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SAB200132340000

Tunnel Damage from Ground Shock (U)

Jon Rogers

Dept. 5412

June, 1997

M Burkhard 10/23/00

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~~Classified by R. G. Easterling Org. 5412~~
~~Title Systems Modeling & Analysis Dept. Date 12/1/97~~

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DEPARTMENT OF ENERGY DECLASSIFICATION REVIEW

1ST REVIEW-DATE: 2/23/98	DETERMINATION [CIRCLE NUMBER(S)]
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SNL-(97-180-J)-C-5400-1-2

98SA20B000107

Issue: Hard Target Defeat (U)

- **Briefing Outline**
  - Motivation
  - Previous Analyses
  - Example
  - Areas of Concern
  - Proposed Further Analyses

Why look at Tunnel Vulnerability? (U)

[redacted]

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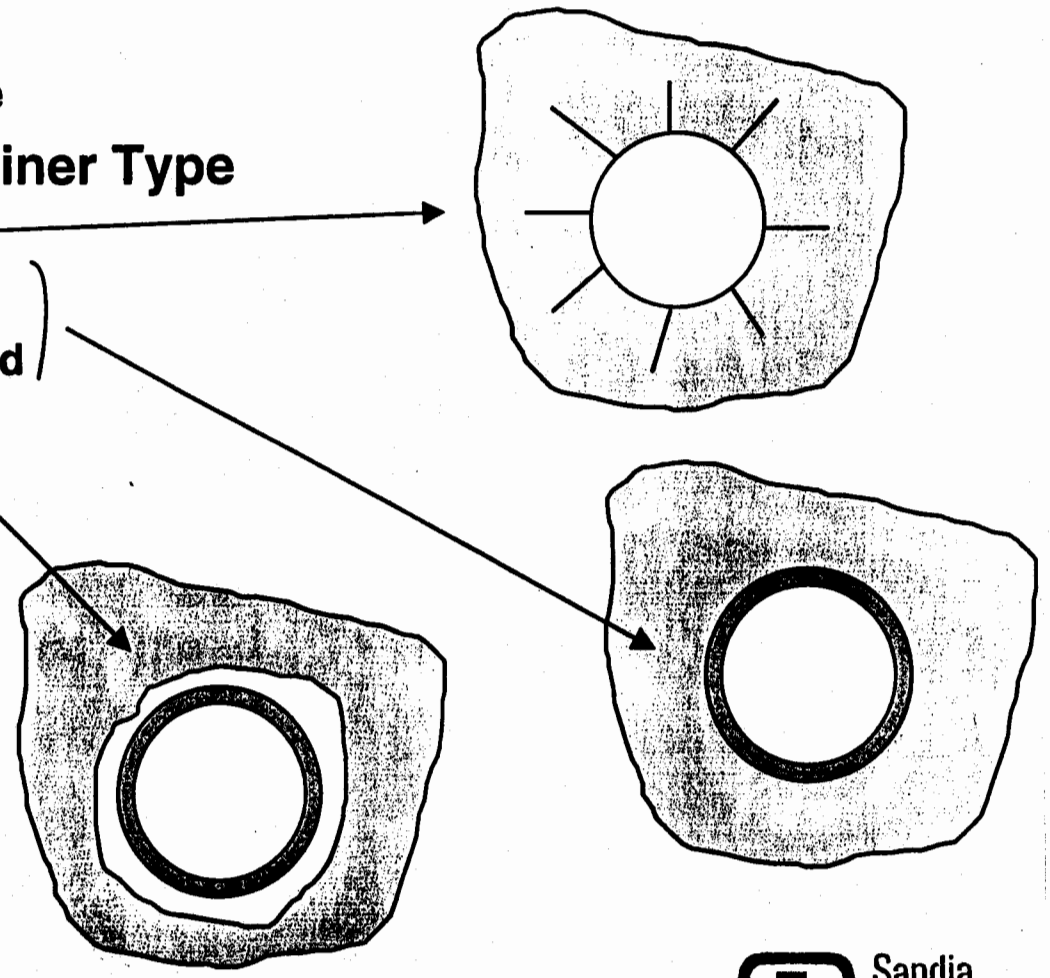
DOD (b)(1)

Attack Tunnels Using Nuclear Weapons (U)

DOE
b (3)

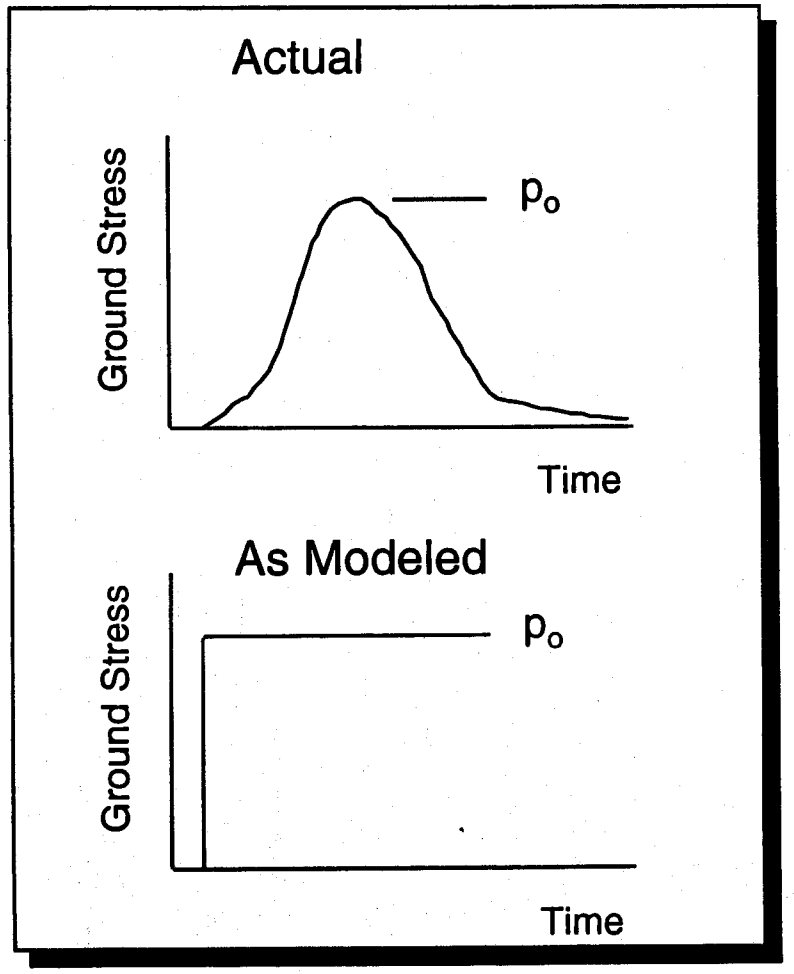
First Define the Tunnel (U)

- **Geology**
  - local to the site
- **Construction/Liner Type**
  - Rockbolted
  - Concrete lined
  - Composite lined
  - Backpacked



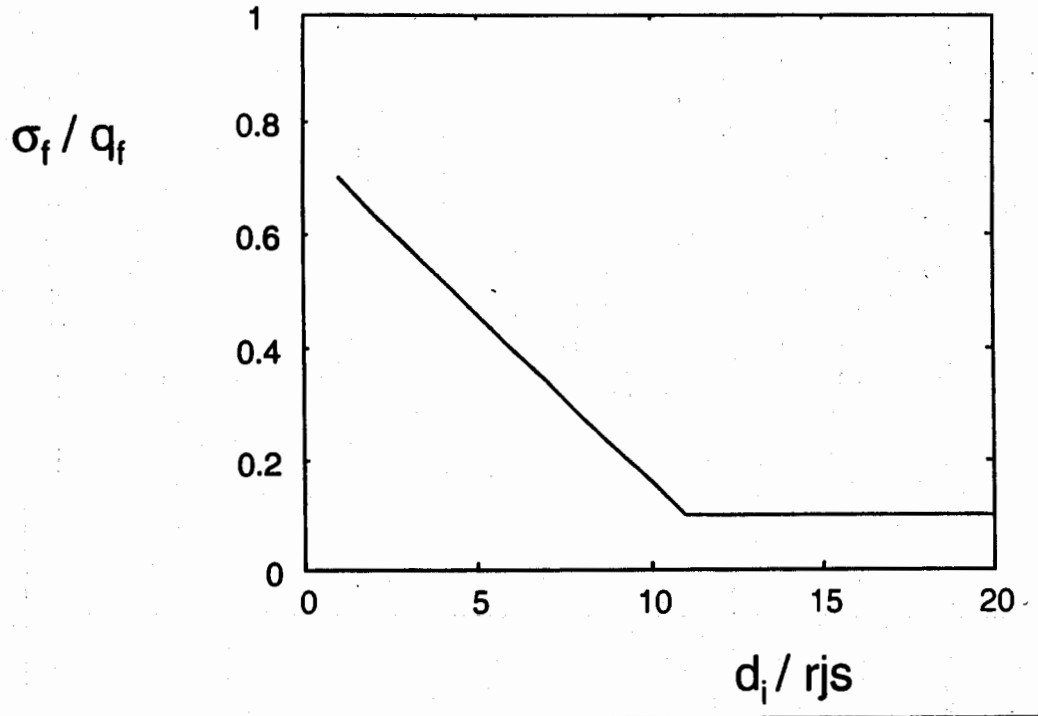
Hendron and Aiyer Analysis (U)

