAN/UDMHN HAN/TMHN — Non-volatile hydrazine salts, more energetic f components than TEAN and contain less carbon.
- HAN/ATA HAN/DATA — High-nitrogen heterocyles. Inert, positive heats of formation. Water soluble. Too basic?
- NM/NC — Nitromethane has good characteristics. Low nitrogen NC may lower temperature, aid ignition and gell NM.
- NC/TAGN — TAGN lowers flame temperature and GMW, but may increase impact sensitivity.

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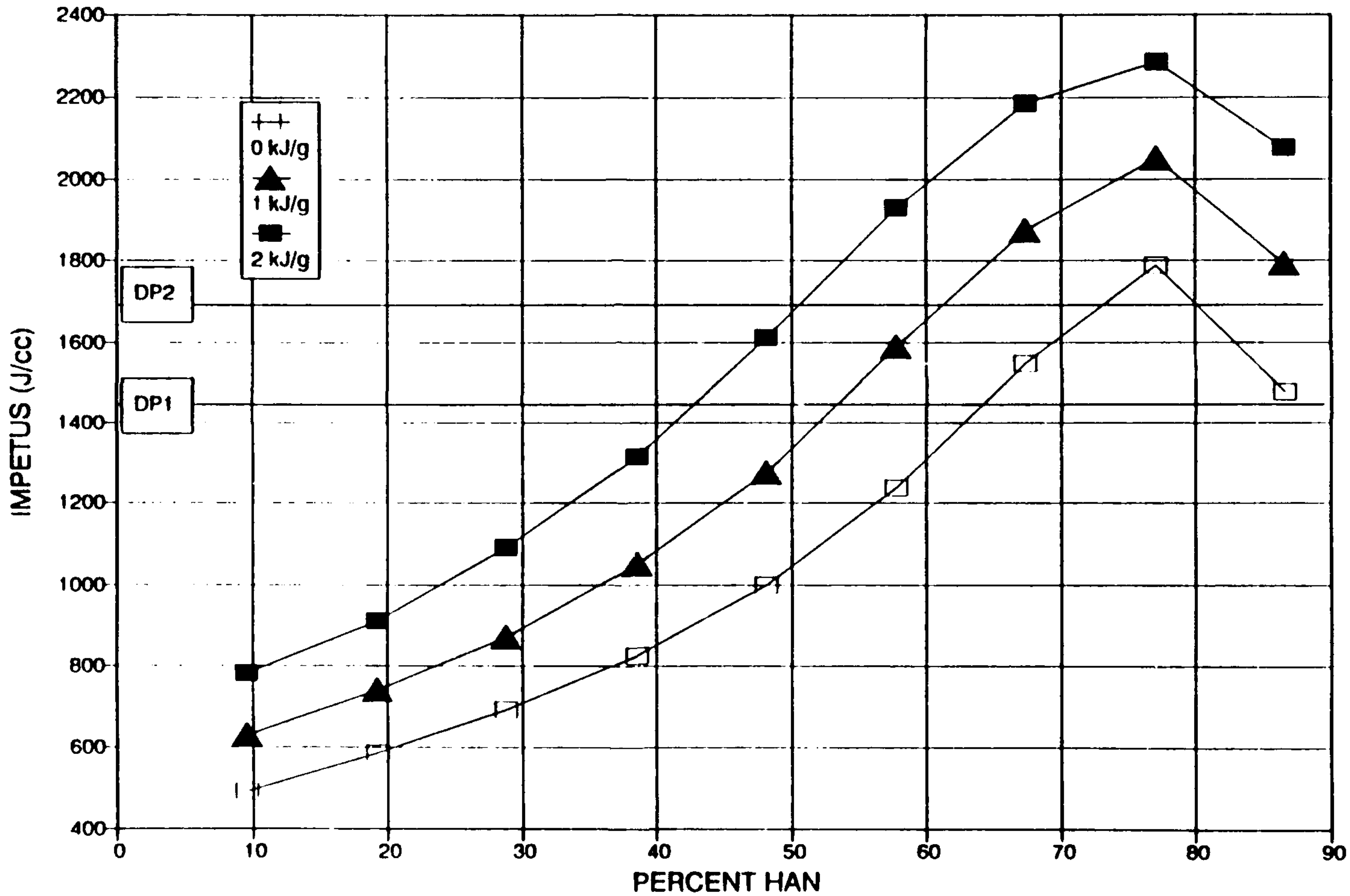
THEOR. SPECIFIC IMPETUS
HAN + DEG + 3.7% H2O



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ET-C CANDIDATES
BLAKE RESULTS

THE COMPOSITION IS

NAME	PCT WT	PCT MOLE	DEL H-CAL/M	FORMULA
HAN	77.068	66.889	-8.7600E+04	$N_2H_4O_4$
DEG	19.218	15.096	-1.5000E+05	$C_4H_{10}O_3$
H2O	3.713	17.181	-6.8315E+04	H_2O_1
ELEC	.000	.834	2.3780E+06	$ELEC_1$

THE HEAT OF FORMATION IS -877.46 CAL/GRAM = -7.3143E+04 CAL/MOLE.

THE ELEMENTS AND PERCENT BY MOLE

N	13.680
H	46.311
O	33.748
C	6.175
ELEC	.085

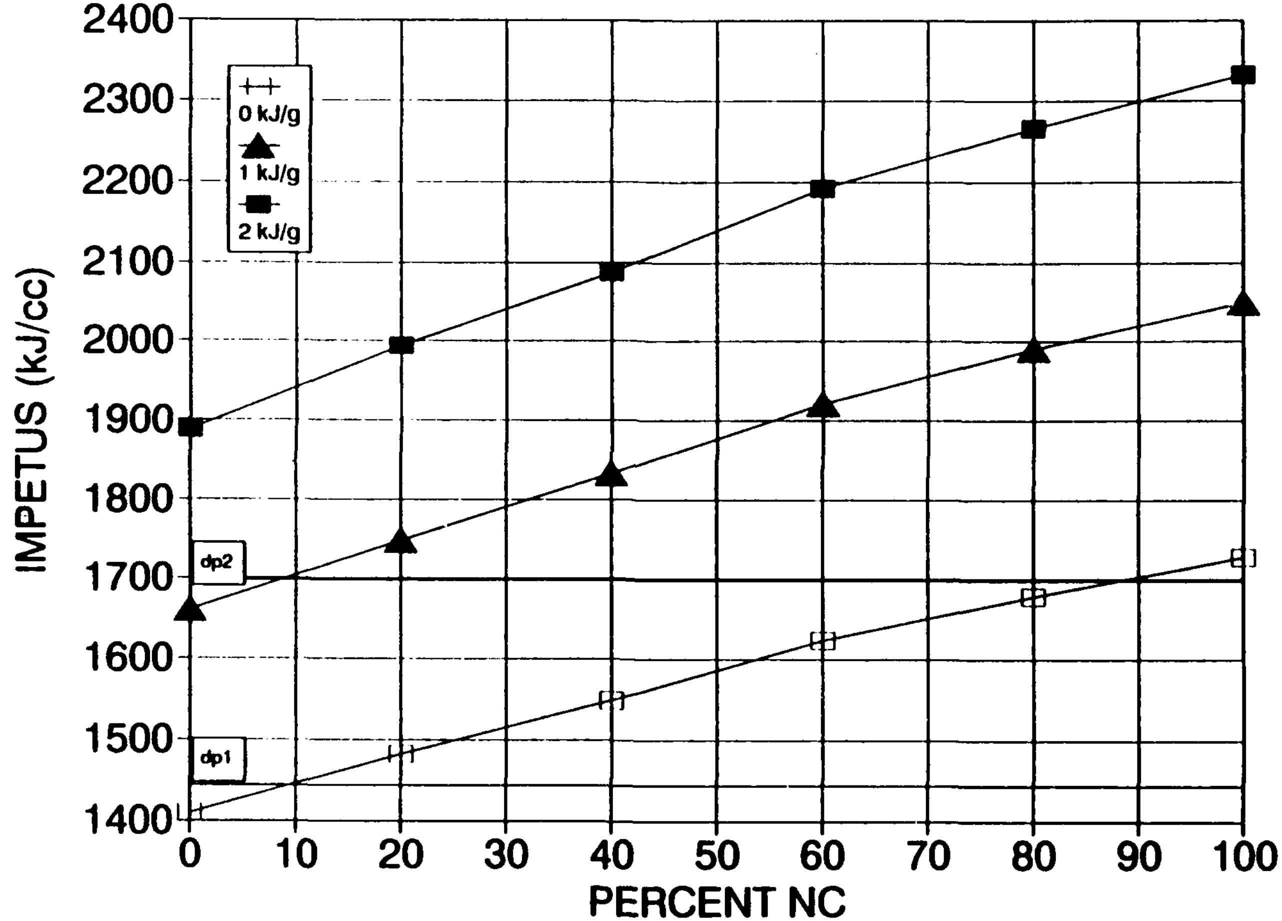
ET774KJ1

* * SUMMARY OF PROPELLANT THERMO PROPERTIES * *

TRUNCATED VIRIAL EQUATION OF STATE WITH L-J 6,12 POTENTIAL IS BEING USED

	RHO/L G/CC	TEMP K	PRESSURE MPA	IMPETUS J/G	MOL WT GAS	CO-VOL CC/G	FROZEN GAMMA	CP(FR) J/MOL-K	B(T) CC	C(T) CM**6	GAS VOL CC/G	S J/G-K	H J/G	E J/G	ADEXP	PHI
1)	.2000	3425.	295.02	1228.6	23.180	.835	1.2036	53.13	19.79	412.	[illegible].000	10.15	-2196.2	-3671.3	1.4018	1.2006

THEOR. SPECIFIC IMPETUS
NC1300 - NITROMETHANE



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ET-C CANDIDATES
BLAKE RESULTS

NAME	PCT WT	PCT MOLE	DEL H-CAL/M	FORMULA
NM	80.156	99.237	-2.7900E+04	C 1 H 3 N 1 O 2
NC1310	19.844	.005	-1.6508E+08	C 6000 H 7382 O 10237 N 2618
ELEC	.000	.758	2.3780E+06	ELEC 1

THE HEAT OF FORMATION IS -245.01 CAL/GRAM = -1.8516E+04 CAL/MOLE.

THE ELEMENTS AND PERCENT BY MOLE

C	15.716
H	40.343
N	13.549
O	30.302
ELEC	.091

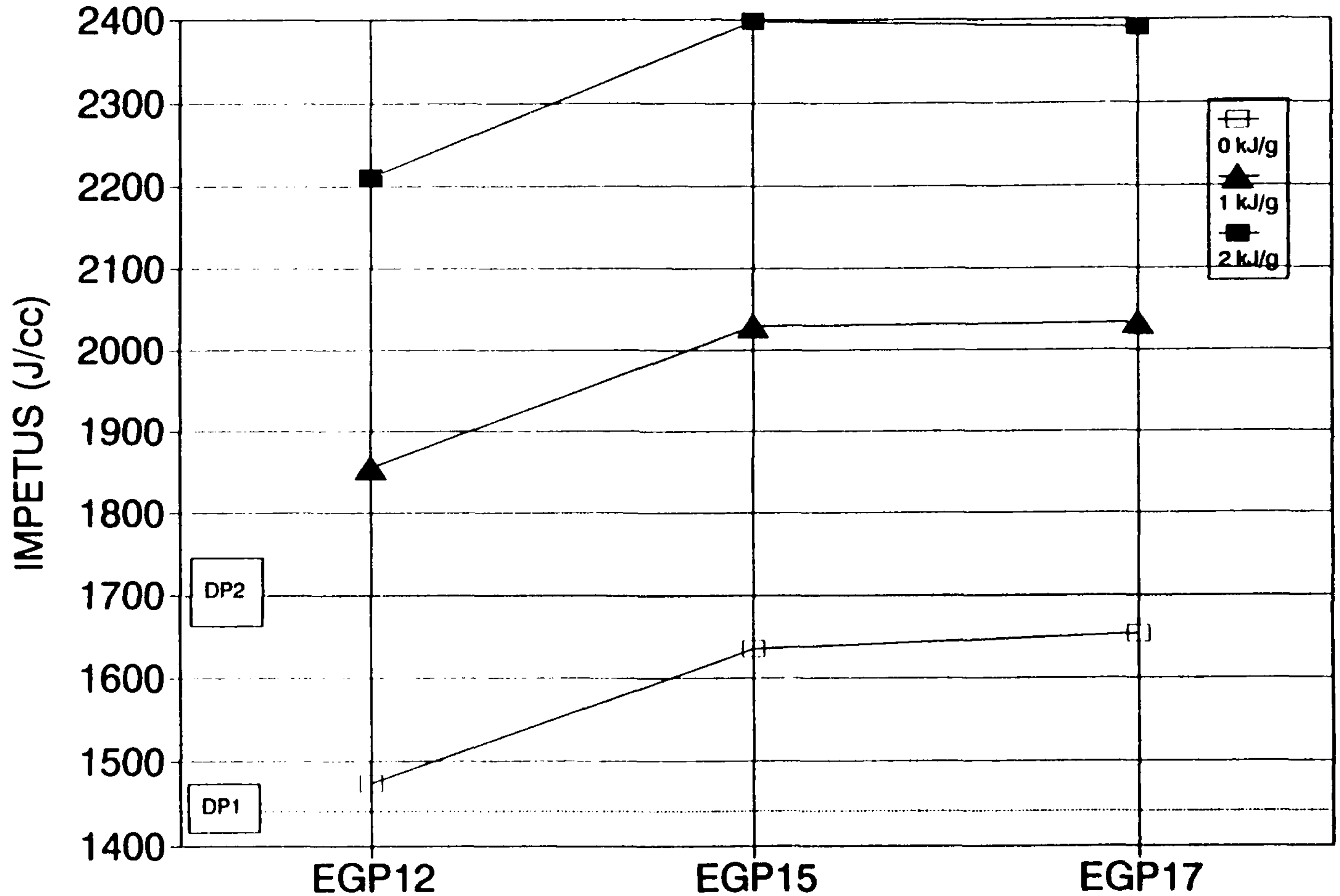
NM -NC ET561KJ1

* * SUMMARY OF PROPELLANT THERMO PROPERTIES * *

TRUNCATED VIRIAL EQUATION OF STATE WITH L-J 6,12 POTENTIAL IS BEING USED

	RHO/L G/CC	TEMP K	PRESSURE MPA	IMPETUS J/G	MOL WT GAS	CO-VOL CC/G	FROZEN GAMMA	CP(FR) J/MOL-K	B(T) CC	C(T) CM**6	GAS VOL CC/G	S J/G-K	H J/G	E J/G	ADEXP	PHI
1)	.2000	3607.	361.21	1422.3	21.083	1.062	1.2327	45.12	23.91	480.	5.000	10.36	780.9	-1025.1	1.5196	1.2698

THEORETICAL SPECIFIC IMPETUS
NC TAGN DBP



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ET-C CANDIDATES
BLAKE RESULTS

THE COMPOSITION IS

NAME	PCT WT	PCT MOLE	DEL H-CAL/M	FORMULA
NC1300	81.892	.296	-1.6591E+08	C 6000 H 7416 O 10168 N 2584
DBP	8.076	29.206	-2.0140E+05	C 16 H 22 O 4
TAGN	10.032	60.427	-1.1500E+04	C 1 H 9 N 7 O 3
ELEC	.000	10.071	2.3780E+06	ELEC 1

THE HEAT OF FORMATION IS -315.42 CAL/GRAM = -3.1752E+05 CAL/MOLE.

THE ELEMENTS AND PERCENT BY MOLE

C	22.606
H	33.180
O	32.460
N	11.655
ELEC	.099

EGP 12KJ1

* * SUMMARY OF PROPELLANT THERMO PROPERTIES * *

TRUNCATED VIRIAL EQUATION OF STATE WITH L-J 6,12 POTENTIAL IS BEING USED

	RHO/L G/CC	TEMP K	PRESSURE MPA	IMPETUS J/G	MOL WT GAS	CO-VOL CC/G	FROZEN GAMMA	CP(FR) J/MOL-K	B(T) CC	C(T) CM**6	GAS VOL CC/G	S J/G-K	H J/G	E J/G	ADEXP	PHI
1)	.2000	3152.	306.87	1196.5	21.901	1.101	1.2512	42.28	26.04	534.	5.000	9.62	214.6	-1319.7	1.5612	1.2823

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LIST OF RRC CANDIDATE PROPELLANTS FOR TASKS 2,3,4 (STRAWMAN)

EWS 29 June 1991

OXIDIZER	FUEL	SOLVENT/DILUENT	1 kJ/g Optimum specific impetus, J/cm3
70% Ammonium nitrate	30% 5-Aminotetrazole		2099
93% Ammonium nitrate	7 % JP-4		2009
45% Ammonium nitrate	55% EDDN		1999
83% Ammonium nitrate	17% Ammonia		1890
48% 13-M HAN	52% MEAN		1870
86% Ammonium nitrate	14% Ethylene glycol		1863
60.79% HAN	19.19 % TEAN	20.02 % Water	1790
54% Ammonium nitrate	46% GuN		1783
45% 13-M HAN	55% GuN		1687
50, 60, 70% HN	None	50, 40, 30% H2O	
None	90, 80, 70% TAGN	10, 20, 30% H2O	

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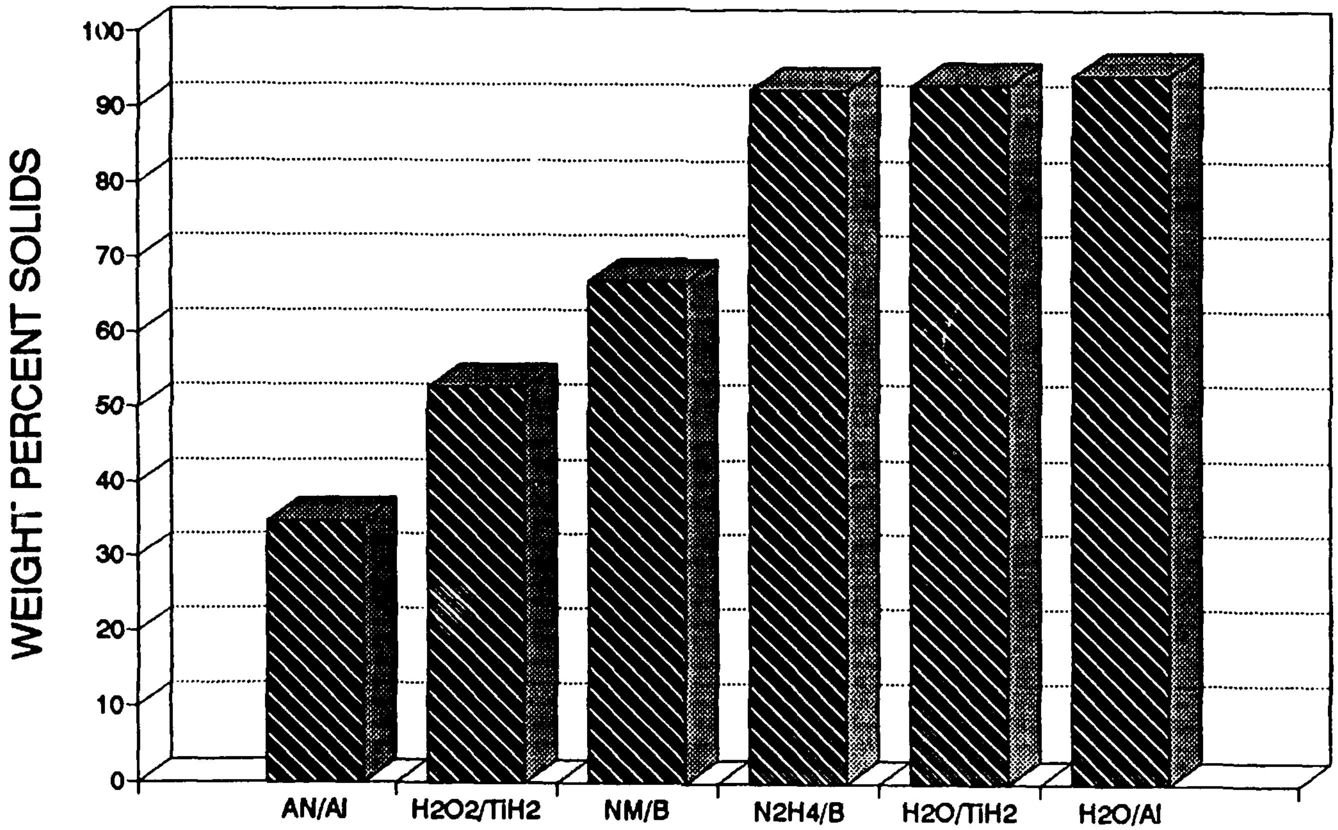
SOLIDS CONTENT IN EXHAUST
OF CANDIDATE ET-C PROPELLANTS



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TASK 2

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TASK 2
INGREDIENT COMPATIBILITY AND STABILITY
STATUS (JULY 2, 1991)

- REPRESENTS DOWNSELECT FROM TASK 1
- TEST TUBE MIXTURES FOR PRIMARY COMPATIBILITY
- ~ 60 DSC TESTS ON "MARKERS" AND MIXTURES
- DSC DATA BASES (84 SAMPLES) FUTURE RELEASE
- ORDERING BY ONSET OF EXOTHERM, OTHER SORTING POSSIBLE
- AVAILABLE MATERIAL SAFETY DATA SHEET COLLECTED
- LISTING OF TOP 17 RRC CANDIDATES AVAILABLE NOW
- LISTING OF TOP 40 OC CANDIDATES AVAILABLE NOW
- NEXT QUARTER: COMPLETE DSC's OF STRAWMAN LIST, COMPILE DSC LISTS, DETERMINE ACTIVATION ENERGIES ON SELECTED SAMPLES

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TASK 2

- DSC's of most Cheshire candidates completed.
- Glass pans evaluated vs. aluminum.
- Several more required to cover selected candidates.
- Activation energy proportional to storage stability. May be of comparative interest to relate to well-characterized propellants.