- **Published by Corps of Engineers in 1972**
  - Extension of work by Newmark (1969)
  - These are "Big Names" in Rock Mechanics
- **Assumes static loading**
  - Uniform external pressure, p_o
  - p_o is the maximum ground stress
  - Elastic/Plastic analysis with dilatency
  - Uses Coulomb-Navier failure criteria
- **Calculate Hoop Strain for a given external pressure**



Hendron and Aiyer Analysis - Cont'd (U)

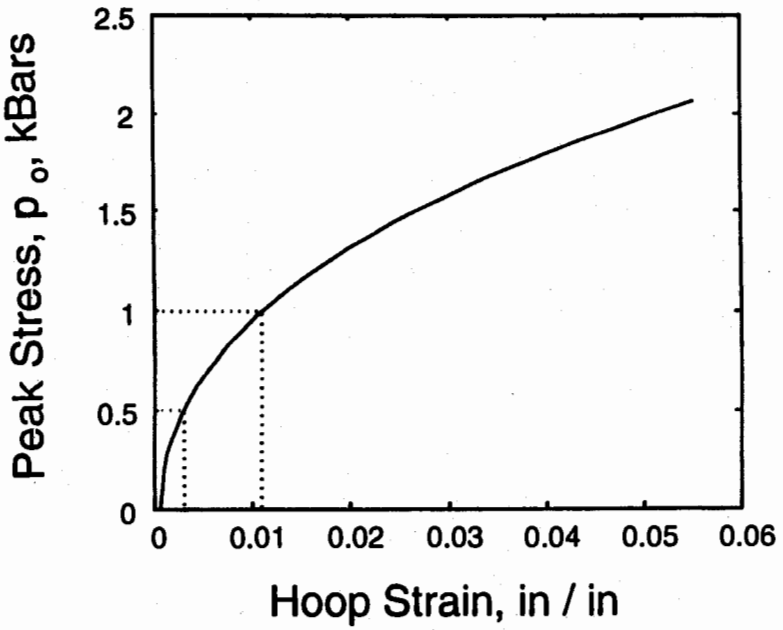
Use a Rock Strength Reduction Factor (SRF)



σ_f = in-situ rock strength
q_f = unconfined laboratory rock strength
rjs = rock joint spacing
d_i = rock opening diameter

Hendron and Aiyer Analysis Results (U)

Stress - Strain Curve for Tunnel



- Curve Depends on:
  - Liner
  - Rock Properties
  - Tunnel Size
- Similar / Identical sections in different locations have different peak stresses (p_o) but the same curve.
  - Different hoop strains
  - Identify failure/survival strain
- Many issues to consider

Issues to Consider (U)

- **Dynamic loading effects**
  - Rock tends to be a lot stronger under dynamic loads than under static loads
  - Impulse versus peak load analysis
- **Liner/Rock interface not well modeled**
- **Test data come from 2 geologies**
  - Granite
  - Tuff
- **What are the inherent biases of the analysis?**

"Calibration" of Hendron and Aiyer Results (U)

- "Calibrated" for various construction types
  - Much of data from 3 UGTs
    - Piledriver and Hard Hat - tests in Granite
    - Mighty Epic - test in Tuff
  - Lots of tunnel sections and liner types, few large sections
    - Most sections 6 - 7 feet in diameter
    - Most sections loaded side-on
- Work was in support of Deep Basing (1983)
  - Goal was protection of U.S. assets
  - Focus was on "Sure Safe" design
    - Choose to err on the side of "defender conservative"

"Calibration" Continued (U)

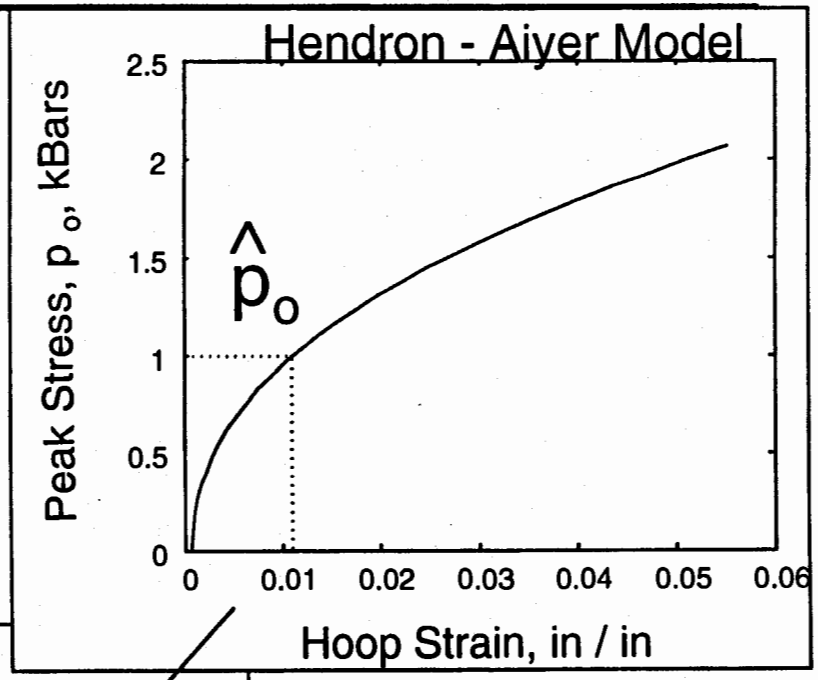
- The project officer made a post-test damage assessment
  - Severe Damage: Requires Remining
  - Moderate Damage: Major Repairs
  - Light Damage: Minor Repairs
  - Undamaged
- These categories were further reduced to
  - Survived
  - Failed

"Calibration" Continued (U)

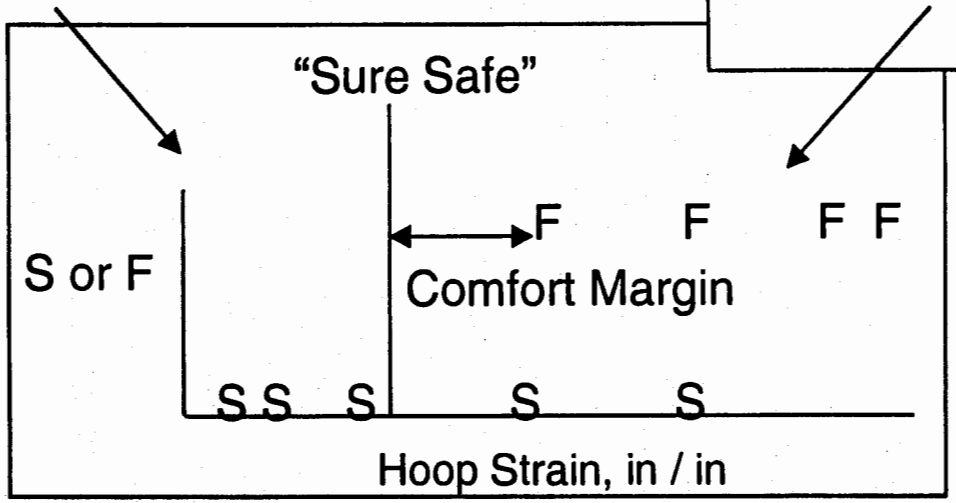
- **The Survived/Failed descriptor was calibrated**
  - Mapped to calculated hoop strain
    - Used best estimate of p_o
    - Best estimates of p_o have +/- factor of two error bars
    - Large values of hoop strain ignored as "not meaningful"
- **Limiting values of hoop strain were selected**
  - Values for "Sure Safe" designs
    - Values below which no failures were seen
    - Usually with a "comfort margin"

The "Calibration Trail" (U)

{Instrumentation} → $\hat{p}_o$ →



{Survive / Fail Assessment}



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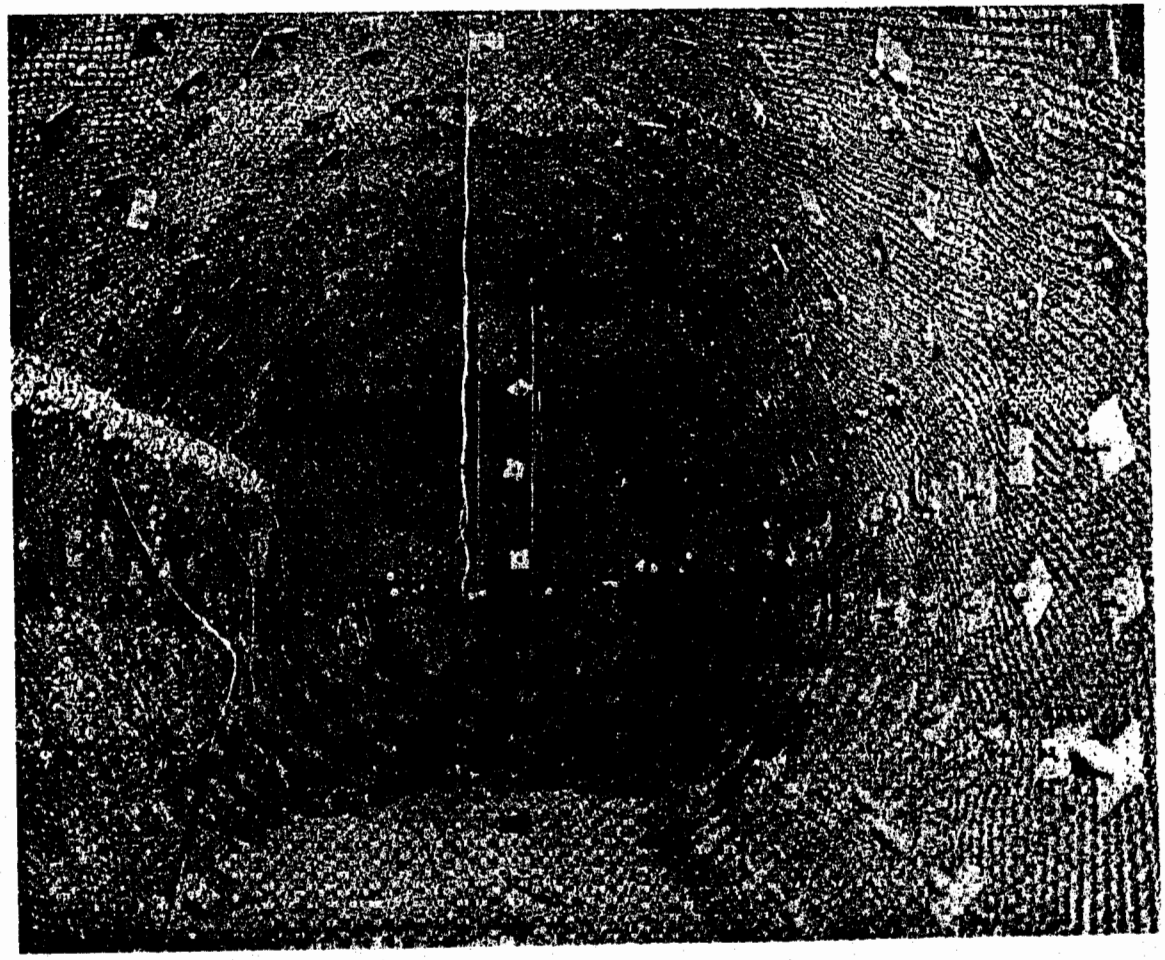
Results from Piledriver Test (U)

- Piledriver test was 62 kT
- 72 test structures
- Peak ground stress at test structures ranged from 6 kBar to 1 kBar
- Figure shown is the CR5 and CR6 drifts
  - 16 ft. diameter
  - Rock bolts only
  - End loaded by test
  - Peak ground stress about 2 kBar
  - Undamaged



Results from Piledriver Test Cont'd (U)

- Test section BR1 is shown
- 16 ft. dia. rock opening
- 7 ft. dia. concrete liner
  - Liner thickness 6 in.
  - 150 psi foam backpack
  - Backpack 48 in. thick
- Peak ground stress about 3 kBar
- Concrete liner 28-day strength about 5000 psi
- Tunnel section destroyed

Interest in Threat Facilities (U)

- **SEPW Program (about 1988)**
  - Several years after Deep Basing tests
- **Needed to analyze threat facilities**
  - Vulnerability to ground shock
  - Revisited the Deep Basing work

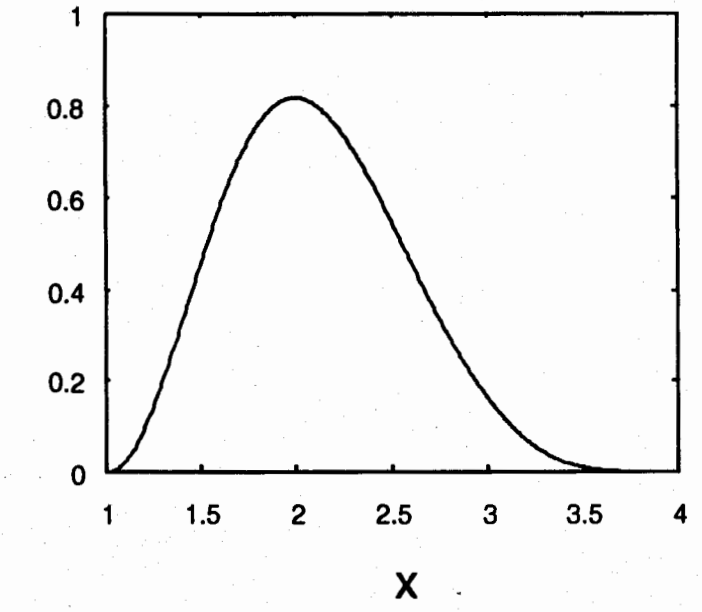
Ground Shock Vulnerability Calculation (U)

- **1990 DIA Report Describes Method**
  - Uses Hendron and Aiyer Method for p_o - hoop strain relationship
  - Converts "Sure Safe" hoop strains to "Failure Strains"
  - Large Monte Carlo simulation representing uncertainty in target parameters
- **Results in a distribution of failure stresses, p_o**
  - Failure values for p_o are fit to a Beta-distribution
  - Published tables give min, max, mode, and t-value
  - These values are used for GVN determination
    - See later chart for more details
  - GVNs are used in PDCALC 6.2

What is the Beta distribution? (U)

- **The Beta distribution has several convenient characteristics.**
  - **Bounded**
  - **Can take on almost any shape**
  - **Described by 4 parameters**
    - **minimum value**
    - **maximum value**
    - **mode**
    - **t - peakedness**
- **Uniform distribution**
  - **t = 2**

Beta distributed variable, x
min = 1, max = 4, mode = 2, t = 9



Calculating "Failure" Strains (U)

Calculating Tunnel Vulnerability (U)

- Select minimum and maximum values for all important parameters, for the target of interest
  - Geological characteristics
  - Liner characteristics
  - Size
  - "Sure Safe" strains (from earlier table)
- Select Beta distribution characteristics for each parameter
  - Peakedness, (t), and mode
- Run Monte Carlo simulation
  - Example has 10,000 draws from 13 distributions

Tunnel Vulnerability Example (U)

DoD 6(1)

Rock and Liner Properties (U)

Tunnel Hardness Results (U)