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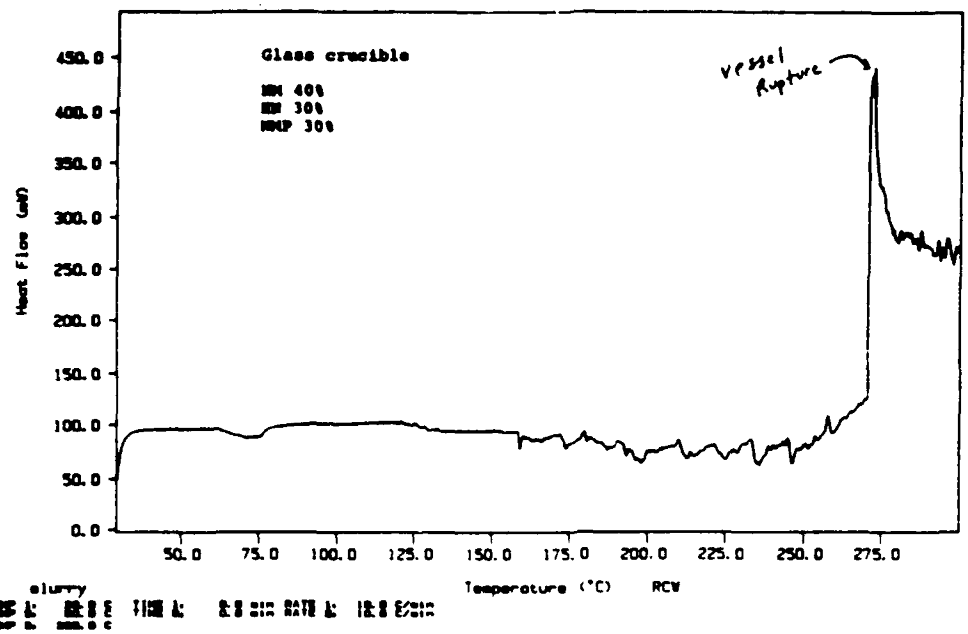
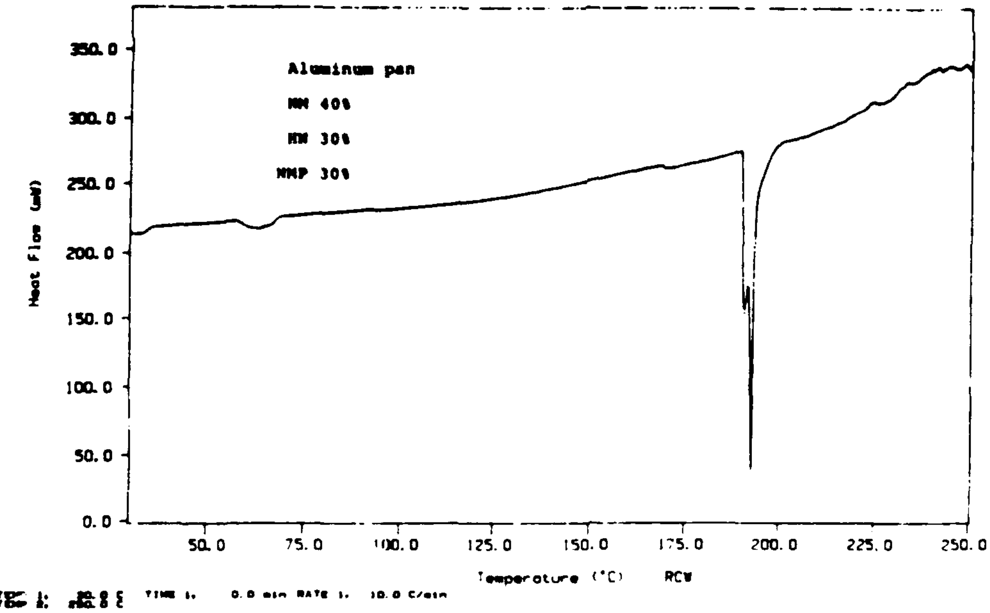
DSC - GLASS vs ALUMINUM PANS



DSC Data File: ar8
Sample Weight: 9.800 mg
Thu Sep 15 17:00:17 1988
b08872-4

PERKIN-ELMER
7 Series Thermal Analysis System



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DSC RESULTS - ET-C ALTERNATE PROPELLANTS

OXIDIZER	FUEL	DEC. ONSET oC		PAN MATER.	REF #	REMARKS
HN	AH	300	EXO	G	B96869-8	
EDDN	AH(gel)	290	EXO	G	B96872-1	VESSEL BURST
HN	NM/NMP	260	EXO	G	B96872-4	
TAGN	AH	250	EXO	G	B96869-5	
EtNENA	NC	233	EXO	G	B96879-6	
DNPN	AH	229.2	EXO	G	B96879-2	
DNPN		228	EXO	G	B96876	
EtNENA		227	EXO	G	B96879-5	
HAN	TEAN/W	226	EXO	G	B96891-1	LP1846
HAN	NMP	225	?	G	B96869-6	BR. GAS, REFLUX.
HAN	UDMHN/	225	EXO	Al	B96858-5	
HAN	MMHN/W	224	EXO	G	B96891-12	
HAN	NM/NMP	220	ENDO	G	B96872-2	VESSEL BURST
DNPN	NM	210.4	EXO	G	B96879-3	
HAN	HNTO	210	EXO	G	B96869-2	
EtNENA	TAGN	210	EXO	G	B96879-7	
HAN	NMP	208	?	Al	B96869-6	PAN LEAKED
TAGN	NC	207	EXO	G	B96869-4	DETONATE?
HAN	4ATA/W	195	ENDO	Al	B96857-1	LEAK?
DNPN	NC	194.7	EXO	Al	B96879-1	
TAGN	NC	190	EXO	Al	B96869-4	
HN	NM/NMP	190	ENDO	Al	B96872-4	PAN LEAKED
HAN	TEAN/W	187	EXO	Al	B96857-2	LP1845
DNPN	TAGN	186.5	EXO	Al	B96879-4	
TAGN	AH	180	ENDO	Al	B96869-5	
DNPN	NM	176.3	ENDO	Al	B96879-3	PAN LEAKED
DNPN		175	ENDO	Al	B96876	PAN LEAKED
HAN	TAGN	175	EXO	G	B96869-1	
HAN	EDNA	170	EXO	G	B96869-3	
HAN	HNTO	152	ENDO	Al	B96869-2	PAN LEAKED
HAN	PEG/W	151	EXO	Al	B96857-5	
HAN	TAGN	150	ENDO	Al	B96869-1	PAN LEAKED
AH	BORON	138	ENDO	Al	B96869-7	PAN LEAKED
HAN	NM/NMP	135	ENDO	Al	B96872-2	PAN LEAKED
NM	NC	130	ENDO	Al	B96855	PAN LEAKED
EDDN	AH(gel)	130	ENDO	Al	B96872-1	PAN LEAKED
AH	BORON	125	EXO	G	B96869-7	ALSO AT 200 & 235
HAN	EDNA	120	EXO/END	Al	B96869-3	PAN LEAKED
HAN	TFTA	120	EXO	G	B96872-3	
HAN	TFTA	BROAD ILL DEFINED		Al	B98672-3	

STATUS OF TASK 2 - INGREDIENT COMPATIBILITY, THERMAL STABILITY, STORABILITY

COMPLETED

84 DSC RUNS ENTERED IN DATA BASE
30 MICRO-COOKOFF TESTS
6 JANAF THERMAL STABILITY TESTS

PLANNED FOR NEXT QUARTER

COMBINE DSC FILES OF OLIN RRC AND OLIN CHEMICALS.
REPEAT SELECTED DSC RUNS FOR DETERMINATION OF ACTIVATION ENERGY.

Dr. Eckart W. Schmidt
Olin Rocket Research Company

Olin ORDNANCE

SEVENTEEN THERMALLY MOST STABLE CANDIDATE PROPELLANTS

Oxidizer	Fuel	Onset Exo 1	Other Exo
Hydrazinium nitrate	Ethylene glycol	228	
Ammonium nitrate	Kerosene JP-4	230	
Ammonium nitrate	Triethanolammonium nitrate	232	
Ammonium nitrate	Hydrazinium cyanurate	235	
Ammonium nitrate	Ethylenediamine dinitrate	236	
Ammonium nitrate	Ethylene glycol	241	
Hydrazinium nitrate	Hydrazinium cyanurate	242	
Hydrazinium nitrate	Guanidinium nitrate	243	
Ammonium nitrate	Methylammonium nitrate	255	
Ammonium nitrate	5-Aminotetrazole	257	
Hydrazinium nitrate	Ethylene glycoldimethylether	260	320
Ammonium nitrate	Triaminoguanidinium nitrate	265	
Ammonium nitrate	RJ-4	270	285
Ammonium nitrate	Guanidinium nitrate	290	
Ammonium nitrate	JP-10	290	
Ammonium nitrate	Methylcellosolve	290	
Ammonium nitrate	Cyanoguanidine(Dicyandiamide)	320	

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TASK 3

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TASK 3
FORMULATION STUDIES
STATUS (JULY 2, 1991)

- BASED ON DOWNSELECT FROM TASK 2
- CRITERIA ARE:
  - PERFORMANCE
  - TOXICITY
  - SAFETY / SENSITIVITY
  - THERMAL STABILITY
  - AVAILABILITY OF INGREDIENTS
- SAMPLE PREPARATIONS SUPPORT TASK 4 AND 6
- TEST FORMULATIONS MADE FOR METHODS CHARACTERIZATION
- NEXT QUARTER: WILL PREPARE 150-200 G SAMPLES TO SUPPORT TASK 4 TESTING

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TASK 3

- Additional candidates may be identified as limited Blake evaluations continue.
- No gross chemical hazards noted.
  NC, NM are nitro compounds.
  HAN - watch for dermal effects.
- Production of larger amounts for physical properties properties and Task 4 evaluations.

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STATUS OF TASK 3 - PROPELLANT FORMULATION STUDIES

COMPLETED

PHYSICAL PROPERTIES DETERMINED ON SEVERAL CANDIDATE PROPELLANT FORMULATIONS.

GELLING AGENT IDENTIFIED FOR GELLING OF LIQUID PROPELLANTS.

PLANNED FOR NEXT QUARTER

PREPARE LARGER (100-gram) BATCHES OF CANDIDATE PROPELLANTS.

STUDY THE FEASIBILITY OF FUSING THE NITRATE SALT MIXTURES AND GRANULATING THEM BY POURING FROM THE MELT, FORMING SPHEROIDAL GRANULES.

Dr. Eckart W. Schmidt
Olin Rocket Research Company

Olin ORDNANCE

CHEMICAL HAZARDS DATA

- MSDS sheets on hand for all but a few of the ingredients in the candidate formulations.
- Remaining sheets on order or have been requested from environmental hygiene group.
- Will be included in 3QTR report.

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*** FILE TOXICITY.PRN Last update 20 Jun 1991

Today's date 26-Jun-91

SUMMARY OF INGREDIENT PROPERTIES ET-C GUN PROP

ROW NUMBER	NAME	FLAMMABILITY LIMIT IN AIR % BY VOLUME LOWER	UPPER	FLASH POINT DEG C	METHOD ASTM	AUTOIGN.TEMP. IN AIR DEG C	T O X I C I T Y: TLV (1990) mg/m3	LC50 mg/l	LD50 mg/kg	MODE OF ADM.- TEST ANIMAL	MSDS ON HAND?
1	1,1-DIMETHYLHYDRAZINE	2	95	-15	COC	250	0.05	25	122	ORAL-RAT	YES
3	1,2-DIHYDRAZINOETHANE			>38							YES
6	1,3,5,7-TETRANITRO-1,3,5,7-TREAZOCINE										YES
9	3-NITRO-1,2,4-TRIAZOL-5-ONE							>200	>5000	ORAL-RAT	YES
13	5-AMINOTETRAZOLE							>200	900	ORAL-MICE	YES
15	ALUMINUM										YES
19	AMMONIUM NITRATE								4820	ORAL-RAT	YES
20	BIS-(2,2-DINITROPROPYL) FORMAL-ACETAL										YES
21	BORON (AMORPHOUS)								2000	ORAL-RAT	YES
22	BUTYL-2-(NITRATOETHYLNITRAMINE)										
26	DICYANDIAMIDE										
27	DIETHYLENEGLYCOLDINITRATE										
28	DIMETHYLFORMAMIDE	2.2	15.2	57	CC	444	1	8400	2800	ORAL-RAT	YES
29	ETHYL-2-(NITRATOETHYLNITRAMINE)										
33	ETHYLENEDIAMINE	2.7	16	34		380	10		500	ORAL-RAT	YES
36	ETHYLENEDIHYDRAZINE										YES
37	ETHYLENEDINITRAMINE								540	ORAL-MICE	
39	ETHYLENEGLYCOL										
40	ETHYLENEGLYCOL DIMETHYLETHER										
41	ETHYLENEGLYCOL DINITRATE										YES
43	GLYCIDYL AZIDE POLYMER										YES
44	GUANIDINIUM NITRATE								1028	ORAL-MICE	YES
46	HEXAHYDRO-1,3,5-TRINITRO-1,3,5-TRIAZI					197	1.5				YES
49	HYDRAZINE	4.7	100	51	OC	270	0.01	57	60	ORAL-RAT	YES
50	HYDRAZINE HYDRATE	3.5	100	>93			0.01	75	60	ORAL-RAT	YES
54	HYDROGEN PEROXIDE, 30%						1.4	2000	2000	ORAL-MICE	30%
56	HYDROXYLAMMONIUM NITRATE, 13-M							>2600	>100	ORAL-MICE	YES
61	KEROSENE JP-4						100		28 g/kg	ORAL-RABBIT	
62	LITHIUM BOROHYDRIDE										YES
63	LITHIUM NITRATE										YES
64	LP-1845										YES
65	LP-1846										YES
67	METHYL-2-(NITRATOETHYLNITRAMINE)										
69	METHYLAMMONIUM NITRATE										(YES)
70	METHYLHYDRAZINE	2.5	97	21		196	0.02		32	ORAL-RAT	YES
72	METHYLPYRROLIDONE	1.3	9.5	86		270			3914	ORAL-RAT	YES
77	NITROETHANE								1100	ORAL-RAT	YES
78	NITROFORM								300	ORAL-MICE	
80	NITROMETHANE	7.3	100	36	TCC	418	250		940	ORAL-RAT	
90	RJ-4										YES
93	TETRAHYDRODICYCLOPENTADIENE										YES
94	TITANIUM HYDRIDE										YES
95	TRIAMINOGUANIDINIUM NITRATE								3650	ORAL-MICE	YES
97	TRIETHANOLAMMONIUM NITRATE										YES
98	TRIETHYLENEGLYCOLDINITRATE										
100	TRIMETHYLOLETHANE TRINITRATE										
102	UREA										

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TOXICITY CONCERNS

- CARCINOGENICITY
- ACUTE INHALATION
- ACUTE DERMAL
- ACUTE ORAL

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TASK 4

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TASK 4
PROPELLANT SAFETY TESTING
STATUS (JULY 2, 1991)

- BASED ON DOWNSELECT FROM TASK 3
- CHARACTERIZATION TESTS
  - CAP
  - CARD GAP
  - IMPACT
  - ELECTROSTATIC
- SAFETY TESTS SUPPORT TASKS 6, 8,
- SCATTERED IMPACT DATA TAKEN FOR INGREDIENTS
- NEXT QUARTER: BEGIN CAP SENSITIVITY TESTING

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STATUS OF TASK 4 - PROPELLANT SAFETY CHARACTERIZATION

COMPLETED

DROP WEIGHT SENSITIVITY (50% POINT) DETERMINED ON SEVERAL CANDIDATE PROPELLANTS.

TABULATED TOXICITY DATA FROM PUBLISHED DATA.

IN PROGRESS

LIST OF CANDIDATE PROPELLANTS FOR CAP SENSITIVITY BEING CIRCULATED AMONG OLIN TEAM MEMBERS. SELECTION OF TEN BEST CANDIDATES FOR CAP SENSITIVITY TEST IN PROGRESS.