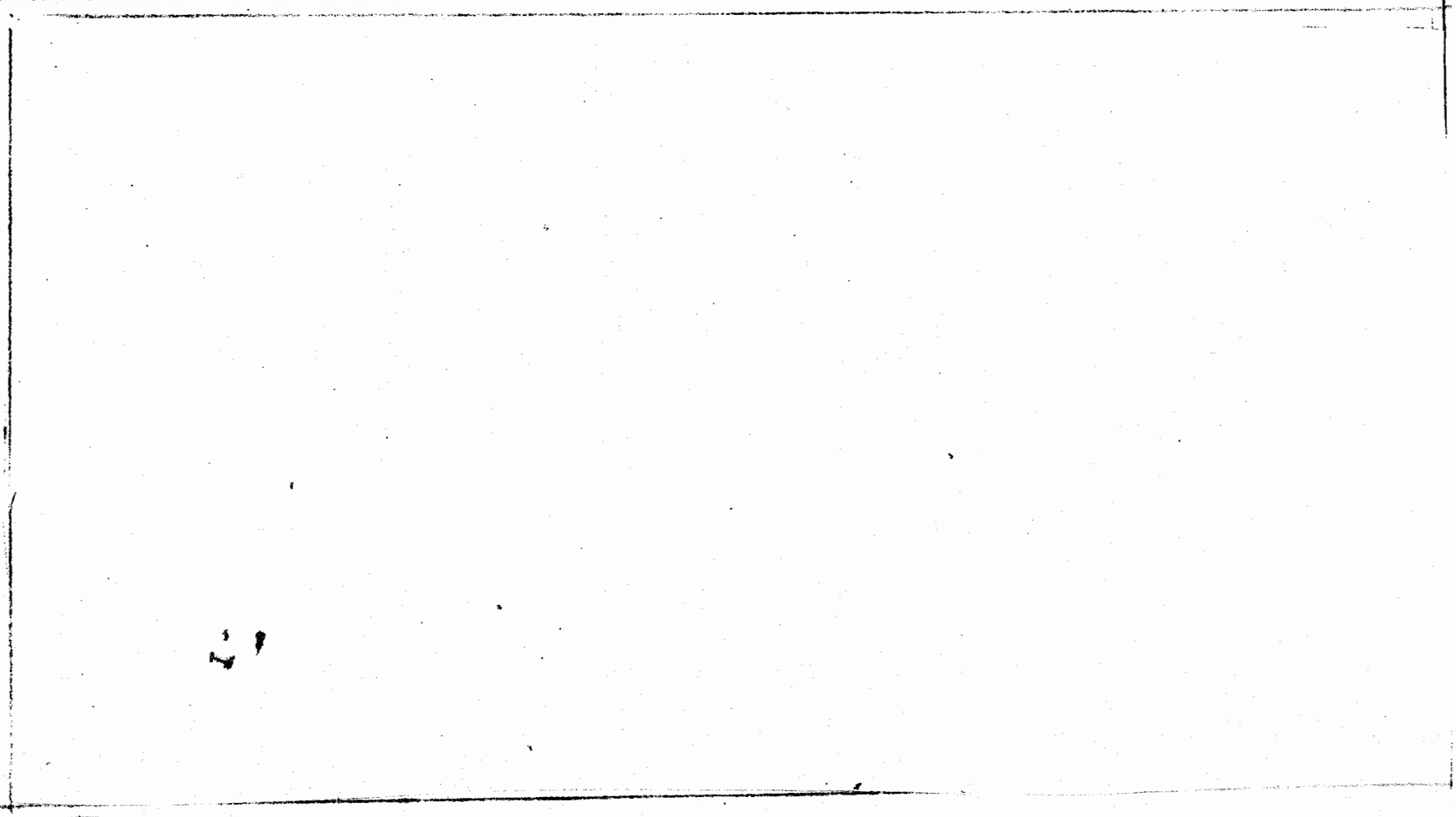
Observations and Issues (U)

- The distributions represent uncertainty about the site parameters, not within site variability
  - E.g., Sure safe hoop strain
    - Assumed Beta Distribution ranges from:
      - 0.004 to 0.025 (Unreinforced concrete to very heavily reinforced)
      - The tunnel liner itself does not vary
- Choosing the resulting p_o mode is approximately the same as running a nominal case analysis - uncertainty is nearly irrelevant
- Uncertainty distributions have weak supporting rationale
  - Ranges, peakedness, independence

Hendron and Aiyer Analysis Issues (U)

- **Hendron and Aiyer Method assumes static loads**
  - Rock is much stronger under dynamic loads than static loads - strain rate effects
    - Tunnel is stronger than static load predicts
    - Conservative assumption for tunnel designer
  - Requires full engulfment of structure in ground shock wave
    - Probably OK for nuclear - not even close for conventional weapons effects
  - When failure occurs - loading or unloading - may be important but is not included in analysis

Tunnel Vulnerability Analysis Issues (U)



DOD b(1)

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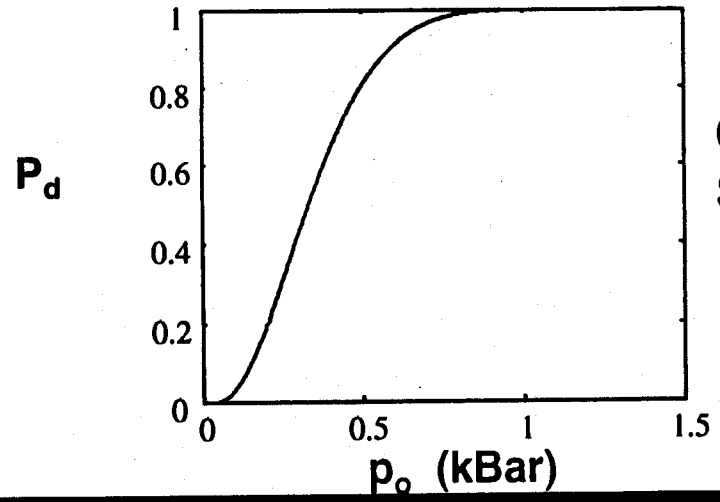
Where do GVNs come from? (U)

- **Step 1: Pick a target**
  - Geology (DUG-1C parameters)
  - Hardness (from preceding analysis)
  - Depth (Intelligence estimate)
  - All these parameters are given distributions
- **Step 2: Use the Hardness CDF**



Curve is Target Specific

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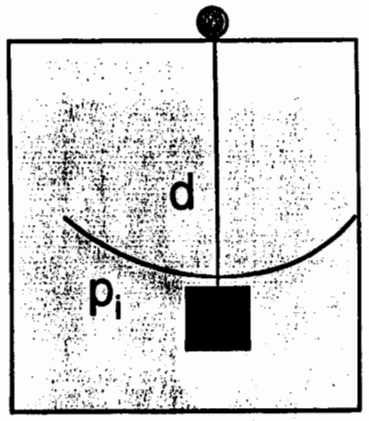
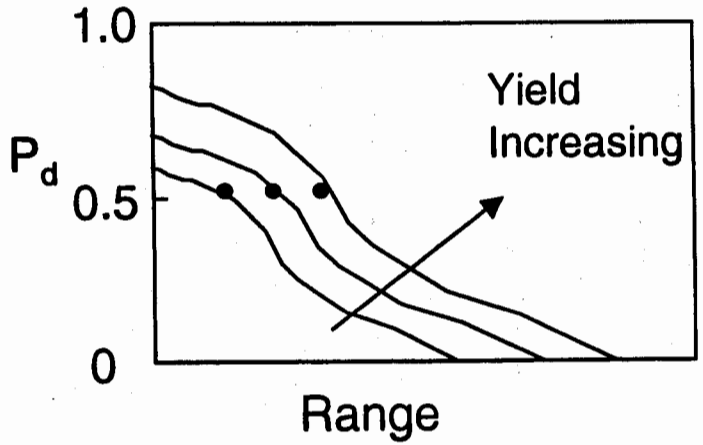
Where do GVNs come from? (2) (U)

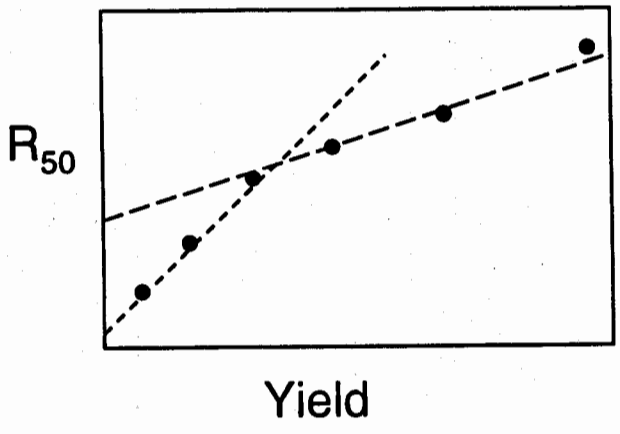
- **Step 3: Pick many weapon yields**
  - Evenly spaced on log scale from min to max
  - HOB is 0.5 meters
- **Step 4: Monte Carlo simulation drawing from distributions on:**
  - Facility depth (assumes weapon directly above facility)
  - Geology parameters
  - Result: p_i, the peak ground stress at the facility
  - Compare to the chart in Step 2 to get P_d for that trial
  - Save P_d and depth for that trial associated with the yield.



Where do GVNs come from? (3) (U)

- **Step 5: Repeat the process for many yields**
  - Fit P_d vs. Range to lognormal for each yield
  - Select R_{50} for each yield from fitted curve





- **Step 6: Fit 2 straight lines to 50 % P_d values**
  - Determine GVN (parameters of curve fit)

Further Analyses of Tunnel Vulnerability (U)

- **Review tunnel vulnerability assessment methodology**
  - More sophisticated techniques are available
  - Include dynamic loading effects
- **Look again at failure models and test data**
  - Identify where conservatism exists and quantify
  - Reanalyze for "Sure Kill" levels
- **Consider other treatments of uncertainty**
  - Run selected cases
  - Evaluate parameter effects on p_o

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Unexplored Penetrator Regime

LDRD Renewal (U)

June 1996

M L Burkwald 10/24/00

DEPARTMENT OF ENERGY DECLASSIFICATION REVIEW	
1ST REVIEW-DATE: 6/23/99	DETERMINATION [CIRCLE NUMBER(S)]
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NAME: [illegible]	2. CLASSIFICATION CHANGED TO:
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DOD 6(1)

Briefing Outline (U)

- Underground Facilities are a National Security issue
- The topic is gaining high-level attention
- Our approach to the problem
  - Target characterization
  - Mission analysis
  - Computational activities
  - Design and test activities
- Summary

CINC Priorities for Counterproliferation Capabilities (U)

CINC Priority	CINC's Counterproliferation Capabilities
1	Detection/characterization of BW/CW Agents
2	Intercept cruise missiles
3	Defeat underground targets
4	Characterize and identify underground targets
5	Collect and analyze intelligence
6	Passive defense enabling operations
7	Support for operations in NBC environment
8	Biological vaccines
9	Planning and targeting for above ground infrastructure
10	BW/CW agent defeat
11	Detection and tracking of shipments
12	Prompt mobile target kill
13	Support for Special Operations Forces
14	Locate, detect, and disarm WMD in CONUS/OCONUS

CINC Priorities for Counterproliferation (U)

- Combatant CINCs listed their priorities for countering NBC proliferation
- Identification, characterization, and defeat of underground targets was the #3 priority
  - "...our forces must have weapons that are capable of penetrating through walls and other barriers that provide protection for above- and below-ground structures."
  - "These systems must be able to perform their missions in scenarios in which NBC targets are protected by air defenses and (in the future) missile defenses."
  - "Improving the state of knowledge in weapons effects and target vulnerability/response is required..."

Proliferation: Threat and Response, April, 1996
William Perry, Secretary of Defense

External Interactions

- *Defense Intelligence Agency*
- *Waterways Experiment Station*
- *University of Dayton*
- *Eglin Air Force Base - Wright Lab*
- *USSTRATCOM*
- *Defense Nuclear Agency*

Uniqueness

- Team Approach: Nationally Recognized Members
  - 30 Years of EPW Experience
  - Large Scale Computational and Modeling Capability
  - Unique SNL/USSTRATCOM Analysts
- Success Oriented
  - Technically Credible Approach
  - Target Assessment/Mission Analysis

    Low Risk
  - Design Methodology/Analytical Tool Development

    Medium-High Risk

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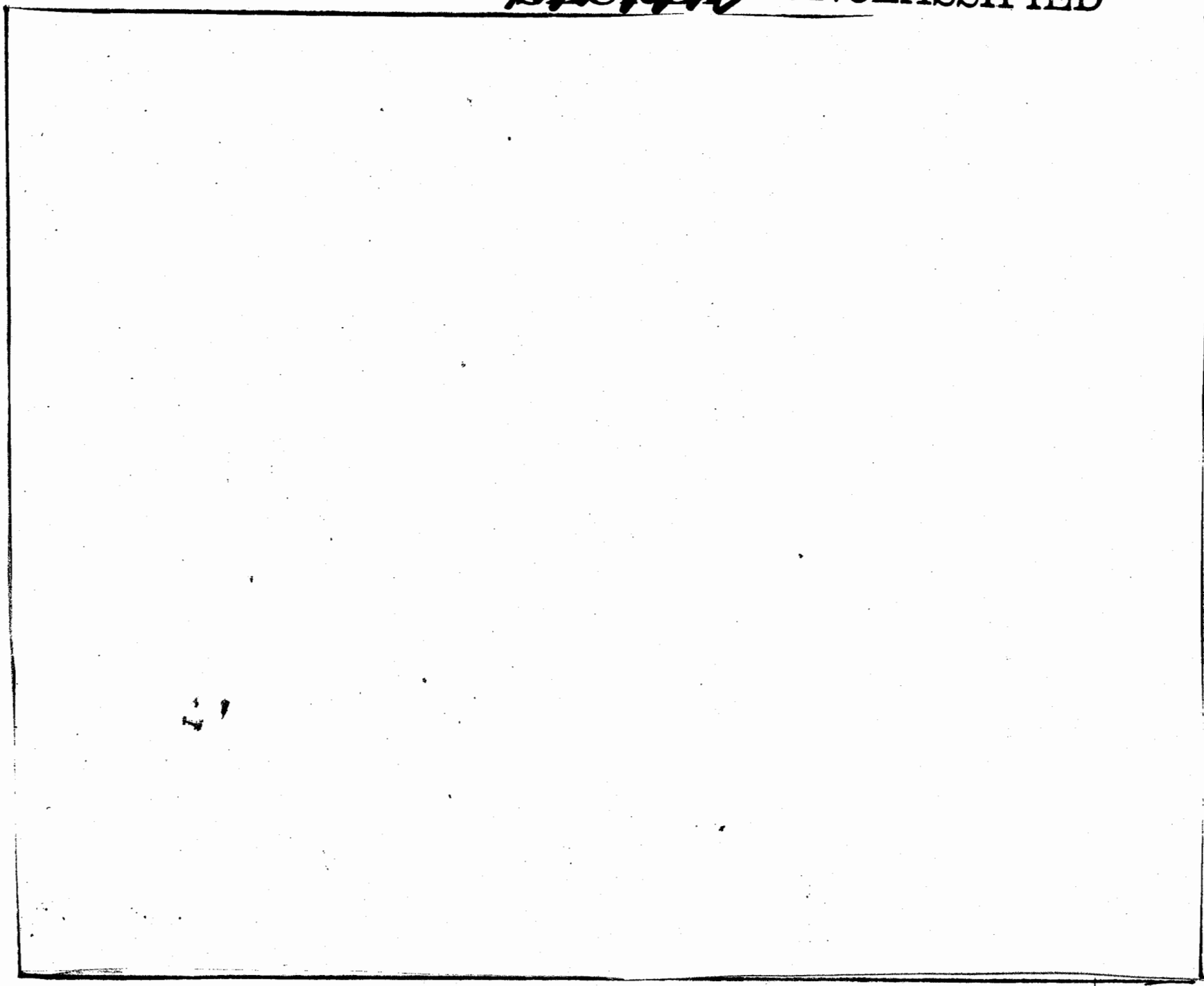

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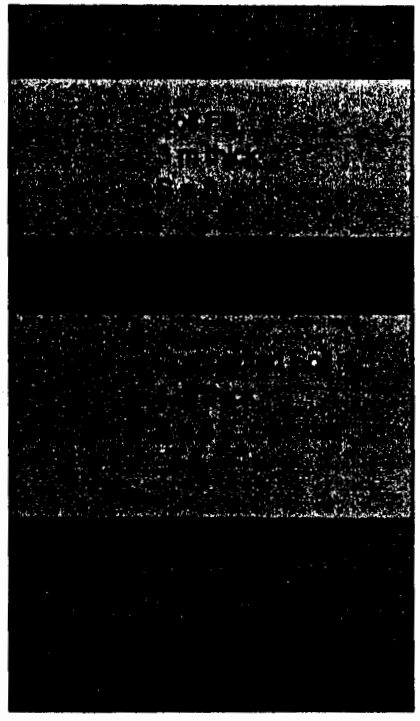
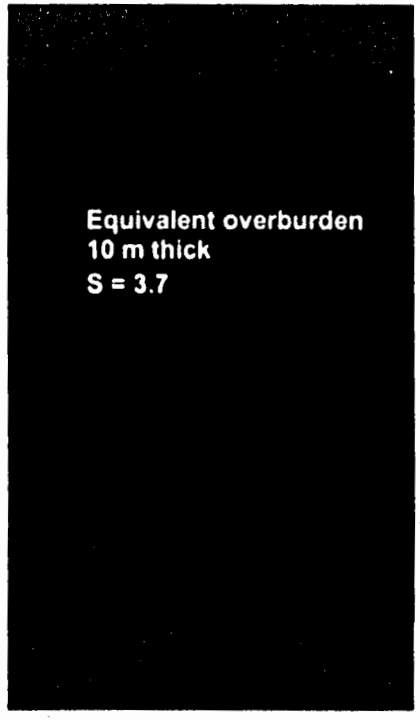
Illustration of Equivalent S-number Process (U)

Actual Facility with Layered Geology or Construction



Facility modeled with uniform geology/construction and equivalent S-number



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Target Characterization/Mission Analysis Milestones (U)

Milestone	Date	Accomplishments
Select representative UGFs	Dec., 1994	Characterized larger set of targets
Target damage evaluation of targets from current weapons	July, 1995	Preliminary weapons effects calculations
Mission assessment for conventional and nuclear EPWs	Oct., 1995	Assessments for current weapons against some targets
UGF vulnerability assessment	April, 1996	Conventional must penetrate target - Nuclear methodology being reviewed
Evaluate mission constraints	Sept., 1996	Work in process
Assess mission effectiveness improvements	FY97	