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LIST OF RRC CANDIDATE PROPELLANTS FOR TASK 4 CAP SENSITIVITY TEST

CANDIDATE LIST FOR CAP SENSITIVITY per TB 700-2

EWS 29 June 1991

OXIDIZER	FUEL	SOLVENT/DILUENT	1-kJ/g Optimum specific impetus, J/cm3
70% Ammonium nitrate	30% 5-Aminotetrazole		2099
93% Ammonium nitrate	7 % JP-4		2009
45% Ammonium nitrate	55% EDDN		1999
83% Ammonium nitrate	17% Ammonia		1890
48% 13-M HAN	52% MEAN		1870
86% Ammonium nitrate	14% Ethylene glycol		1863
60.79% HAN	19.19 % TEAN	20.02 % Water	1790
54% Ammonium nitrate	46% GuN		1783
45% 13-M HAN	55% GuN		1687
50, 60, 70% HN	None	50, 40, 30% H2O	
None	90, 80, 70% TAGN	10, 20, 30% H2O	
13-M HAN	TBD % Gelling agent		

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TASKS 5 & 6

Hugh A. McElroy
Olin Ordnance

Dr. J. Robert Greig
GT-Devices

Olin ORDNANCE

TASK 5, BALLISTIC EXPERIMENTAL PLANNING
TASK 6, ETC GUN AND TESTS
STATUS (JULY 2, 1991)

- PARALLELS TASK 1 - 4
- BALLISTIC TESTING AT GTD
- CONVENTIONAL BALL PROPELLANT BASELINE (WC891, LOT 2)
- GUN SYSTEM
  - IBHVG2 COMPUTATIONS FOR SCALING
  - NEED FOR REDUCED SCALE CAPILLARY FOR TESTS
  - REDESIGN OF CAPILLARY HARDWARE
  - FABRICATION OF NEW CHAMBER / CAPILLARY ASSY
  - EFFECTS OF IGNITER GEOMETRY ON PRESSURE OSCILLATIONS
- READY TO PERFORM TRIAL ETC SHOTS
- NEXT QUARTER: COMPLETE IGNITER MATRIX, INITIATE ETC FIRINGS WITH BALL POWDER (WC 891)

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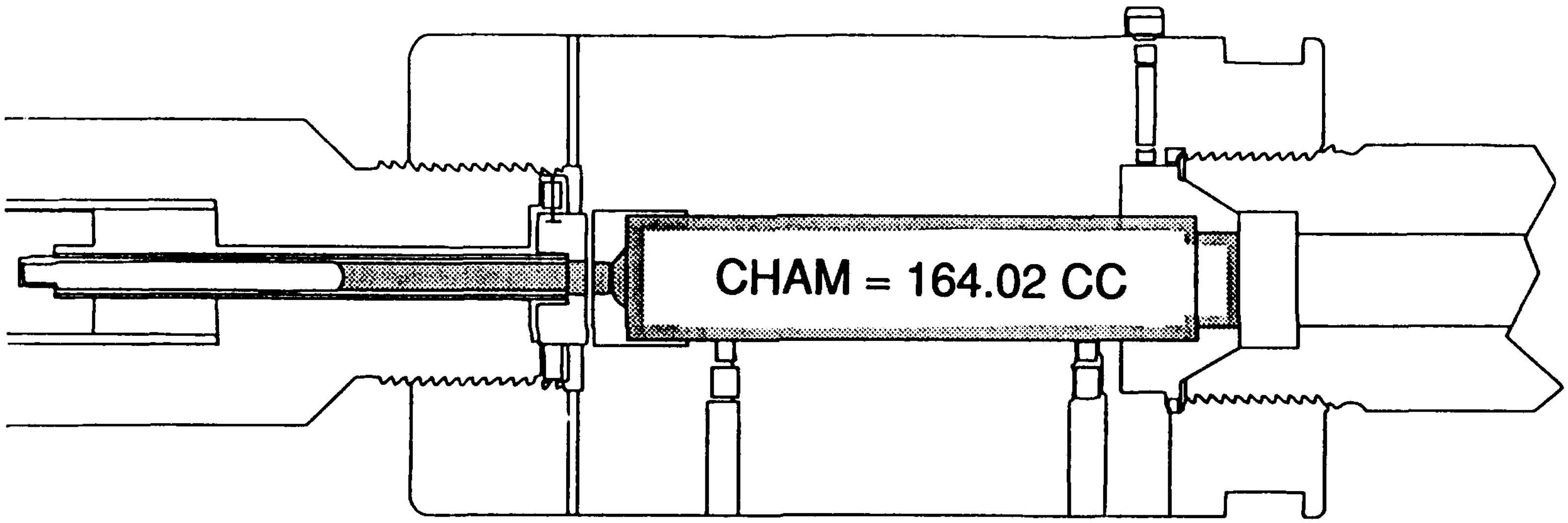
INITIAL SYSTEM BALLISTIC BASELINE
TEST SETUP
TASK 6



CUBE LAW SCALING

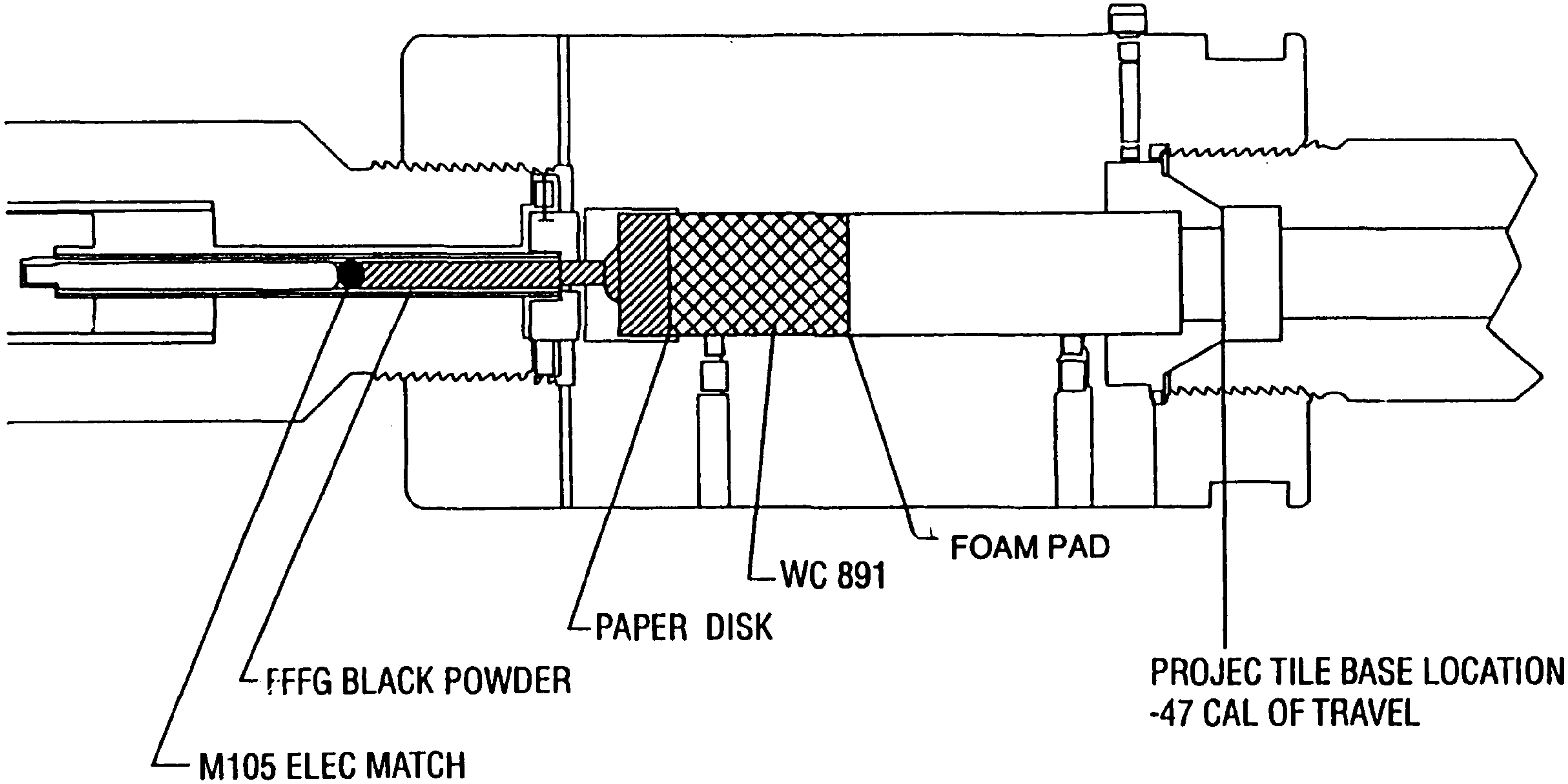
WP = 328.8 GMS (155 SIM)
BORE DIA. 30 MM
SHOT START = 200 bar

Olin ORDNANCE

VG1182 4/91 6812 FH

BALLISTIC BASELINE TEST 1

M105 ELECT MATCH
FFFG BLACK POWDER IGNITER - 8.32 GMS/2.77 GMS/1.00 GMS
WC 891 BALL POWDER MAIN CHG. - 65.3 GMS



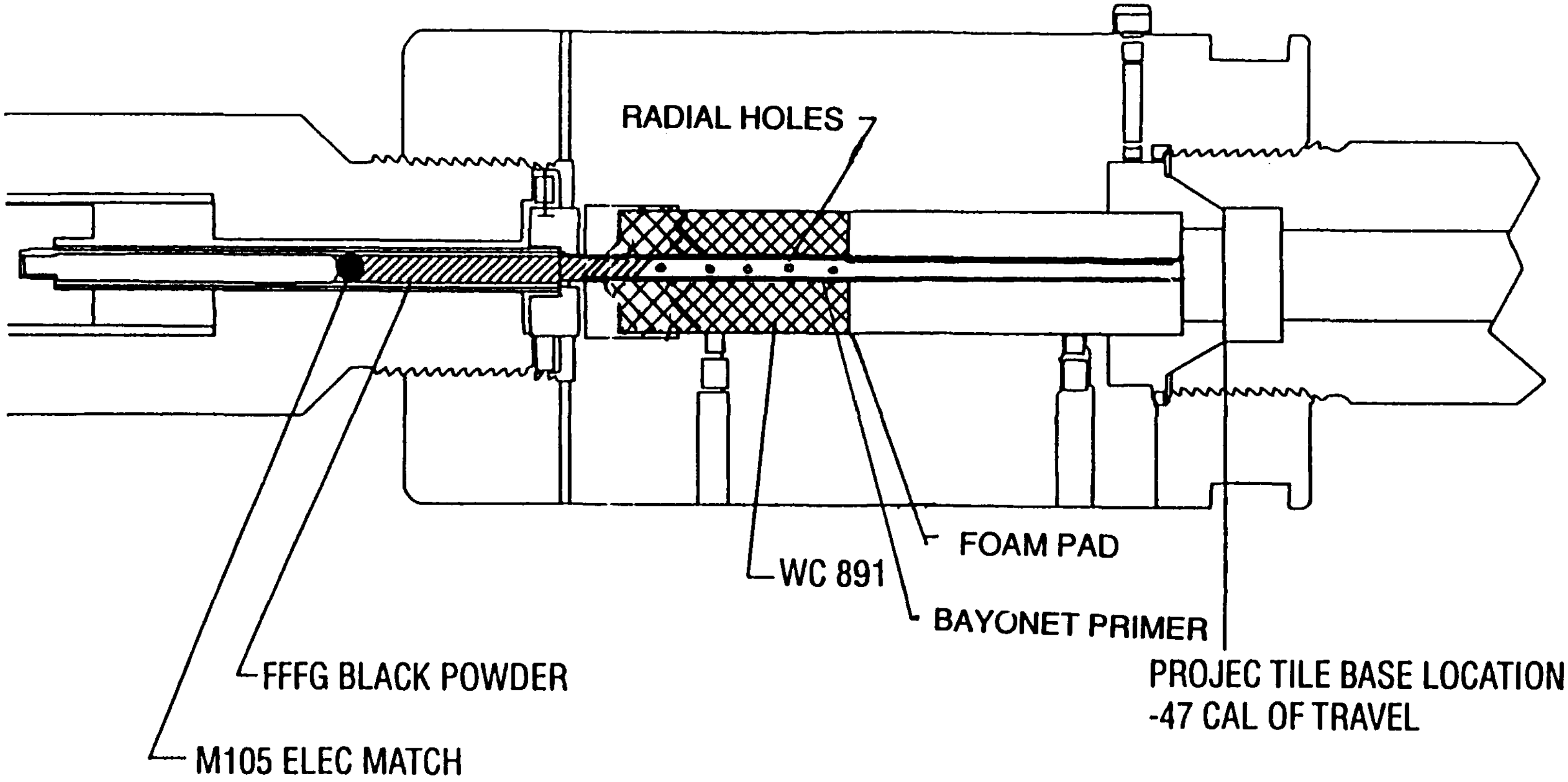
NOT TO SCALE

Olin ORDNANCE

VG1182 4/91 6813FH

BALLISTIC BASELINE TEST 1

M105 ELECT MATCH
FFFG BLACK POWDER IGNITER - 8.32 GMS/2.77 GMS/1.00 GM
WC 891 BALL POWDER MAIN CHG. - 65.3 GMS



NOT TO SCALE

Olin ORDNANCE

VG1182 4/91 6813FH

ET–C CALIBRATION W / ENERGETIC MATERIAL

TEST	SHOTS	IGNITION SYSTEM	MAIN CHARGE
		SIMPLE IGNITION SYSTEM SHOTS	
1A	6	8.32 GM BKP	65.3 GM WC891
	1	2.77 GM BKP	
	1	1.00 FM BKP	
		BAYONET PRIMER SHOTS	
1B	1	8.32 GM BKP	65.3 GM WC891
	1	2.77 GM BKP	
	1	1.00 GM BKP	

EXPECTED VELOCITY ~ 530 MPS

EXPECTED MAX PRESSURE ~ 13.5 KPSI

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TASK 8
SAMPLE DELIVERY
STATUS (JULY 2, 1991)

- NOT APPLICABLE AT THIS TIME
- DEADLINE FOR SAMPLE DELIVERY JUNE 1992
- SUGGEST PARTIAL DELIVERY OF CANDIDATES LAST 3 -4 QUARTERS, WITH COMPLETION IN JUNE 1992

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ORDNANCE

WHAT'S WRONG WITH THERMOCHEMICAL CODES APPLIED TO ETC SYSTEMS?

Eli Freedman
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Baltimore, MD 21209-1525

ABSTRACT

The rocket-propellant community for more than 35 years has obtained thermochemical data for the hot gases formed by its compositions from the NASA code called (in its latest version) CET89. This solid gun-propellant community for much of that time obtained the corresponding data for its compositions from the 'BLAKE' code. Both programs have for better or worse become virtual de facto standards for their respective applications. It was only natural, therefore, for ETC workers to apply one or both of these programs to their systems. Unfortunately, the results have not been completely satisfactory.

This paper undertakes to examine the reasons for this partial failure, especially for 'BLAKE'. Among the more important are: 1) its neglect of ions; 2) its omission of condensed phases from some of the computations; 3) its cranky operation, particularly when solids are formed; and 4) the occasionally wild values of gamma (the ratios of the two specific heats) that it produces. Items 1 and 3 are among the strong points of the NASA program; its main defects are its limitation to ideal gas systems, and its failure to compute properly the ratio of specific heats for systems containing large amounts of solids.

The ability of 'BLAKE' to compute non-ideal gas corrections has long been viewed as its strongest point, but the quality of those computations has never been seriously investigated. (Item 4 in the preceding paragraph probably arises from a defect in computing these corrections.)

Some suggestions for improving this unhappy state of affairs will be briefly discussed.

WHAT'S WRONG with THERMO CODES APPLIED to ETC SYSTEMS ?

Eli Freedman

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Presented to the JANNAF Workshop on
ETC Modelling & Diagnostics
Aberdeen Proving Ground, Maryland
9 July 1991

Supported by USABRL

OUTLINE

A. Introduction and Background

B. The NASA Code (CET86/89)

1. many advantages
2. only one major disadvantage

C. The BLAKE Code

1. only one advantage
2. many disadvantages
3. repeating an evaluation of the accuracy of BLAKE

D. A new old idea for non–ideal gas corrections

E. Summary

BACKGROUND I.

BLAKE and the NASA–Lewis codes:
–> *de facto* standards for gun & rocket calcns, resp.

Would appear to be readily applicable to ETC systems: merely modify the specific energy of the system.

EXAMPLES:

Using NASA CET*nn* (*nn* = 86 or 89):

```
NAMELISTS
  &INPT2  UV=T, RHO=0.2, U=<new total energy>, ... /
```

Using BLAKE:

```
  GUN, 0.2, 10, 0, <added electricity>
```

BACKGROUND II.

But there are problems, *esp.* with BLAKE.

Some problems are general and apply equally to all propellant systems.

Some are specific to ETC systems

There is considerable overlap.

A better distinction: Lumped–parameter *vs.* detailed modelling.

BACKGROUND III.

Lumped parameter systems:

Energy density = $\Delta E / \rho_L$

$\Delta \mathbf{E}$ = available chemical energy (J/gram)

ρ_L = loading density (g/cc)

Result: $T_{flame} < 5000$ K; no ions formed.

BUT: When modelling ETC systems during initial discharge,

$E(elec)$/reacting mass >> $\Delta E / \rho_L$

Result: Very high temperatures and ionization.

THE NASA CODE

It has *many* advantges:

--> fast

--> almost foolproof (not quite idiot proof)

--> uses the *entire* JANAF library (100's of potential products)

--> IONS=T is an option

--> Big temp range: C_P fitted in 2 or 3 ranges: 300 – 1000, 1000 – 5000, 5000 – 20000.

THE NASA CODE *(cont)*

One major disadvantage:

--> $pV = RT$ *everywhere.*

One minor disadvantage:

--> Rigid, awkward input format.

Only the first of these is serious amd difficult to overcome.

THE BLAKE CODE'S ONE ADVANTAGE

It makes non–ideal gas corrections, which are automatically incorporated into all of the computations.

- It can use many non–ideal EOS (but algebra may be a problem)
- default choice is truncated virial eqn of state:

$$pV = RT\left[1 + B(T)/V + C(T)/V^2\right]$$

$B_i(T)$ computed *via* L–J formalism for gas i. For the mixture,

$$B_{mix}(T) = \sum x_i x_j B_{ij}(T)$$

Computing B_{ij} is more art than science: intermolecular i,j potentials are unknown.