LDRD Project: Unexplored Penetrator Regime Against Super-Hard Underground Facilities

Part 2: Review of Tech Base Activities

Technical goal

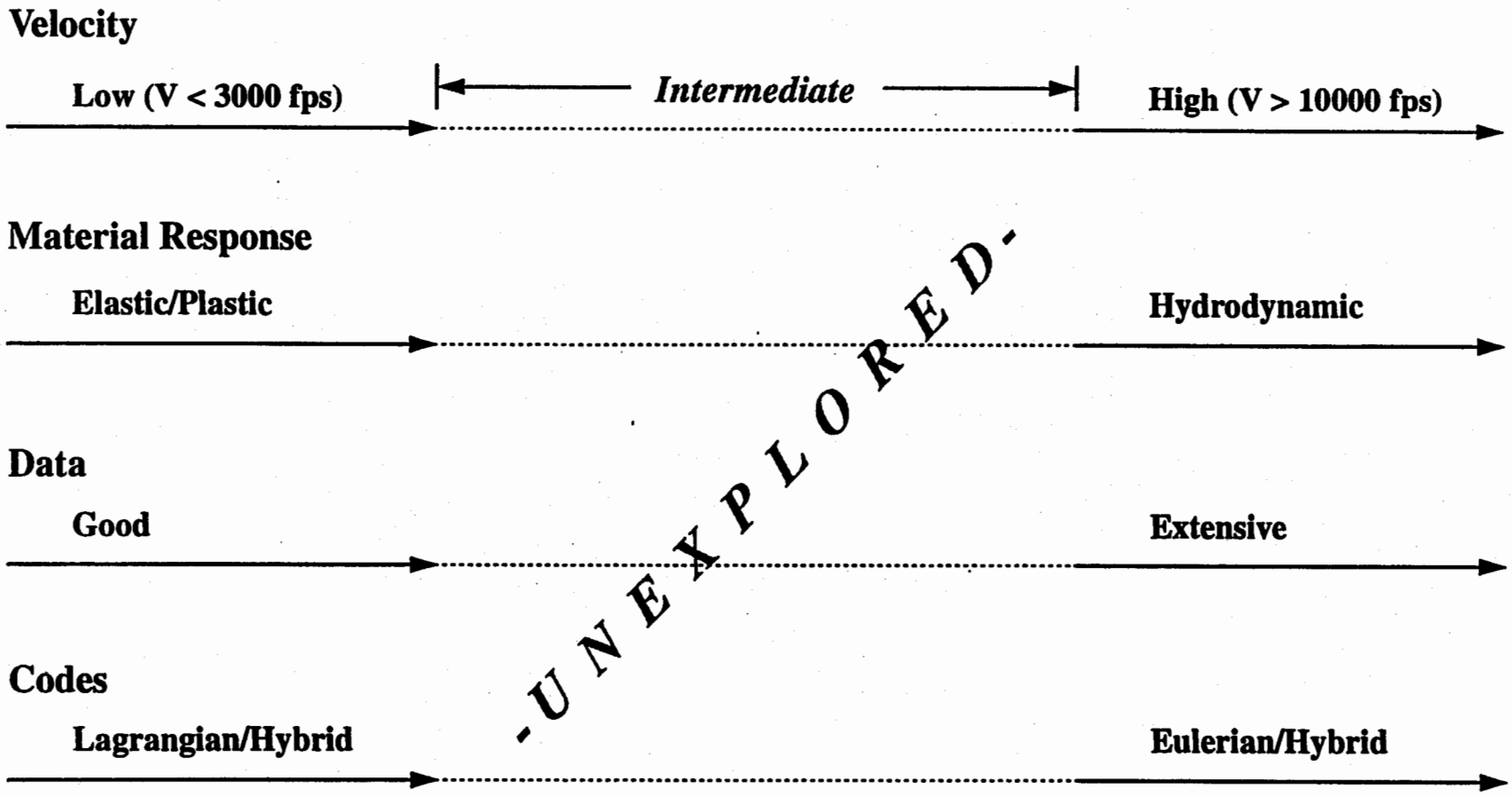
- Develop basic understanding computational models to predict unique features of earth penetration at high velocity:
  - Penetrator abrasion, plastic deformation, and failure

End product is a tool to predict:

- **Survivability:**
  - Predict loads, peak stresses on the penetrator case and warhead.
- **Lethality:**
  - Predict depth of penetration.

EPW LDRD

Modeling Regimes/Capabilities



Background: Computational capabilities

Existing modeling capabilities

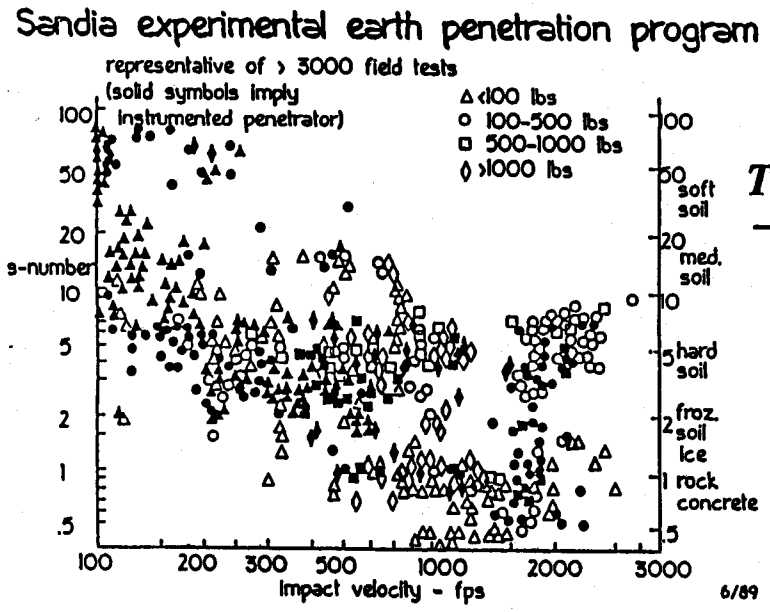
- "Rigid" penetration (low velocity, <600 m/s)
  - Penetration depth and loading, 2D
  - Structural mechanics (under development)
  - 3D (under development)
- Hydrodynamic penetration (very high velocity, >3000 m/s)
  - Penetration depth, 2D and 3D

This project

- "Unexplored" penetration regime (between 600 and 3000 m/s)

This LDRD Project Supports the Shift to Model-Based Design

Traditional Test-Based Approach



This LDRD Project

Model-Based Engineering/Design

Requires

- Physics model development
- Experiments to guide modeling
- Code implementation
- Testing for model verification

Provides

- Modeling tools
- Design guides
- Fewer full-scale tests

Technical challenges

- Overcome lack of understanding of physical processes.
  - Abrasion, friction, other interface phenomena.
  - Material failure: cracking, plastic flow.
- Overcome difficulty in modeling interface numerically
  - Allow gross changes in penetrator shape.
  - Develop ability to remove penetrator material from Lagrangian mesh.
  - Predict structural response while the above are occurring.
- Contribute to penetrator design process in this velocity regime.
  - Materials science basis.
  - Computational tools.

Major Technical R&D Activities

- **Physics model development**
  - Metal penetrator wear/erosion/abrasion
- **Micrographic analysis**
  - Investigate/discover erosion phenomenology
  - Guide model development
- **Ballistic testing**
  - Samples for micrographic analysis
  - Validation data for computational models
- **Production code implementation of penetrator erosion model**
  - Platform for validation of computational models
  - Model-based tool for routine EPW engineering design & analysis

Technical accomplishments: Abrasion model

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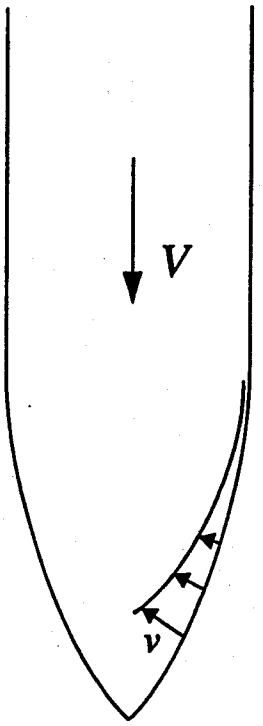
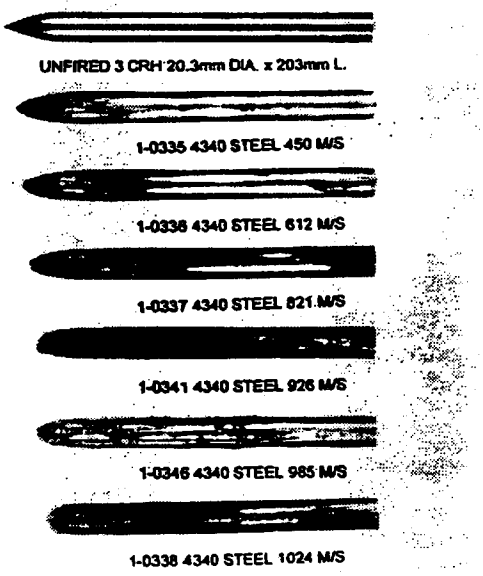
Computational Physics & Mechanics Department

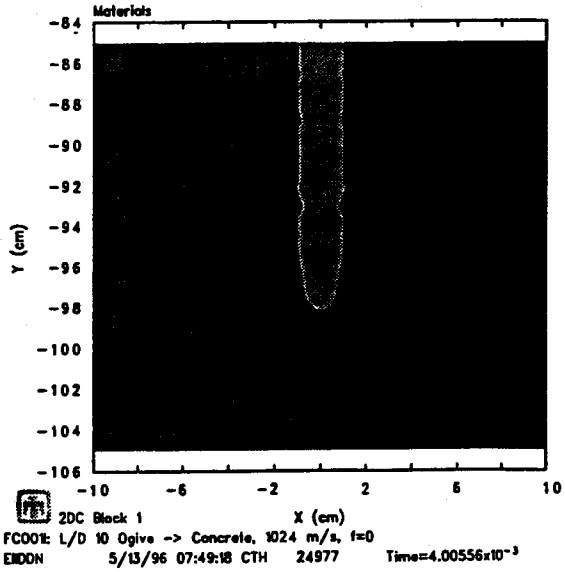
- CTH model removes mass from the surface according to local conditions.
- Data show mass lost is proportional to initial KE. This suggests model shown at right:
- Results agree well with experimental data by Forrestal on mass loss and penetration depth.

$$\nu = \frac{CVp}{\rho}$$

C=constant







Technical accomplishments: Micrographic penetrator analysis

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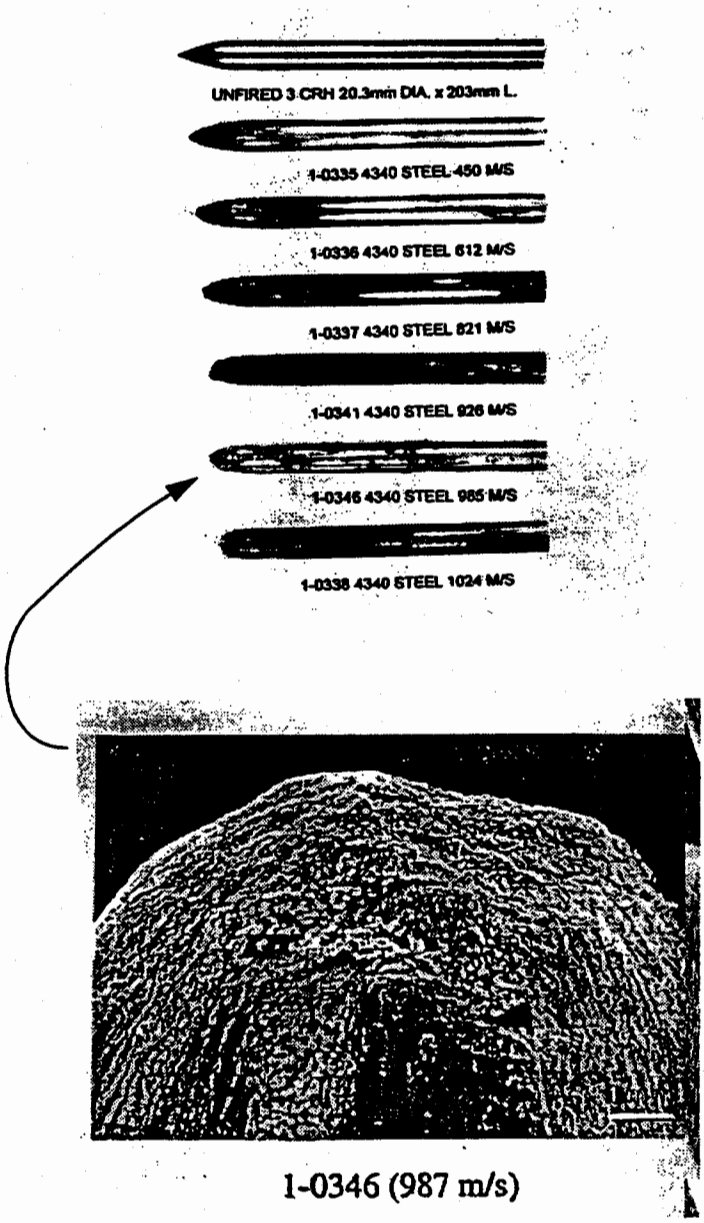
Computational Physics & Mechanics Department

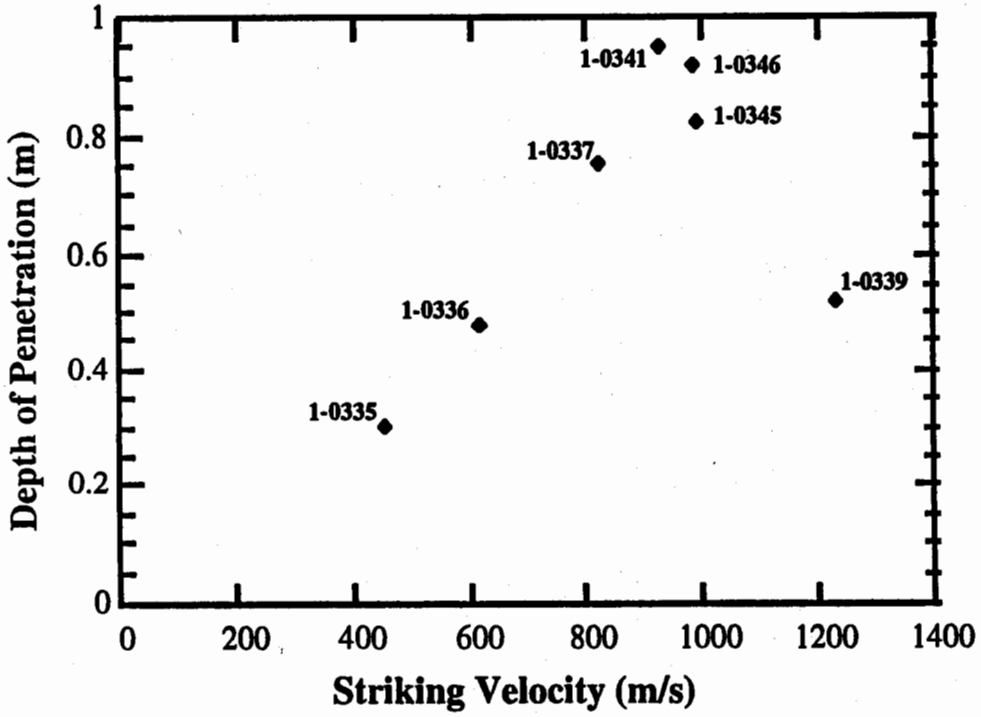
- Study failure mechanisms in high-velocity penetrators.
- Identify favorable materials.

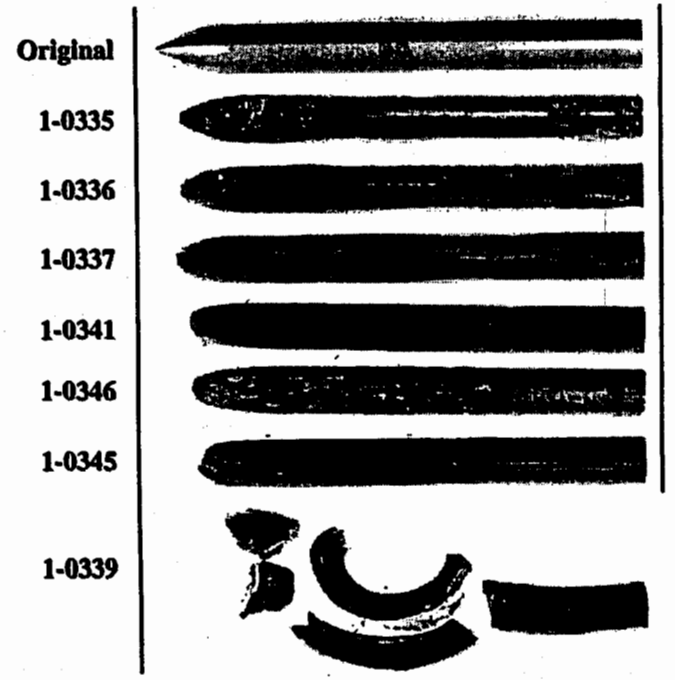


1-0346 (987 m/s)