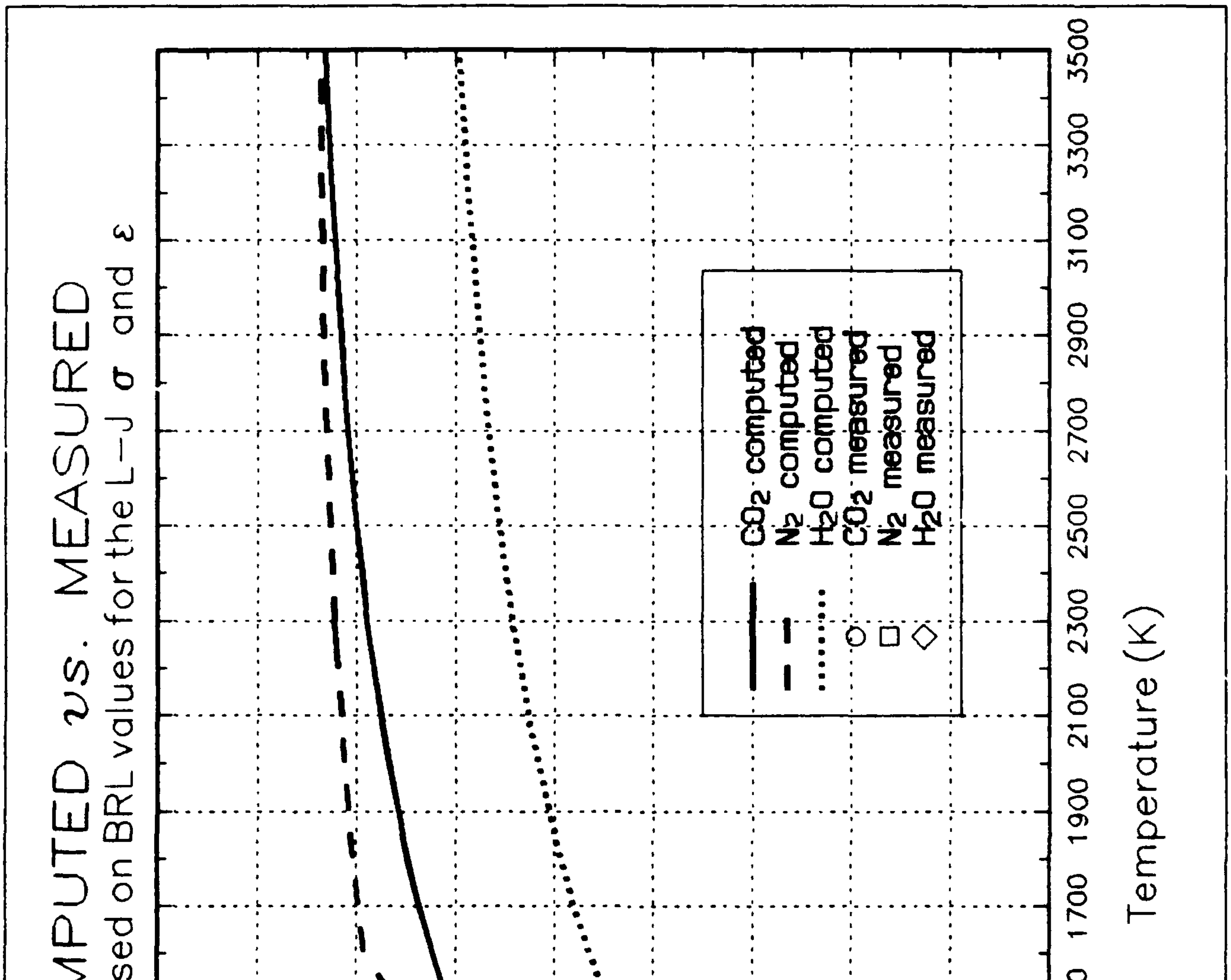
BLAKE CODE *(cont)*

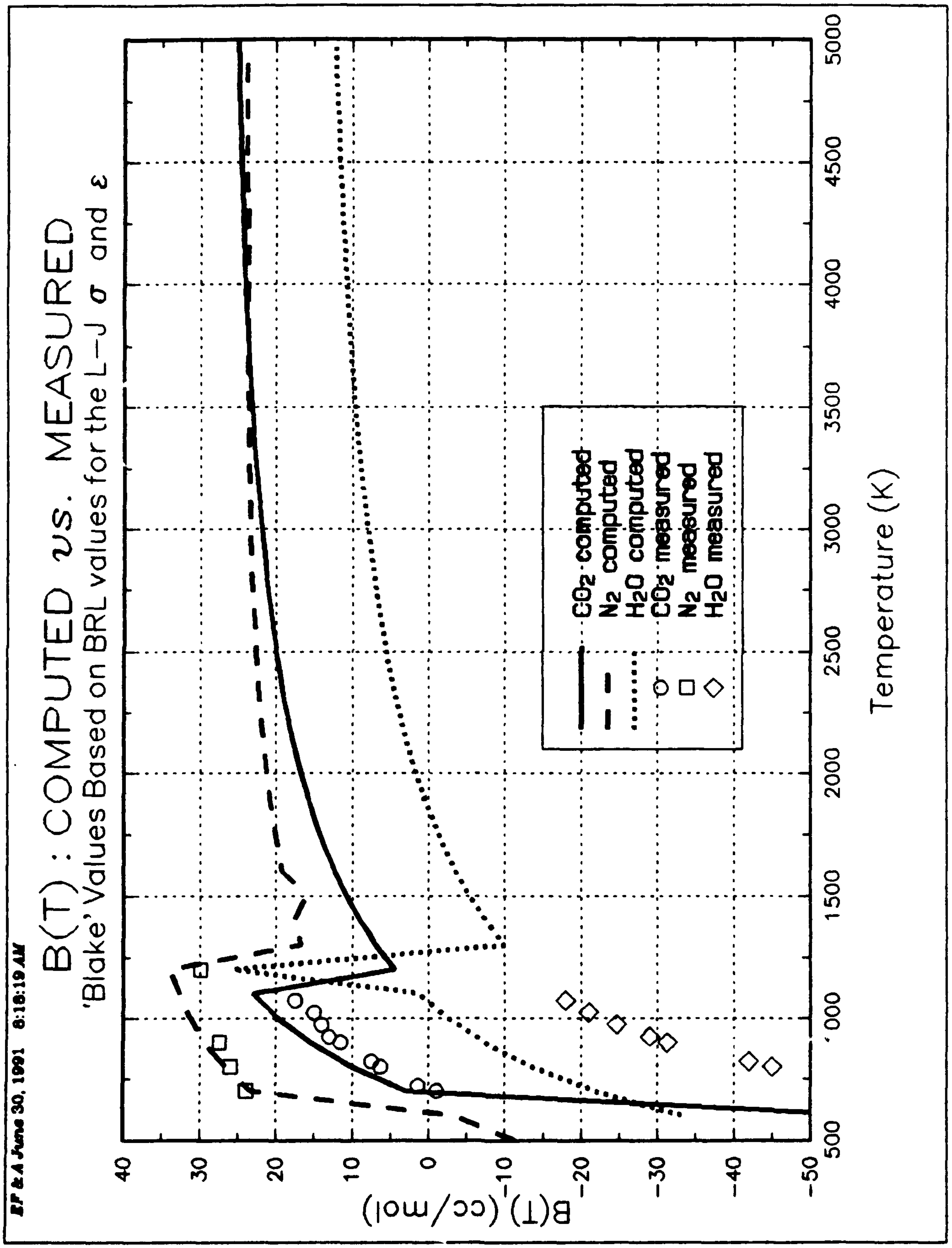
Validity of correction is unknown even for the significant single gases CO_2, CO, N_2, H_2O, and H_2.

Almost nothing is known about mixtures, exc. $H_2O + CO_2$ (not to mention radicals, free atoms, &c).

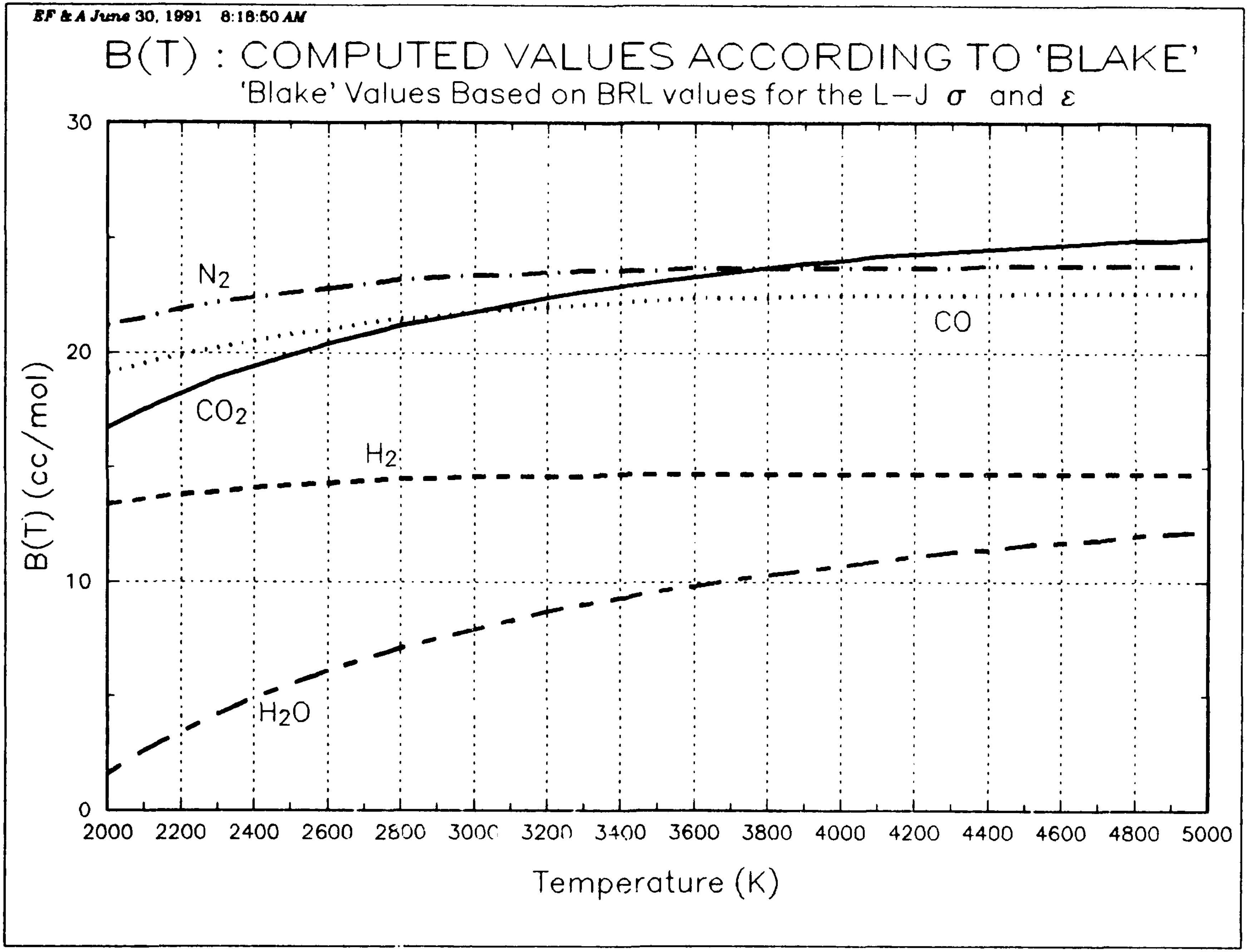
p–V–T measurements on the pure gases don't extend above 1200 K. Is comparison between experimental and computed B(T)'s at lower temps of any value ?

Good agreement at lower temperatures does not assure the validity at higher temperatures--the model is (probably) inadequate for such extrapolation.


EF & A June 30, 1991 8:17:41 AM
B(T) : COMPUTED vs. MEASURED
'Blake' Values Based on BRL values for the L–J σ and ε
CO_2 computed
N_2 computed
H_2O computed
CO_2 measured
N_2 measured
H_2O measured
B(T) (cc/mol)
40
30
20
10
0
-10
-20
-30
-40
-50
500
700
900
1100
1300
1500
1700
1900
2100
2300
2500
2700
2900
3100
3300
3500
Temperature (K)



EF & A June 30, 1991 8:18:19 AM
B(T) : COMPUTED vs. MEASURED
'Blake' Values Based on BRL values for the L–J σ and ε
B(T) (cc/mol)
Temperature (K)
CO2 computed
N2 computed
H2O computed
CO2 measured
N2 measured
H2O measured
40
30
20
10
0
-10
-20
-30
-40
-50
500
1000
1500
2000
2500
3000
3500
4000
4500
5000


BF & A June 30, 1991 8:18:50 AM
B(T) : COMPUTED VALUES ACCORDING TO 'BLAKE'
'Blake' Values Based on BRL values for the L–J σ and ε
N2
CO
CO2
H2
H2O
B(T) (cc/mol)
30
20
10
0
2000
2200
2400
2600
2800
3000
3200
3400
3600
3800
4000
4200
4400
4600
4800
5000
Temperature (K)

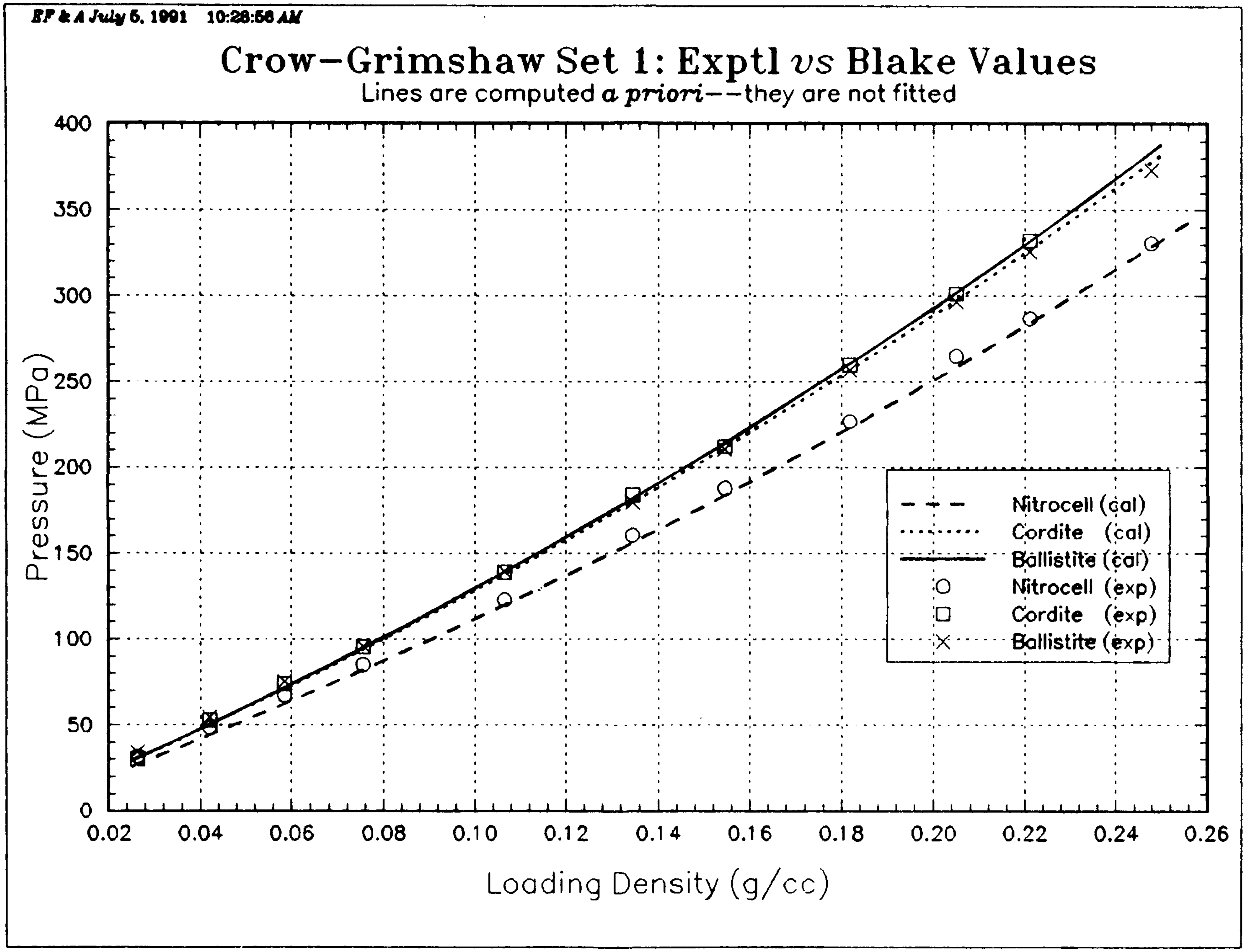
IS THERE A SERIOUS PROBLEM WITH BLAKE ?

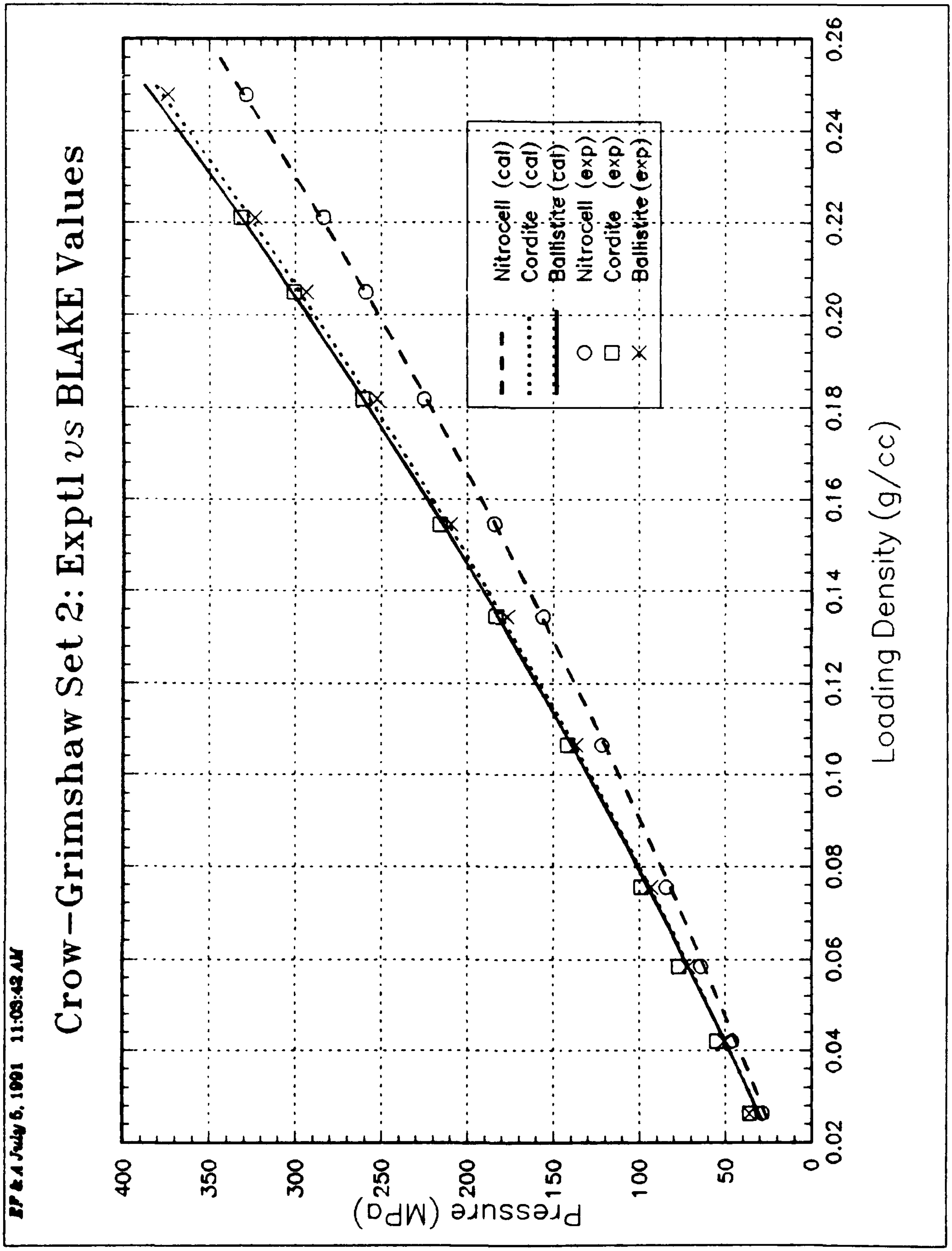
This question applies to both conventional (SP/LP) & ETC systems.

The usual ballistic range measurements cannot answer the question, so long as *relative* results are consistent.

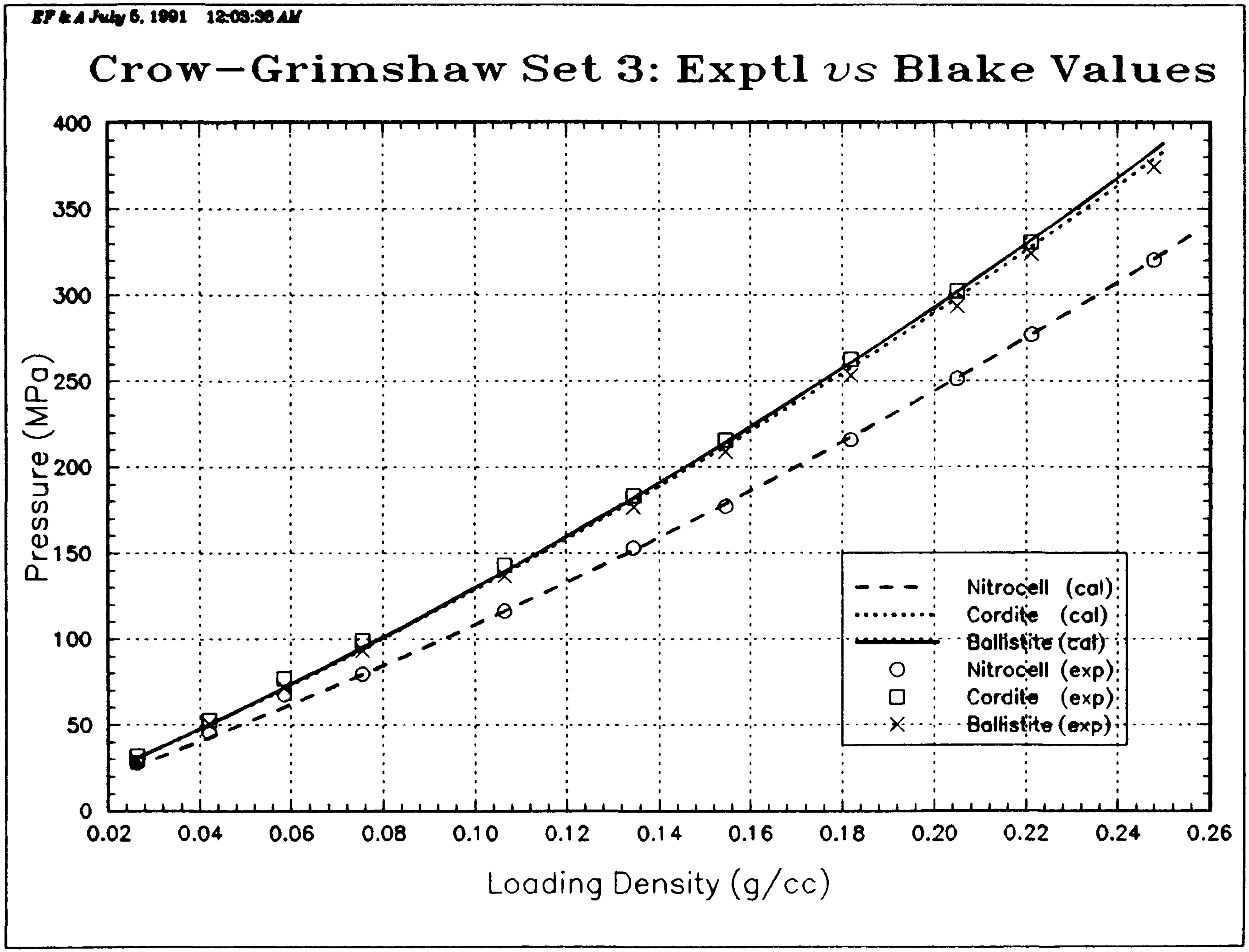
Crow & Grimshaw (1931) to the rescue! They fired 96 closed-vessel shots on 3 propellants; pressures up to 374 MPa; brilliant correction for heat loss.

No expts like theirs have ever been done since.


EF & A July 5, 1991 10:28:56 AM
Crow–Grimshaw Set 1: Exptl vs Blake Values
Lines are computed a priori––they are not fitted
Pressure (MPa)
0
50
100
150
200
250
300
350
400
Loading Density (g/cc)
0.02
0.04
0.06
0.08
0.10
0.12
0.14
0.16
0.18
0.20
0.22
0.24
0.26
Nitrocell (cal)
Cordite (cal)
Ballistite (cal)
Nitrocell (exp)
Cordite (exp)
Ballistite (exp)



EP & A July 5, 1991 11:03:43 AM
Crow–Grimshaw Set 2: Exptl *vs* BLAKE Values
Pressure (MPa)
Loading Density (g/cc)
0
50
100
150
200
250
300
350
400
0.02
0.04
0.06
0.08
0.10
0.12
0.14
0.16
0.18
0.20
0.22
0.24
0.26
Nitrocell (cal)
Cordite (cal)
Ballistite (cal)
Nitrocell (exp)
Cordite (exp)
Ballistite (exp)


EF & A July 5, 1991 12:03:36 AM
Crow-Grimshaw Set 3: Exptl vs Blake Values
Pressure (MPa)
0
50
100
150
200
250
300
350
400
Loading Density (g/cc)
0.02
0.04
0.06
0.08
0.10
0.12
0.14
0.16
0.18
0.20
0.22
0.24
0.26
Nitrocell (cal)
Cordite (cal)
Ballistite (cal)
Nitrocell (exp)
Cordite (exp)
Ballistite (exp)

THE BLAKE CODE'S SERIOUS PROBLEMS

Cannot deal with ions (ignores conservation of charge). Very difficult to change.

Limited temperature range owing to form used for representation of $C_P(T)$ -- only single range is permitted. Can be changed if necessary.

BLAKE has a well-deserved reputation for crankiness, and is sometimes quite slow on a 286 computer, esp. when liquid or solid products are formed.

There is a minor problem with the γ of solids and liquids, but this is readily fixed.

INTERIM CONCLUSIONS

1. BLAKE is well–suited for use with lumped parameter propellant systems, even if it is slow and cranky (and needs a little work on γ).

2. It cannot meet the requirements of an ETC code that must work at high temps with ions present.

3. It is easy to write down the requirements for a new code––meeting them is something else.

RESURRECTING AN OLD IDEA

Use an additivity rule to estimate η (Noble–Abel covolume).

$$\eta = 0.9[17.0\mathcal{N}_i + 7.0\mathcal{H}_i + 29.2\mathcal{C}_i + 3.8\mathcal{O}_i]/\mathrm{M.Wt.}$$

Equation of state: $p(V - \eta) = RT/M$

RT/M is called *IMPETUS*.

If one assumes that a code can compute impetus correctly, then an estimate of η leads to an estimate of the non–ideal (real) pressure.

A NEW APPROACH TO ESTIMATING PRESSURE

NAME	PROPERTY	CET	BLAKE
	Impetus	996.	1001.
	Temperature	2919.	2933
N(1)	Pressure	199.3	250.6
	Covolume	(1.02)	1.01
	Est'd Real P	250.4	
	Impetus	1149.	1166.
	Temperature	3708.	3766.
C(1)	Pressure	229.8	288.4
	Covolume	(0.947)	0.957
	Est'd Real P	283.5	
	Impetus	1181.	1192.
	Temperature	3940.	3987.
B(1)	Pressure	236.1	292.8
	Covolume	(0.903)	0.931
	Est'd Real P	288.3	

ESTIMATING PRESSURE FOR AN ETC MIX

SYSTEM	PROPERTY	CET	BLAKE
Octane + H_2O_2 no added energy	Impetus	1027.	1052.
	Temperature	2604.	2668.
	Pressure	205.4	236.3
	Covolume	(0.864)	0.548
	Est'd Real P	248.3	
Octane + H_2O_2 + 0.8 kJ/g	Impetus	1156.	1181.
	Temperature	2922.	2985.
	Pressure	231.3	268.6
	Covolume	(0.864)	0.603
	Est'd Real P	279.5	

The small covolume computed by BLAKE for this system may indicate a problem in computing the virial coefficient of water.

SUGGESTION FOR FURTHER EXPERIMENTAL WORK

If there is a requirement for improved estimates of the non–ideal gas corrections:

Perform closed–vessel experiments (similar to Crow & Grimshaw's) on a water–rich mixture.

There will be (at least) two problems:

> Correcting for heat transfer (reconsider C–G's approach, which has been ignored by all subsequent workers).

> Finding a composition whose products have a large ratio of H_2O to CO_2. (AN + ethylene glycol is a possibility.)

CONTINUING WORK ON THIS TASK

1. Consider whether coefficients of the additivity equation can be improved.

2. Consider adding the Stockmayer potential to BLAKE to improve its estimate of B(T) for water.

3. Review the work of Powell, Wilmot, ter Haar, and Klein on an improved equation of state for ballistics.

4. Consider the thermodynamic consequences of modifying the pressure computation in CET86.

SUMMARY

1. The demands of ETC gun modellers require an approach to thermo calcns different from those applied to SP/LP systems.

2. This new approach requires a code valid at temperatures up to (at least) 10 000 K, and that can take ions into account.

3. BLAKE , although still a valuable tool for use in lumped parameter analyses, fails on both scores with ETC systems.

4. The NASA–Lewis code is much better, but the problem of correcting for non–ideal gas effects remains open.

ACKNOWLEDGMENTS

It is a pleasure to thank:

William Oberle, Gloria Wren, & Kevin White, all of IBD/BRL, for many helpful discussions.

Sohail Murad, Dept of Chem Eng, Univ of Ill at Chicago, for insights into the computation of virial coefficients.

Robert Lantz, ARDEC, for supplying the eqn for estimating the covolume.

ASSESSING ETC PERFORMANCE FOR SYSTEMS INTEGRATION

L. E. Harris and B. Knutelsky
US Army Armament Research, and Development & Engineering Center
Picatinny Arsenal, NJ 07806-5000

ABSTRACT

Electrothermal/chemical (ETC) propulsion is a candidate for use in future Army tank and artillery gun systems. In ETC propulsion electrical energy is input directly into the gun chamber through formation of a plasma to control and/or augment the release of chemical energy from the propellant. The detailed chemical kinetics and fluid dynamics processes involved in generation of the plasma, time dependent mixing of the plasma with the working fluid and subsequent release of energy resulting in gasification of the working fluid are not known in detail. However, first order models exist for formation of the plasma jet and the interior ballistics of the gun such that with proper coupling upper bound estimates can be made for the gun system performance.

The initial plasma considered is composed of partially ionized hydrogen and carbon atoms of sufficient density that it is optically thick and behaves at steady state as a black body. Internally heat exchange in the plasma is predominantly radiative. Using these assumptions, the plasma model allows calculation of plasma temperature, pressure, density, resistivity and wall ablation rate.

The interior ballistic model is highly idealized, consistent, with system considerations. Initially the breech pressure is assumed constant until the working fluid is exhausted after which the resulting gases are expanded adiabatically. For conventional guns the above model, while accurate as an upper bound to within 5-10%, does not give a representative pressure time or travel curve. However, for ETC guns the plasma time pulse can be shaped to approach the constant breech pressure optimal performance. This optimal shaping is predicted by the coupled plasma model.

A preliminary design is presented for a subcaliber vented vessel/gun geometrical scaled to a 120mm tank gun. ETC pressure time traces are compared to model predictions. The model is also used in investigation of a ETC 120mm tank gun for enhanced performance.

ASSESSING ETC PERFORMANCE FOR SYSTEMS INTEGRATION

L. E. HARRIS AND B. KNUTELSKY
U. S. ARMY ARDEC
PICATINNY ARSENAL

ETC MODELING AND DIAGNOSTICS
JANNAF WORKSHOP
APG, 9 JULY 1991

ASSESSING ETC PERFORMANCE

- COMPARE 120, 140 AND 105MM TANK GUNS WITH ADDED ELECTRICAL ENERGY USING:
  CBP MODEL FOR THE GUN
- INTEGRATE SUBSCALE FIXTURES USING:
  CPR MODEL FOR THE GUN
  LK MODEL FOR THE PLASMA INJECTOR
- ANALYSE FMC JUMPSTART DATA USING:
  CPR MODEL FOR THE GUN
  LK MODEL FOR THE PLASMA INJECTOR
  SIMPLE MODEL FOR PT TRACES

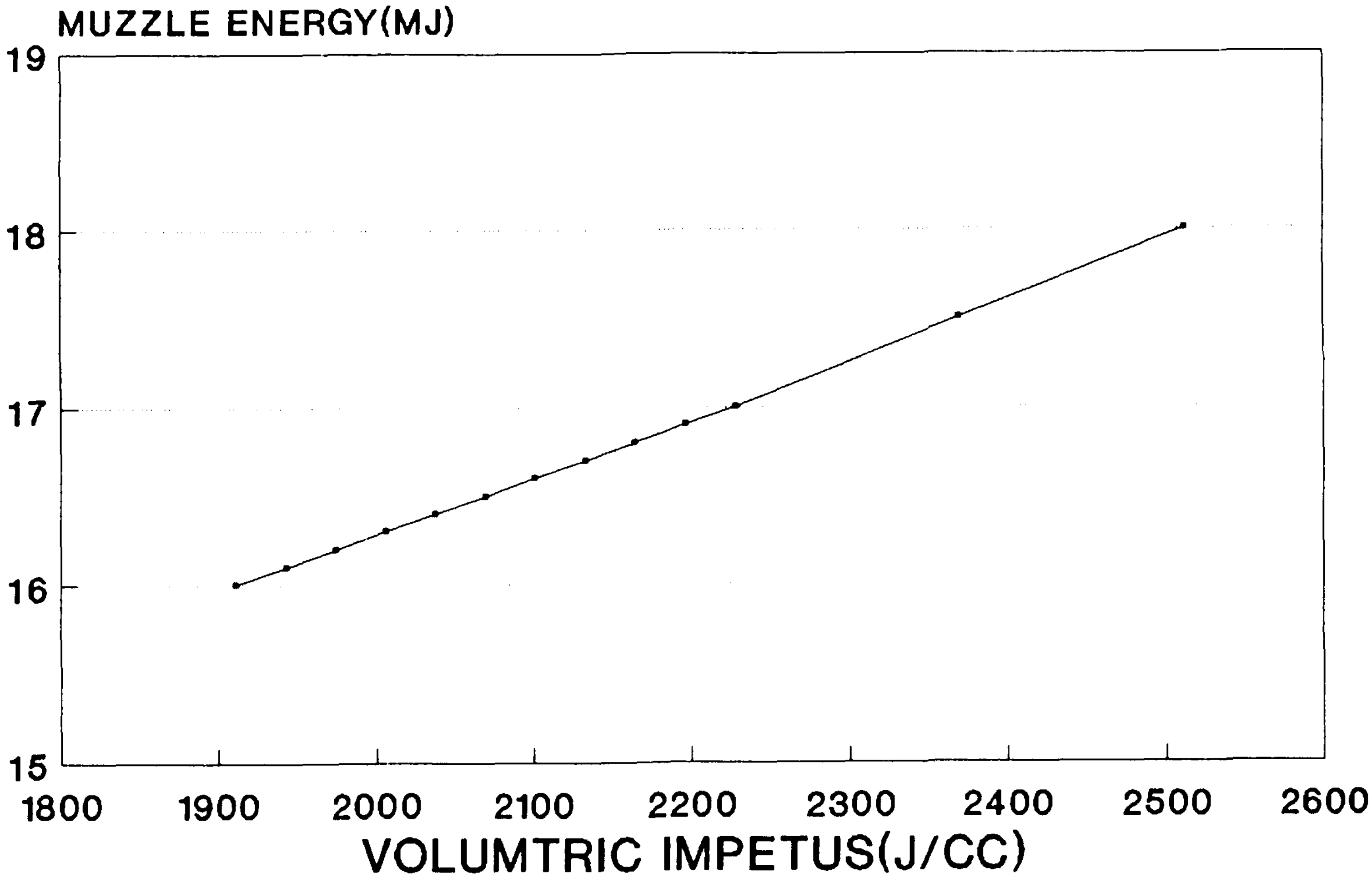
ETC TANK GUNS
ASSESSMENT OF PERFORMANCE

- MODEL PROPELLANT IS JA2 IN LIQUID OR CONSOLIDATED FORM AT A LOADING DENSITY OF 1.67 G/CC. THIS MODEL SYSTEM IS USED TO ASSESS PERFORMANCE OF A VIABLE ETC PROPELLANT
- BLAKE CALCULATIONS ARE USED FOR THE THERMOCHEMISTRY OF JA2 AND JA2 WITH ADDED ELECTRICAL ENERGY
- IBHVG2 CALCULATIONS ARE USED IN THE CONSTANT BREECH PRESSURE MODE FOR 120mm ETC GUN CALCULATIONS
- PERFORMANCE IS ALSO CALCULATED FOR 140mm AND 105mm GUNS GEOMETRICALLY SCALED TO THE 120mm TANK GUN

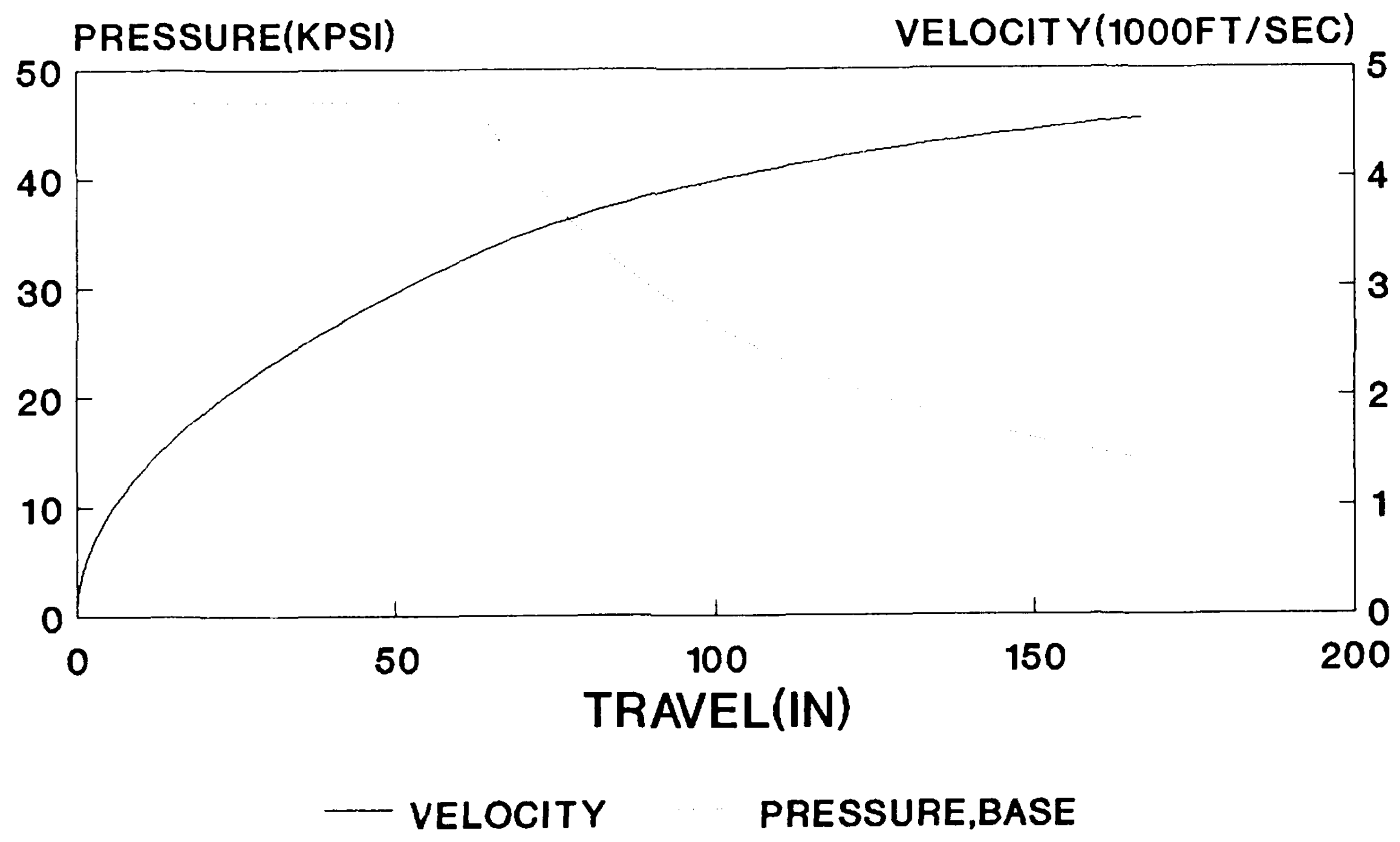
JA2 PROPELLANT THERMOCHEMISTRY WITH VARYING ELECTRICITY ENERGY

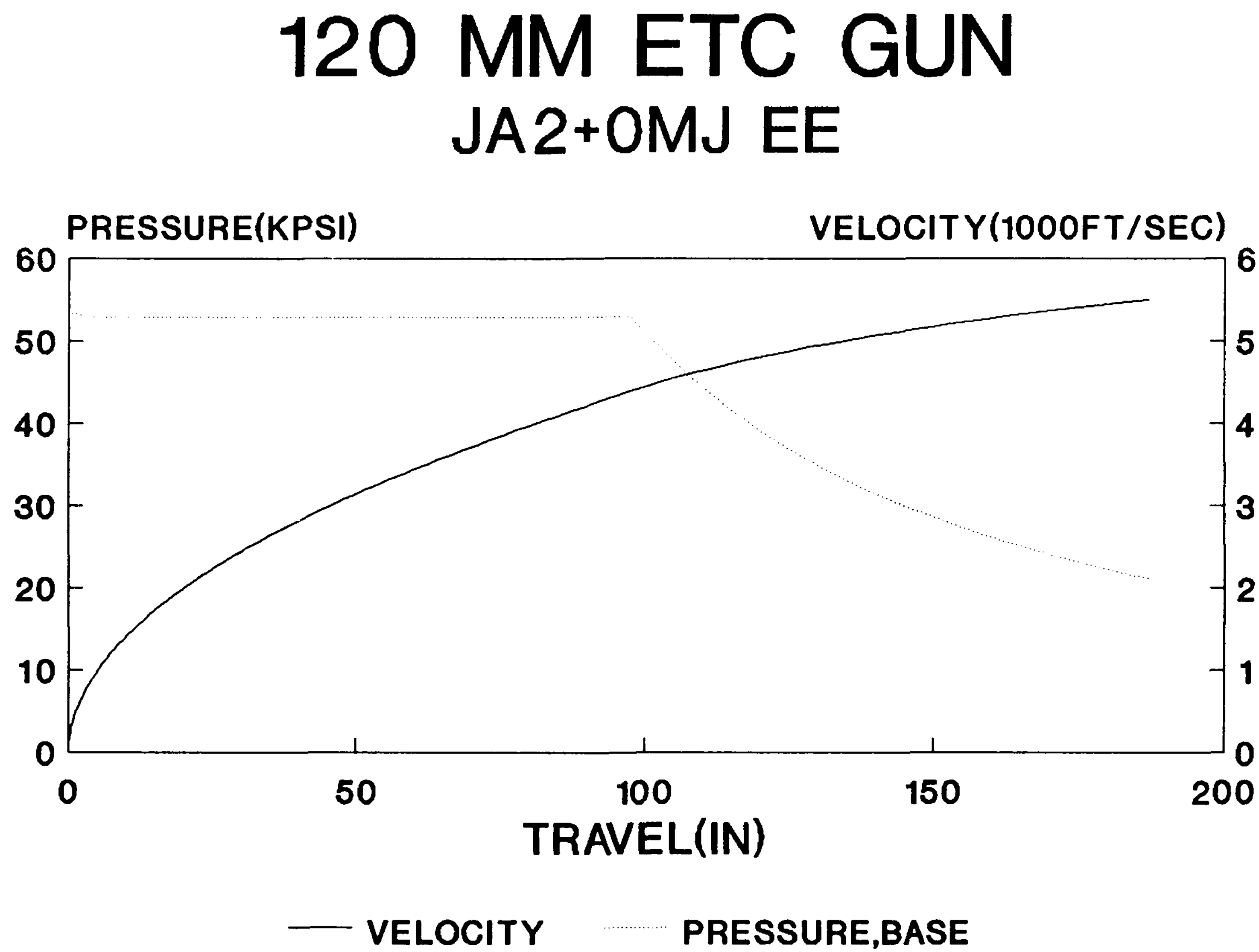
	JA2	+1MJ/KG EE	+2MJ/KG EE
I(J/G)	1143	1333	1504
T(K)	3424	3959	4401
COV(G/CC)	.991	1.000	1.001
GAMMA	1.2254	1.2219	1.2219

MUZZLE ENERGY VS. VOLUMETRIC IMPETUS
120MM ETC GUN WITH CONSLD JA2

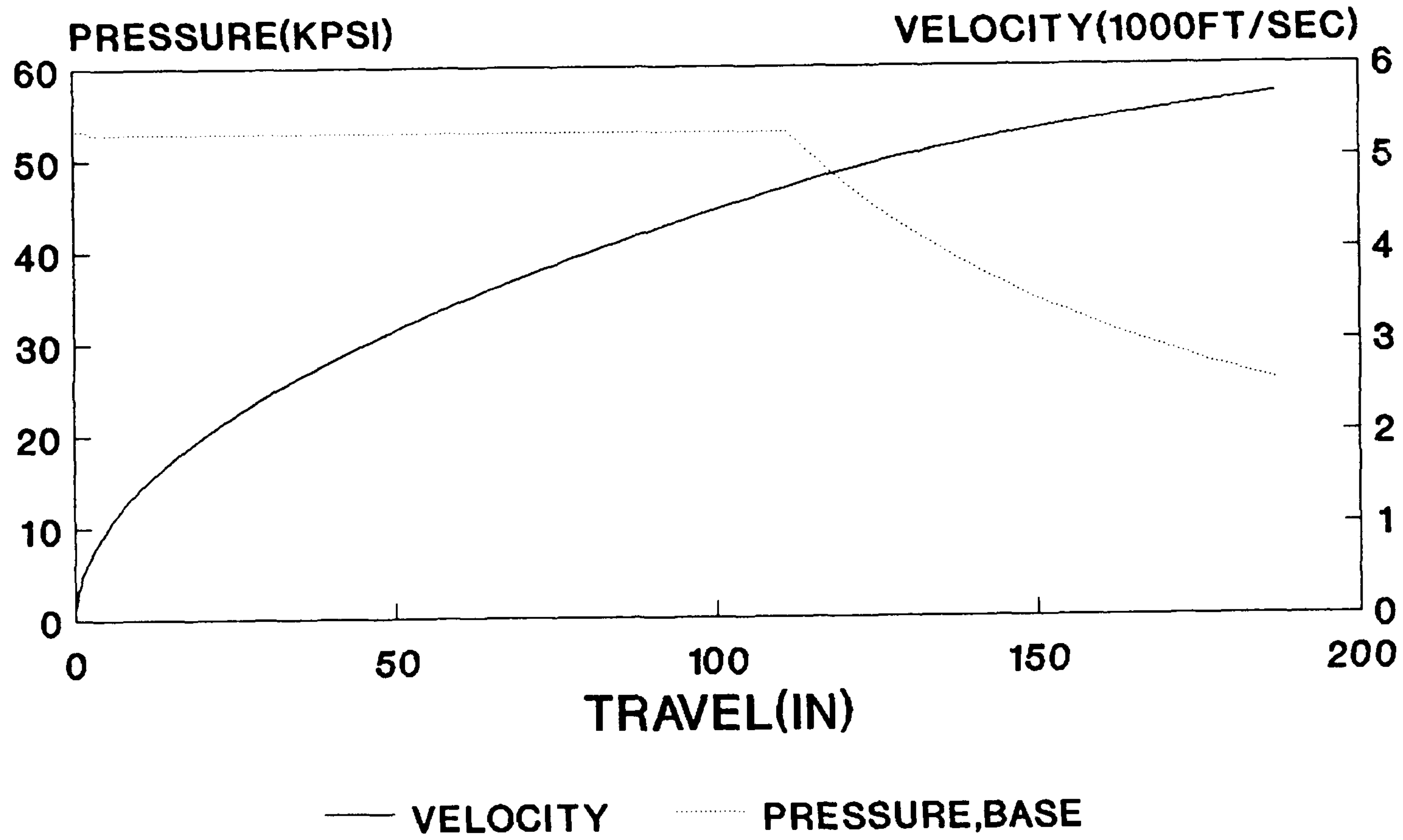


120 MM ETC GUN
JA2 ROOM TEMP

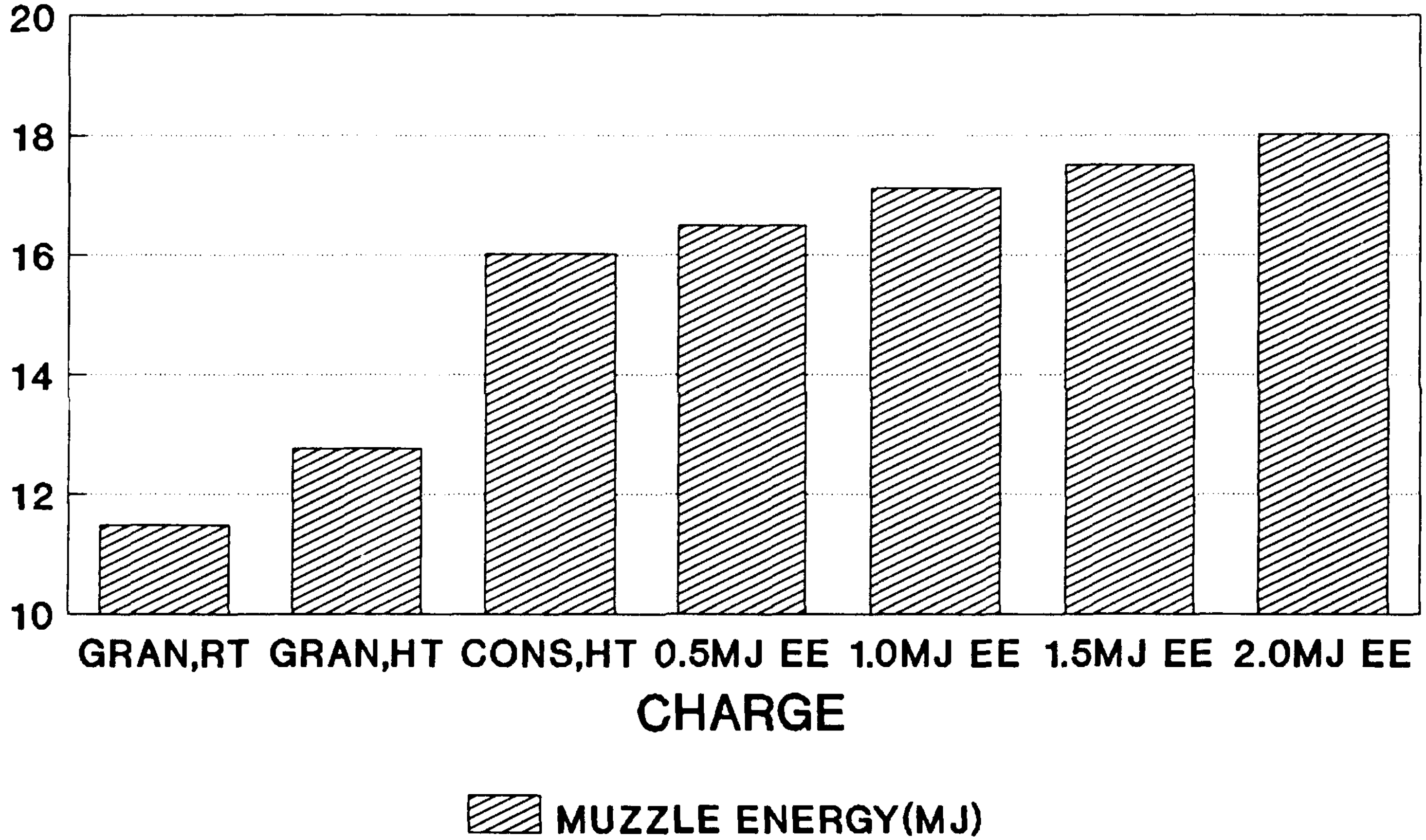



120 MM ETC GUN
JA2+0MJ EE
PRESSURE(KPSI)
VELOCITY(1000FT/SEC)
60
50
40
30
20
10
0
6
5
4
3
2
1
0
0
50
100
150
200
TRAVEL(IN)
VELOCITY
PRESSURE,BASE

120 MM ETC GUN
JA2+1MJ EE

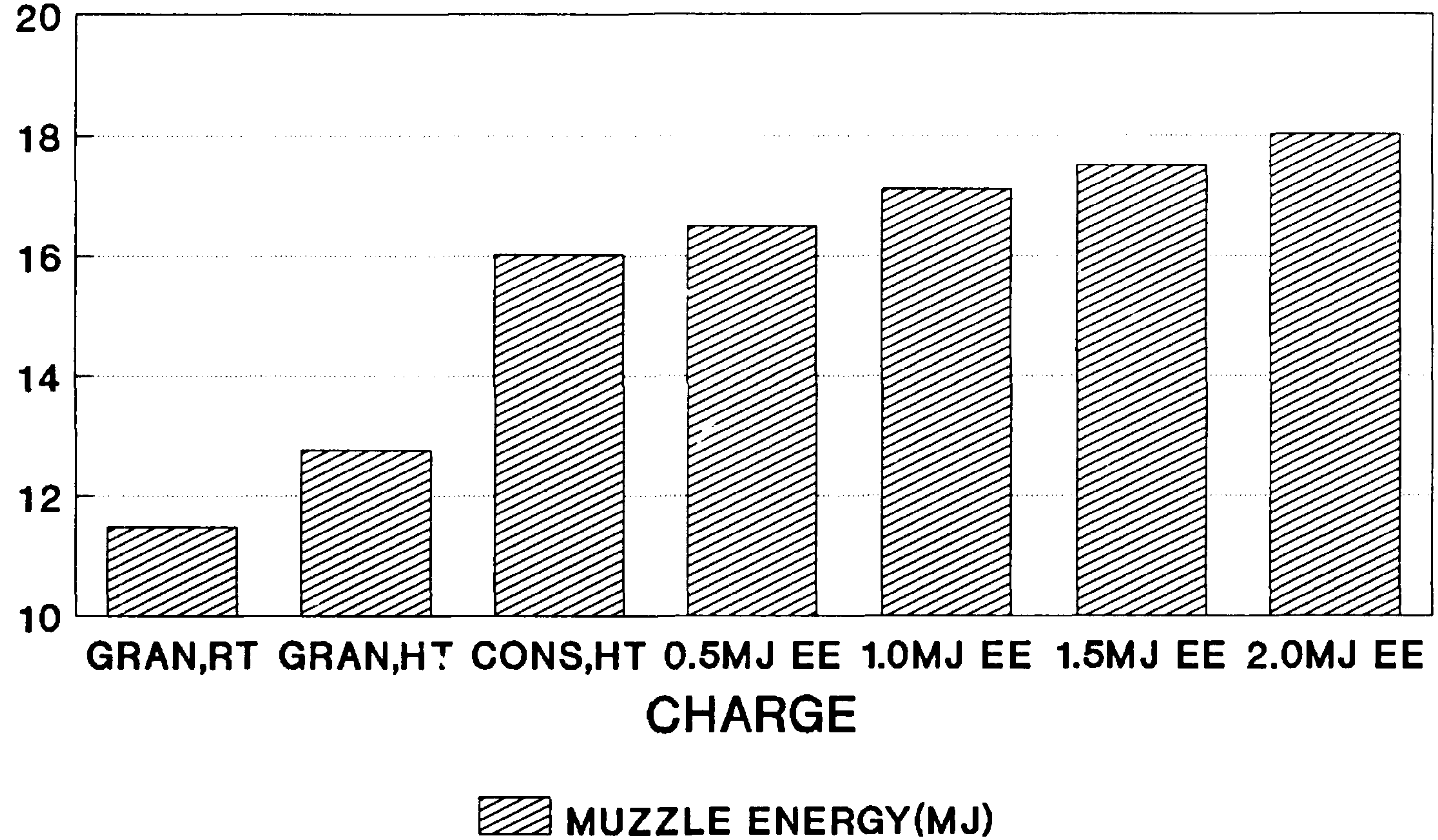


120 MM ETC GUN
JA2 PROPELLANT



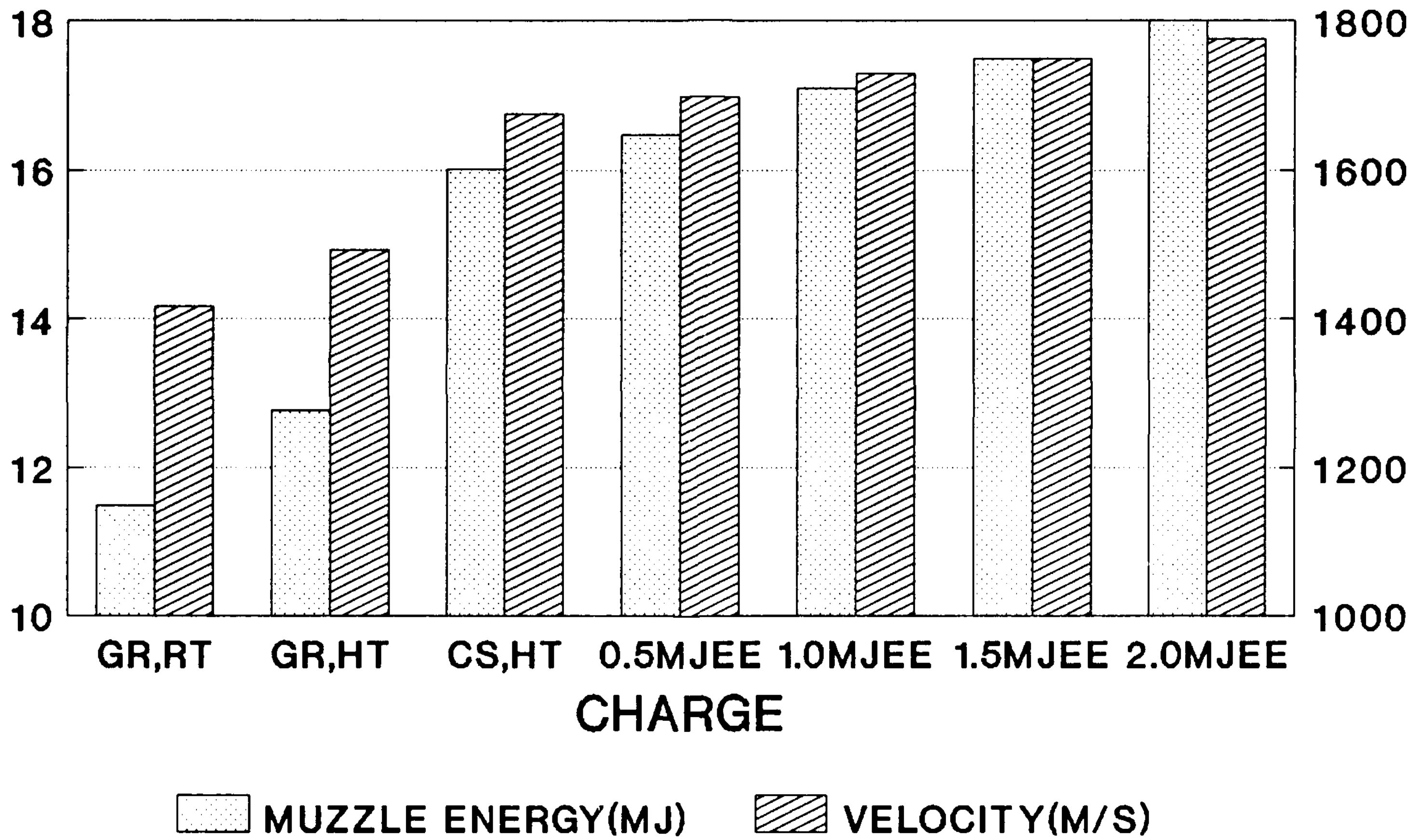
GRAN 7.8KG,CONS 13.0KG,EE IN MJ/KG

120 MM ETC GUN
JA2 PROPELLANT



GRAN 7.8KG,CONS 13.0KG,EE IN MJ/KG

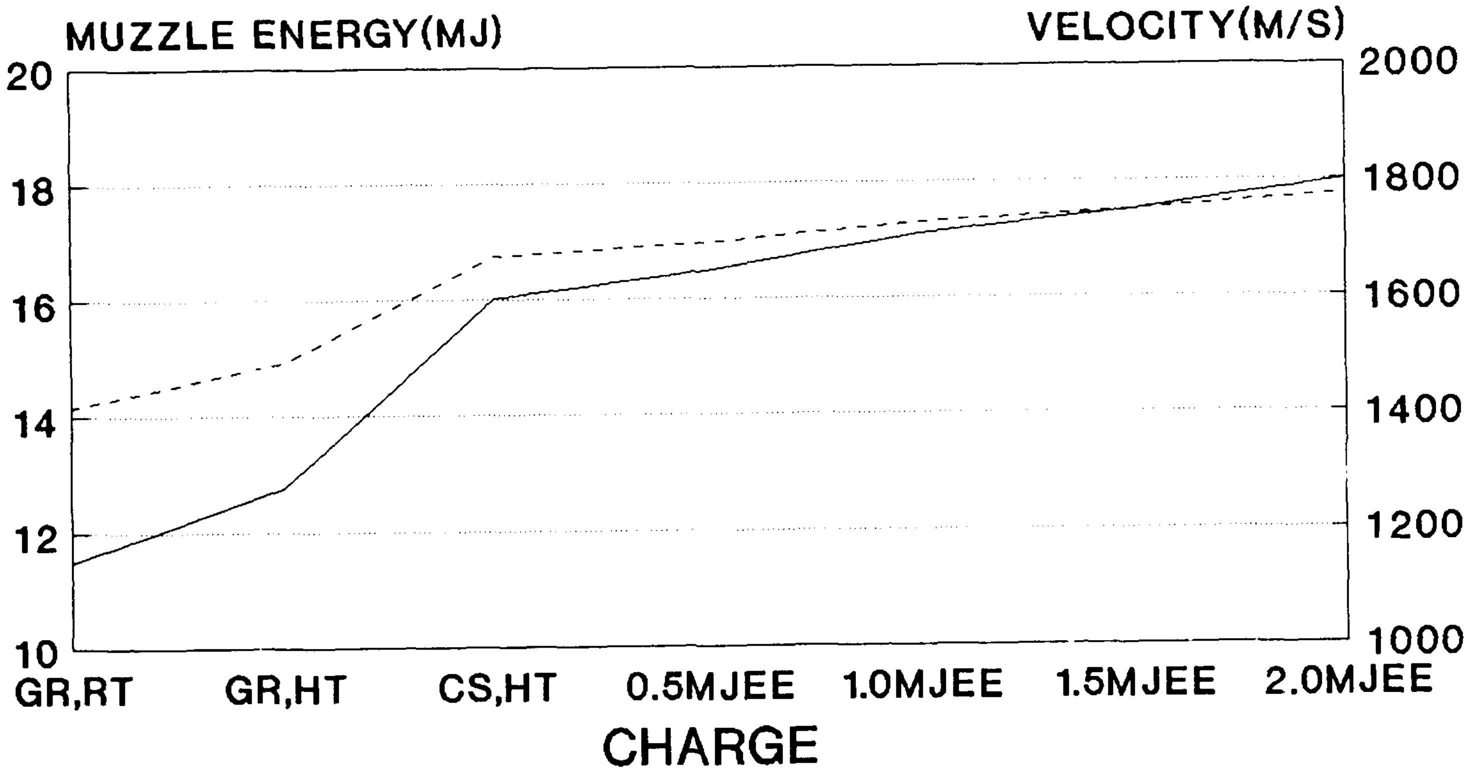
120 MM ETC GUN
JA2 PROPELLANT



GR 7.8KG,CS 13.0KG,EE IN MJ/KG

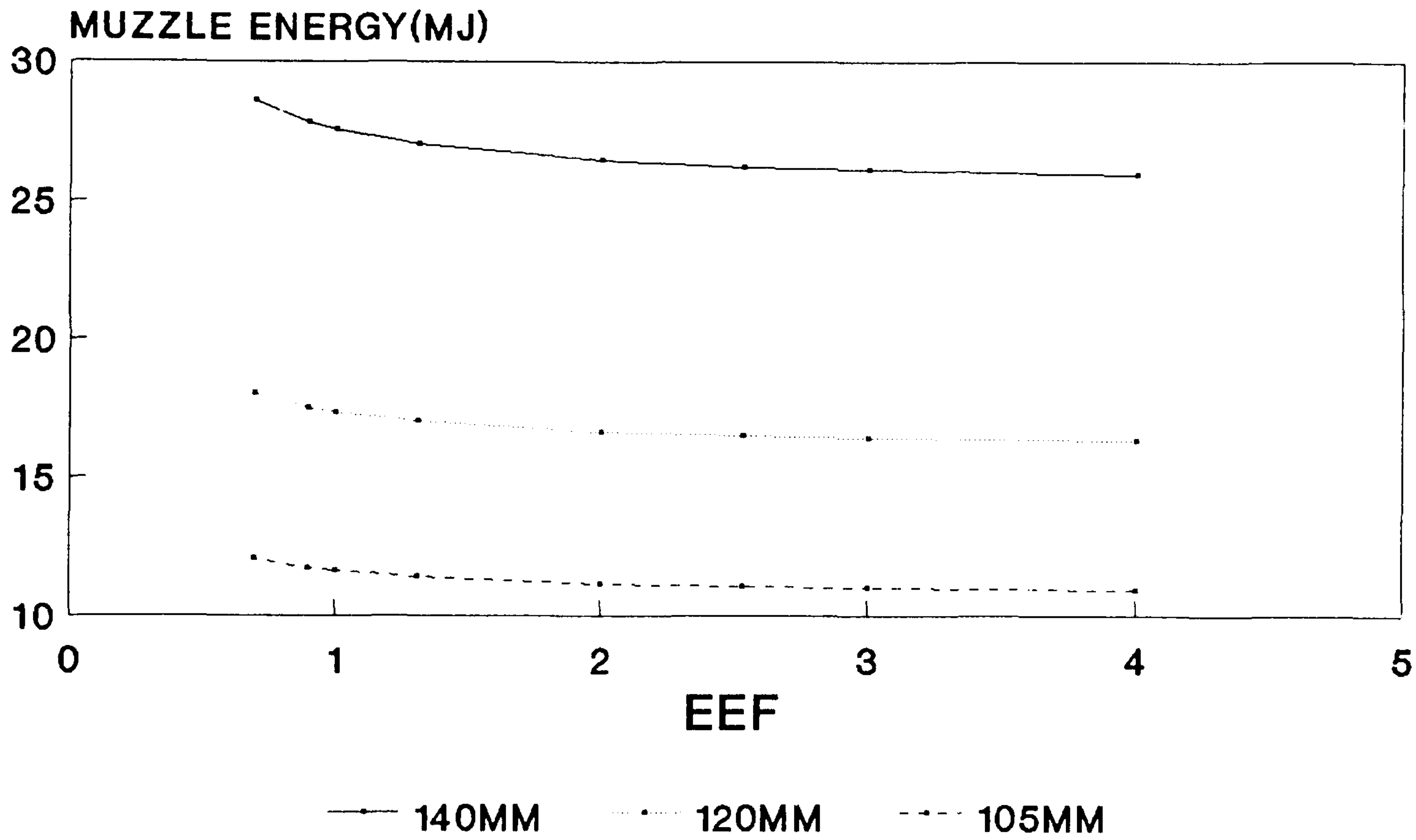
120 MM ETC GUN

JA2 PROPELLANT

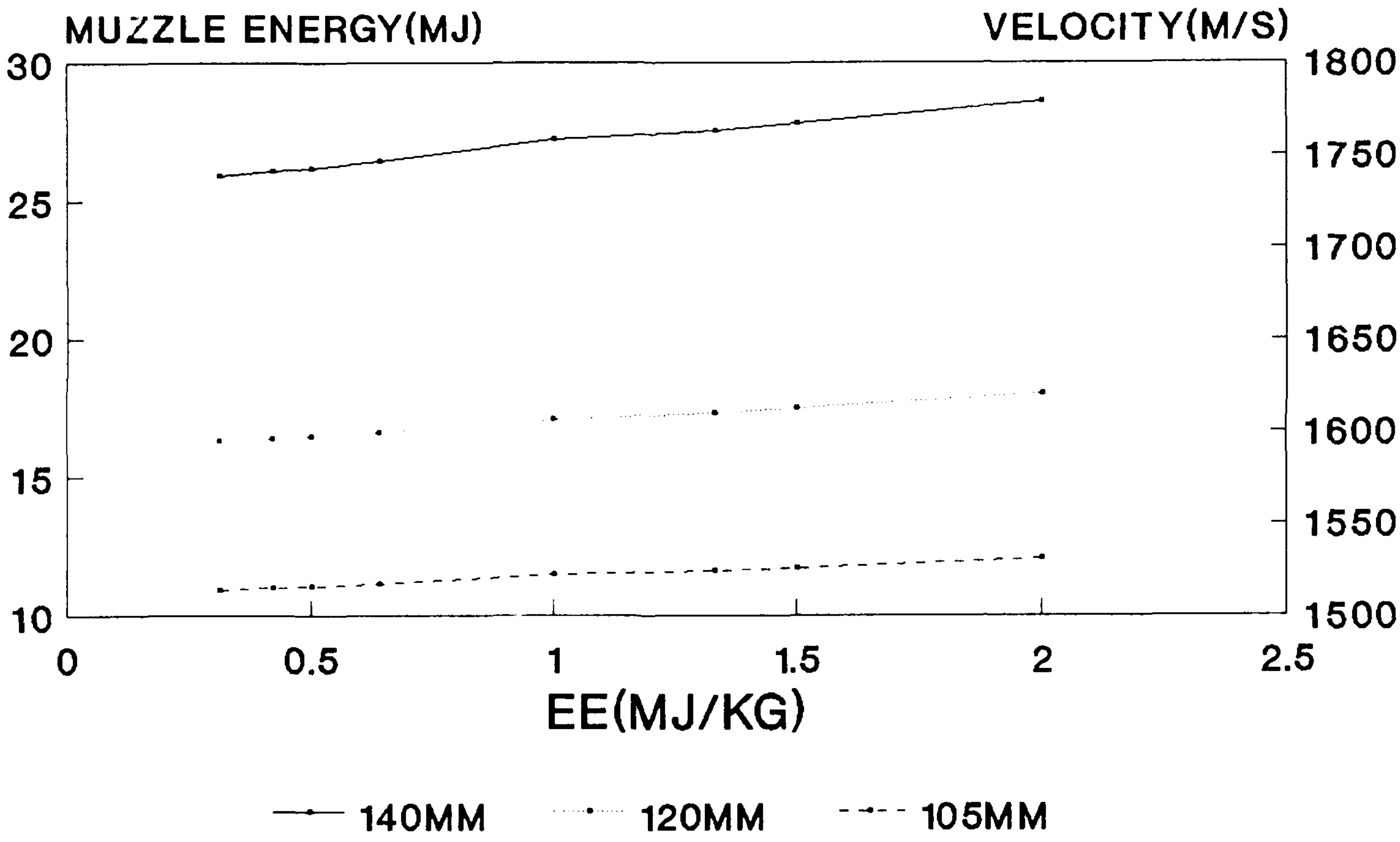


GR 7.8KG, CS 13.0KG, EE IN MJ/KG

ETC TANK GUNS
CONSLD JA2



ETC TANK GUNS
CONSLD JA2

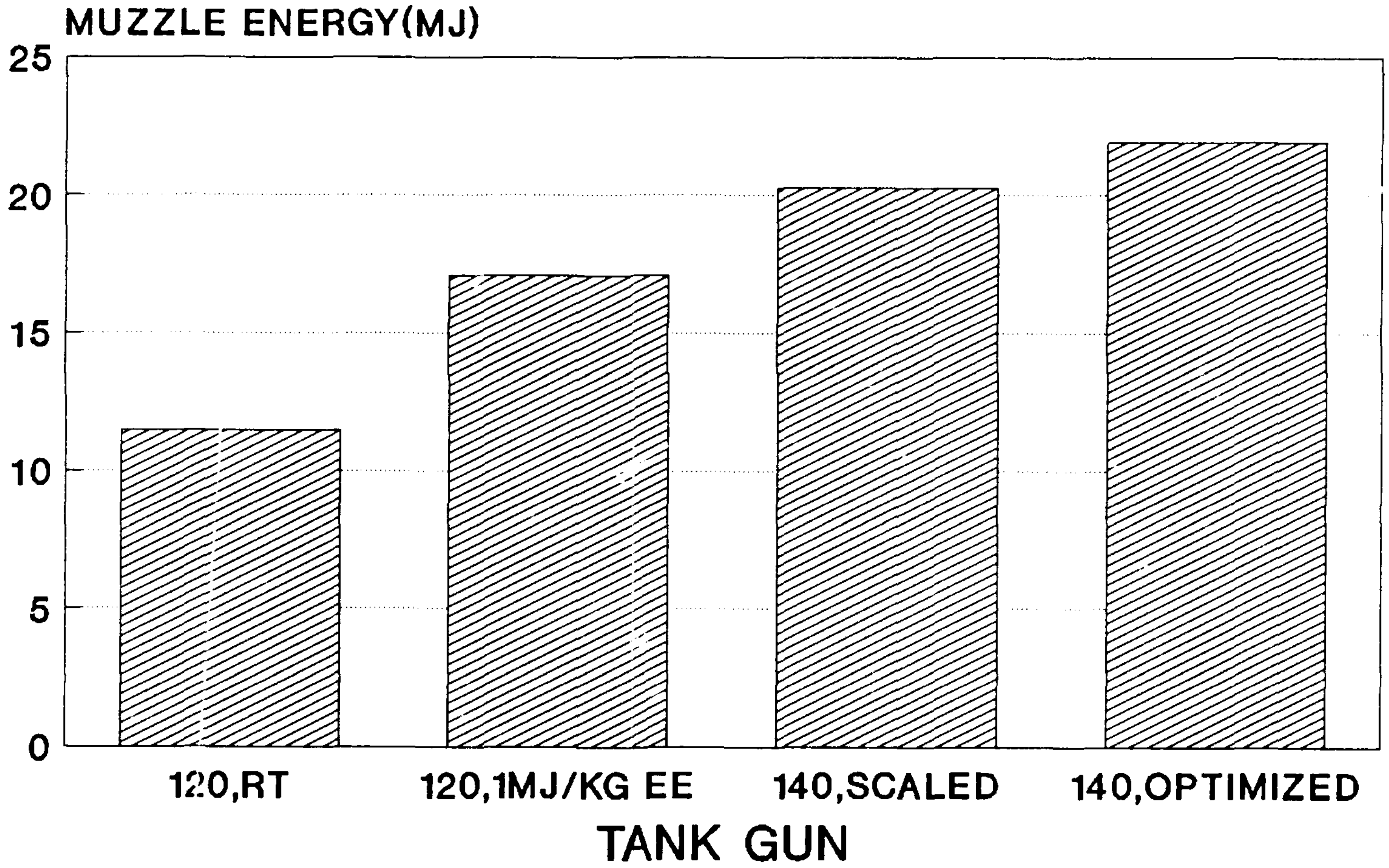


120MM AND SCALED 140MM AND 105MM ETC TANK GUNS

CALIBER(MM)	140	120	105
BREECH P(MPA)	572	572	572
BASE P(MPA)	364	364	364
CHAMBER(L)	12.4	7.80	5.22
TRAVEL(CM)	553	474	415
PROJ(KG)	18.1	11.4	7.64
CHARGE(KG)	20.6	13.0	8.71
PROJ E(MJ)	27.2	17.1	11.5
PROJ V(M/S)	1730	1730	1730
PROJ A(G)	31672	36962	42242
EE(MJ)	20.6	13.0	8.71
EE(MJ/KG)	1.0	1.0	1.0
EEF(MJ/KG)	1.32	1.32	1.32
LENGTH SCALE	1.1667	1	0.8750
VOLUME SCALE	1.5879	1	0.6699

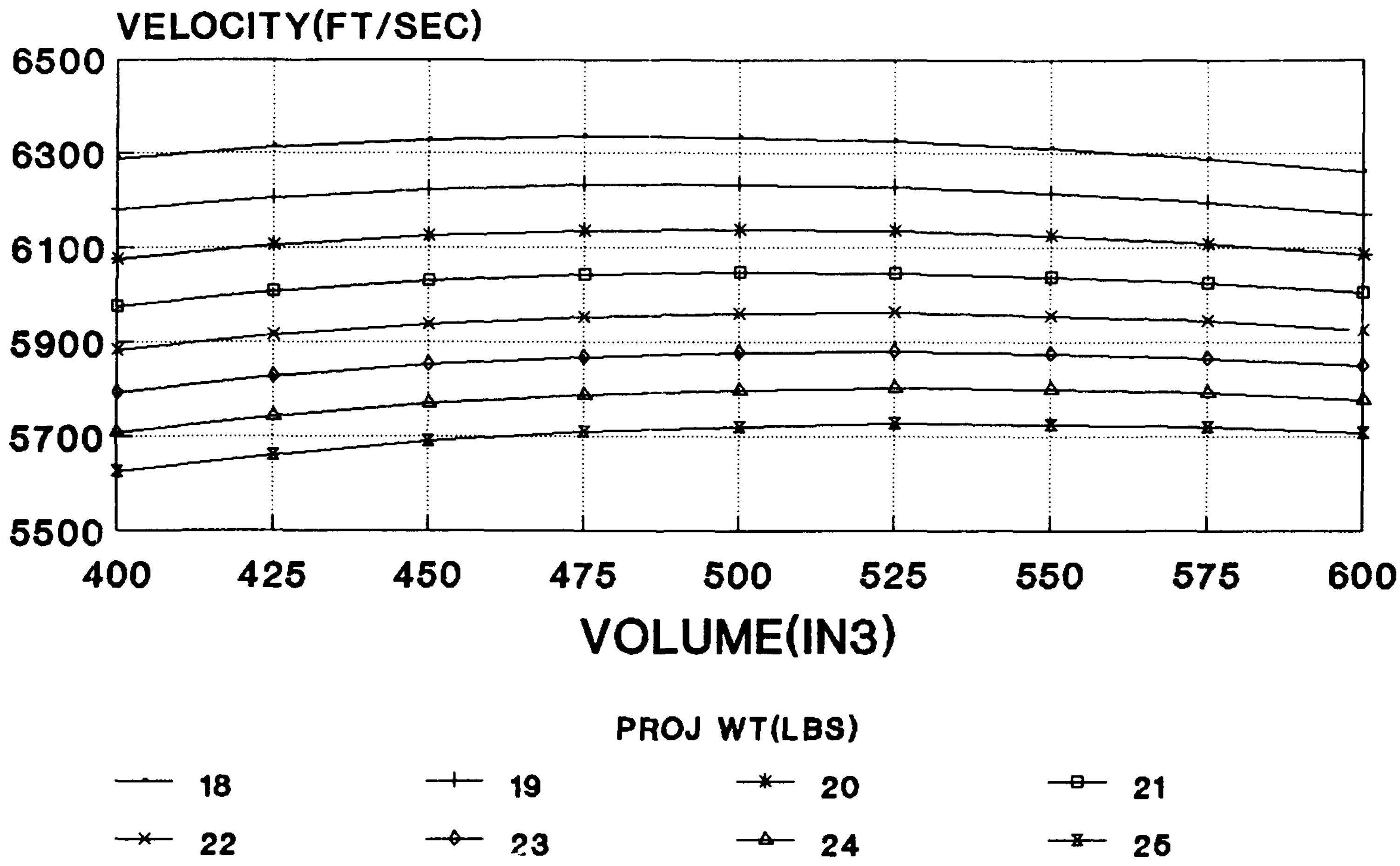
CONSOLIDATED JA2 PROPELLANT

120 AND 140 MM TANK GUNS
JA2 PROPELLANT



RT 63KPSI, OTHERS 82KPSI PMAX

120MM ETC GUN



consolidated ja2 propellant

ARDEC FSAC
Electric Armaments Division

TEST CASE

120mm	CONSOLIDATED	ETC	ETC	ETC	ETC
EE (MJ/KG)	0.0	0.3	0.5	1.0	1.3
EEF	-	4.17	2.53	1.31	1.02
Power Supply					
1991 m^3	-	13.8	23.0	46.0	59.8
1991 KG	-	8541	14235	28470	37011
1995 m^3	-	2.30	3.84	7.67	9.97
1995 KG	-	2539	4232	8463	11002
2000 m^3	-	1.52	2.54	5.07	6.59
2000 KG	-	1650	2750	5500	7149

ARDEC FSAC
Electric Armaments Division

GENERIC ETC SYSTEM

GENERIC PROJECTILE

CALIBER	-	DIAMETER	25mm
PROJECTILE	11.4 KG	L/D	30
PROPELLANT	-	LENGTH	750mm
TYPE	JA2	TUNGSTEN	W
CHAMBER	-	MASS	6.37 KG
TRAVEL	4.74 m	DENSITY	17300 kg/m^3
PEAK PRESSURE	SAME	DRAG	60 m/s/km
		RANGE	3 km
		TARGET	RHA

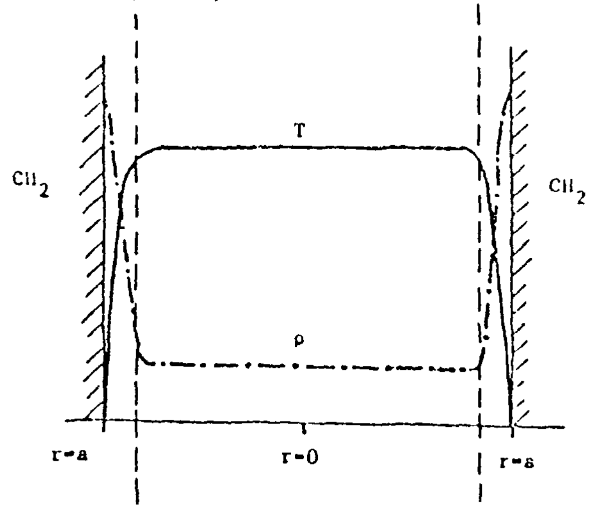
Power (system)		1 MJ	8 MJ
1991	m^3	3.54	28.3
1991	KG	2190	17523
1995	m^3	0.59	4.74
1995	KG	651	5204
2000	m^3	0.39	3.08
2000	KG	423	3381

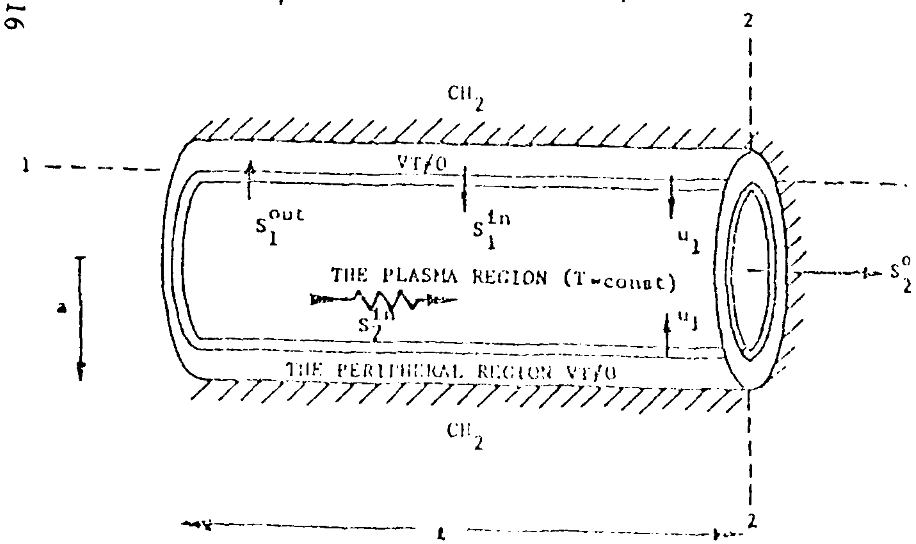
LOEB/KAPLAN PLASMA INJECTOR MODEL ASSUMPTIONS

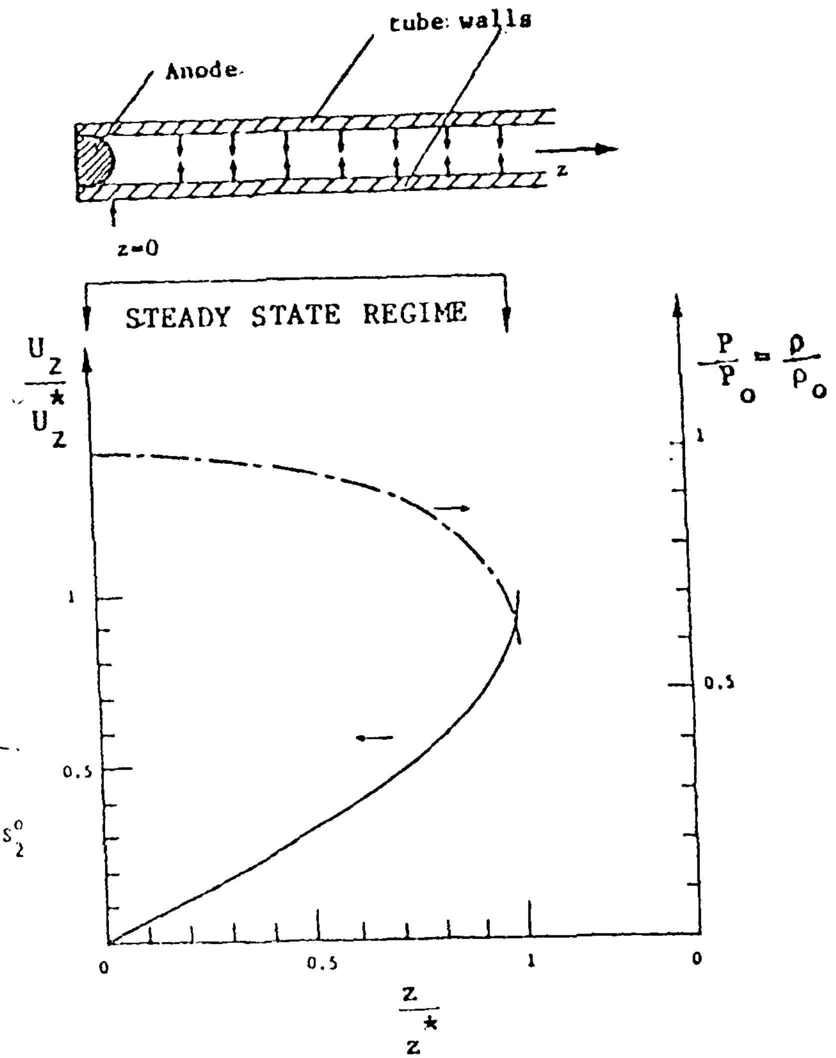
- OPTICALLY THICK PLASMA TREATABLE AS A BLACK BODY
- CONSTANT TEMPERATURE AND DENSITY ALONG THE TUBE
- PLASMA ORIGINATES FROM $(CH_2)_n$ DISSOCCIATED INTO PARTIALLY IONIZED C AND H
- HEAT EXCHANGE BETWEEN THE PLASMA AND WALLS IS PRIMARILY RADIATIVE

A. LOEB AND Z.KAPLAN,IEEE MAG 25,342(1989)

$$S_1^{out} = T^4 \cdot (2\pi a \ell)$$







PLASMA INJECTOR

10MM FIXTURE

INJECTOR	GUN	ROCKET
VOLUME(CC)	0.628	0.377
LENGTH(CM)	5	3
RADIUS(MM)	2	2
I(KA)	50	2
R(OHM)	.0574	.733
POWER(MW)	144	2.94
ENERGY(KJ)	144	2.94
T(EV)	3.84	1.65
ABLATION(MG/MS)	230	10.9
P(KBAR)	3.87	.121
DENSITY(MG/CC)	2.33	.169

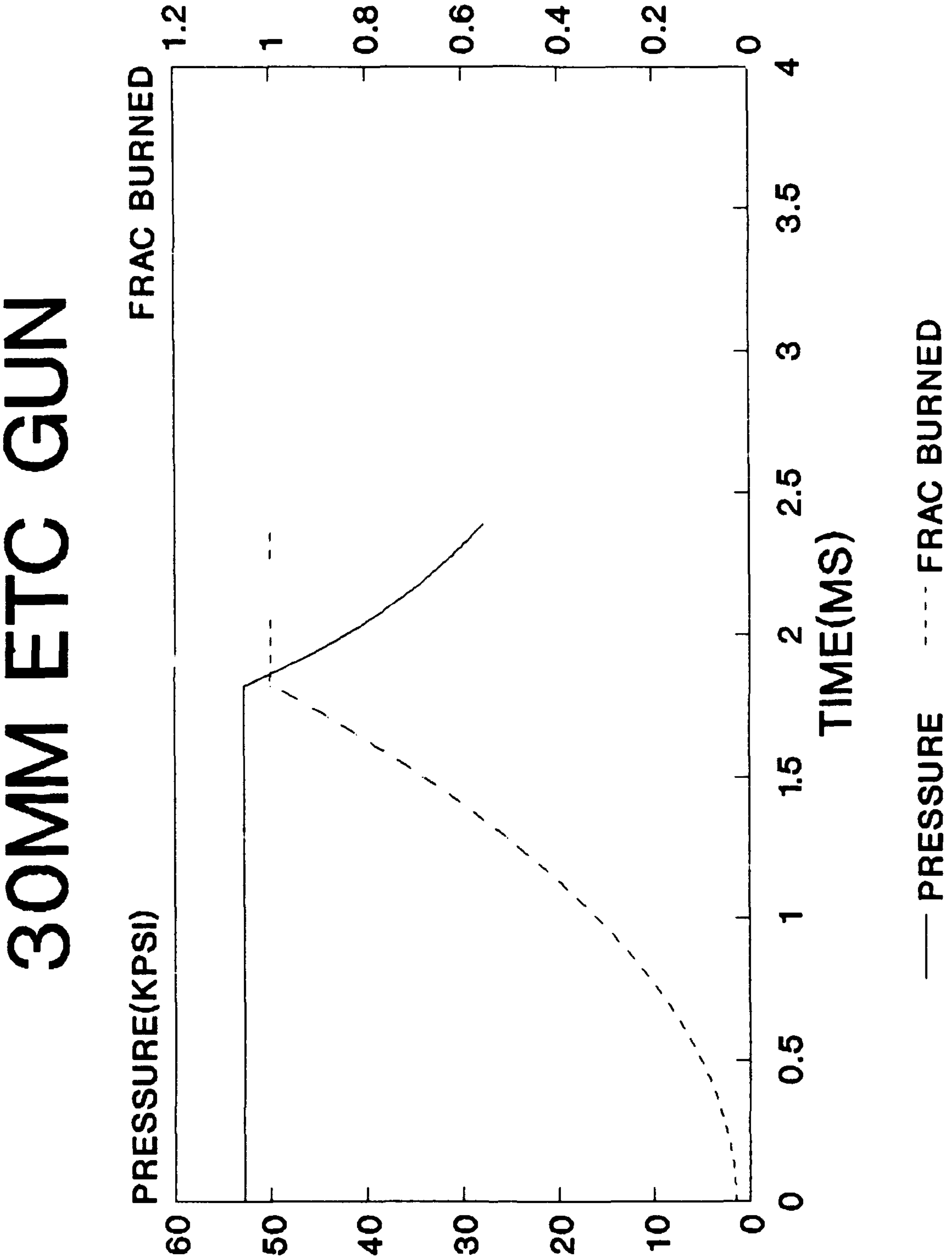
ASSUMING LK MODEL WITH ONE MS SQUARE PULSE

CBP AND LK CALCULATIONS

30MM ETC ARTILLERY GUN

EXP VEL(M/S)	1160
CBP VEL(M/S)	1334
V(EXP)/V(CBP)	0.87
EXP POWER(MW)	256
LK POWER(MW)	102
POWER(EXP)/POWER(LK)	0.40

FMC JUMPSTART S380


30MM ETC GUN
PRESSURE(KPSI)
FRAC BURNED
60
50
40
30
20
10
0
1.2
1
0.8
0.6
0.4
0.2
0
0.5
1
1.5
2
2.5
3
3.5
4
TIME(MS)
PRESSURE
FRAC BURNED

ELECTRICALLY CONTROLLED COMBUSTION(ECC) MODEL

- FRACTION BURNED RELATED TO FRACTION OF THE ELECTRICAL ENERGY ADDED:
  BR(t)=C*(dE/dt)**n

- FORM FUNCTION FOR A CENTER CORE BURNING SINGLE PROPELLANT GRAIN WITH A DIAMETER EQUAL TO THE BORE

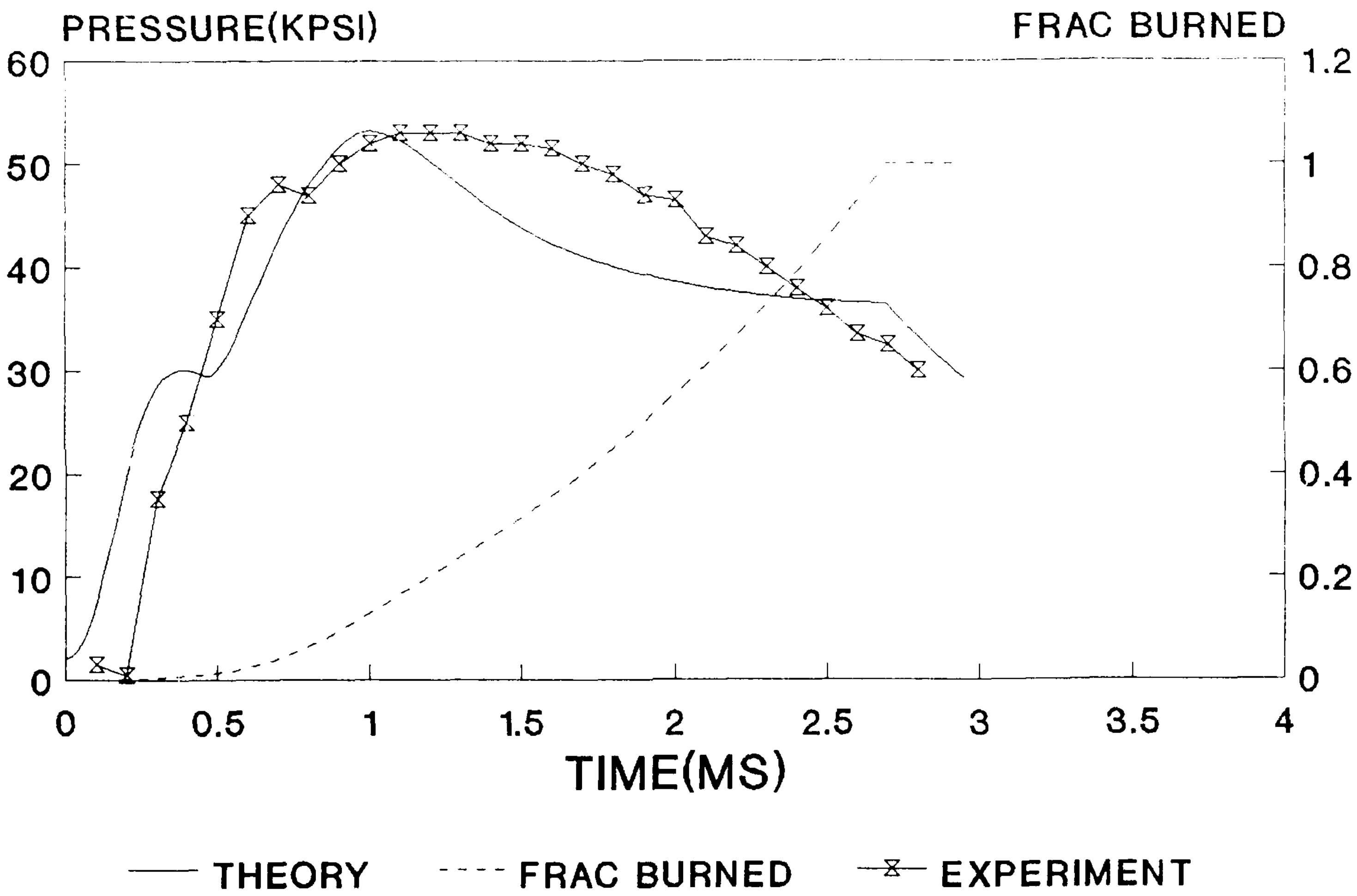
ECC CALCULATIONS

30MM ETC ARTILLERY

BR@ 252MW	
C(IN/S)	ca. 100
n	1
EXP VEL(M/S)	1160
ECC VEL(M/S)	1224
VEL(EXP)/VEL(ECC)	0.95

FMC JUMPSTART S380

30 MM ETC GUN


PRESSURE(KPSI)
FRAC BURNED
60
50
40
30
20
10
0
1.2
1
0.8
0.6
0.4
0.2
0
0
0.5
1
1.5
2
2.5
3
3.5
4
TIME(MS)
THEORY
FRAC BURNED
EXPERIMENT

ETC SYSTEMS PROPULSION
FY92 PLANNED ACCOMPLISHMENTS

- INTERIOR BALLISTIC COMPARISONS USING MODIFIED MODEL INCLUDING EFFECTS OF PROPELLANT BURNING RATE BASED ON EEF JUMP START AND FOLLOW-ON AND AED ETC GUN DATA
- INTEGRATION OF SUBCALIBER(10-30 MM) ETC GUN FIXTURE

JUNE 1991

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APPENDIX A:

FINAL AGENDAS

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JANNAF Workshop on

Electrothermal-Chemical Modeling and Diagnostics

July 9-11, 1991

Ballistic Research Laboratory
Aberdeen Proving Ground, MD

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

A G E N D A

Tuesday, July 9, 1991

8:30	Registration	
8:45	Welcome Administrative Remarks	I. May G. Wren

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

9:00	"National Electric Gun Reviews and Implications for the Army's ETC Gun Technology Program"	W. Oberle
9:30	"Electrothermal Gun Demonstration Program"	C. Dampier
10:15	"Electrothermal (ET) Gun Program"	S. Fowler
10:35	Break	
10:50	"Plasma Discharge in the Electrothermal Gun"	J. Powell
11:15	"Diagnostics and Modeling of an Electrothermal Plasma Source Experiment (SIRENS)"	J. Gilligan O. Hankins
11:40	"Finite Element Analysis of Engineering Electromagnetics of ETC Guns"	R. Boggavarapu
12:05	Lunch	

SESSION II: PROPELLANTS
Chairman: C. Dampier, NSSC

1:15	"Army Atlernate ETC Propellant Program"	D. Downs
1:30	"Overview of Solid Propellant ETC Guns"	A. Juhasz
1:45	"Overview of Gell/Slurry Propellant"	A. Bracuti
2:15	Break	
2:30	"Electrothermal-Chemical (ET-C) Alternate Propellant Systems Investigation and Study Effort"	H. McElroy
3:00	"What's Wrong with Thermochemical Codes Applied to ETC Systems?"	E. Freedman
3:30	"Assessing ETC Performance for Systems Integration"	L. Harris
4:00	Adjourn	

Wednesday, July 10, 1991

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

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

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

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

Thursday, July 11, 1991

SESSION V: LESSONS LEARNED FROM OTHER FIELDS
Chairman: J. Gilligan, NC State U.

8:00	"Electrothermal-Chemical Gun Modeling"	D. King
8:30	"Railgun Research Relevant to Electrothermal Guns"	J. Batteh
9:00	"In-Bore Position and Velocity 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

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Energetic Materials Division, 8357
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Dr. John Gilligan
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