EPW Technology

AISI E4340 SAQ Steel Projectiles into SAC-5 Concrete





EPW Technology

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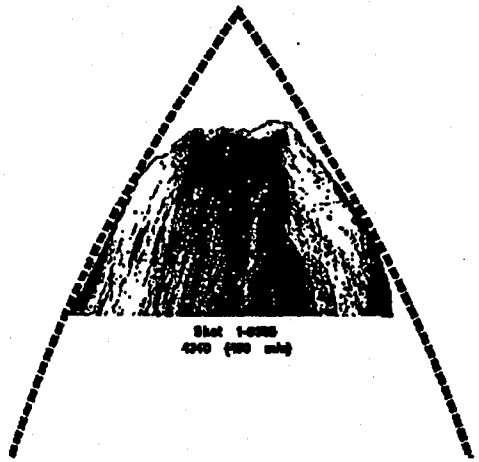

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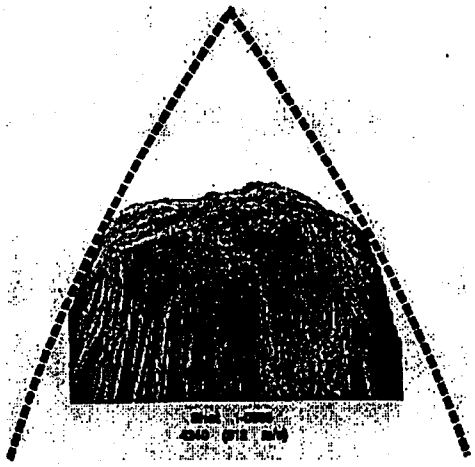
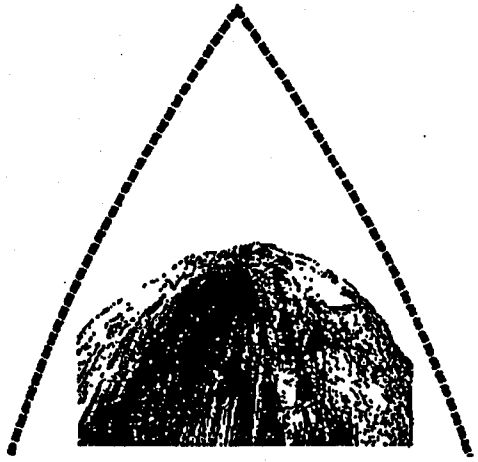
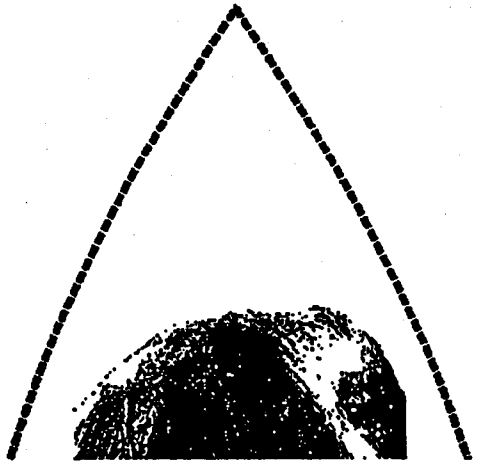


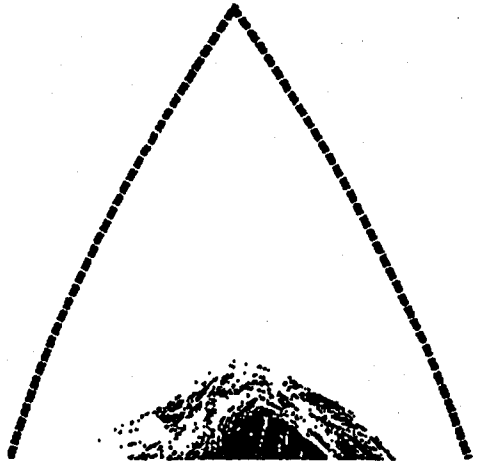
1-0336 (612 m/s)



1-0337 (821 m/s)

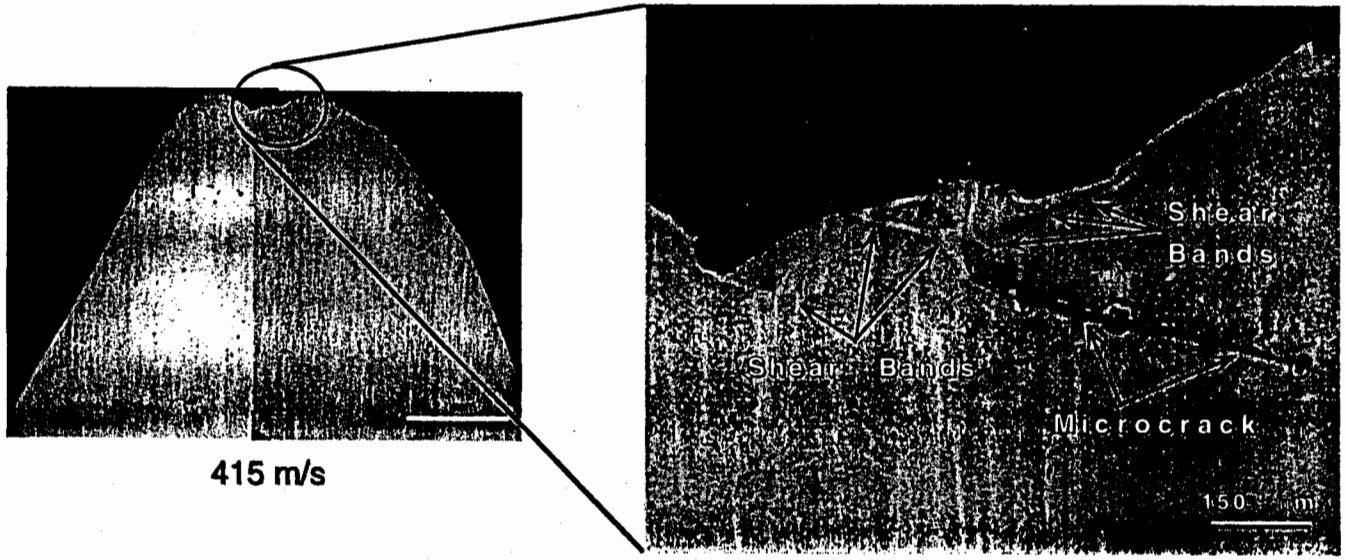


1-0341 (926 m/s)

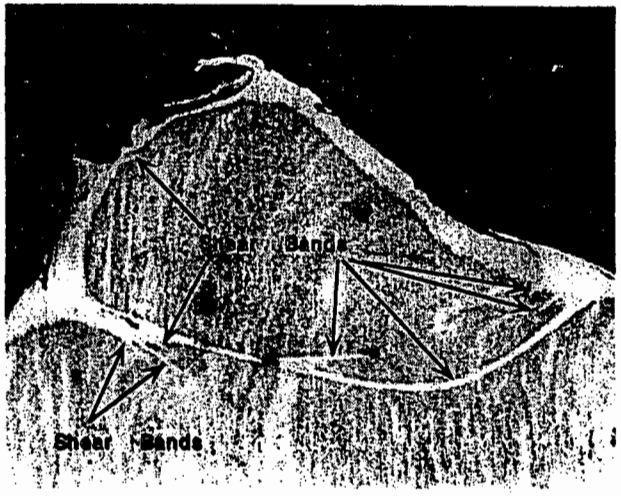


1-0345 (987 m/s)

EPW Technology



415 m/s



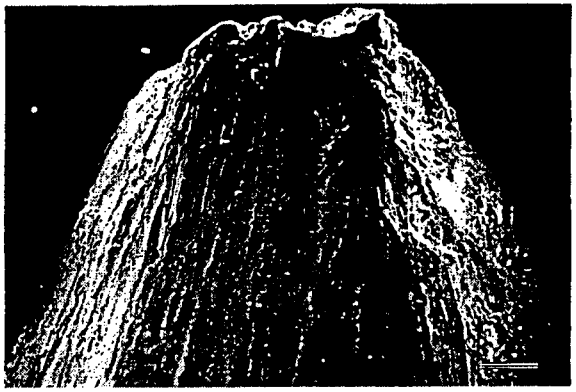
987 m/s

Erosion Process

- Surface friction ⟶ Localized shear instability
- Brittle microcrack formation
- Removal of small surface pieces (≈ 500 μm)

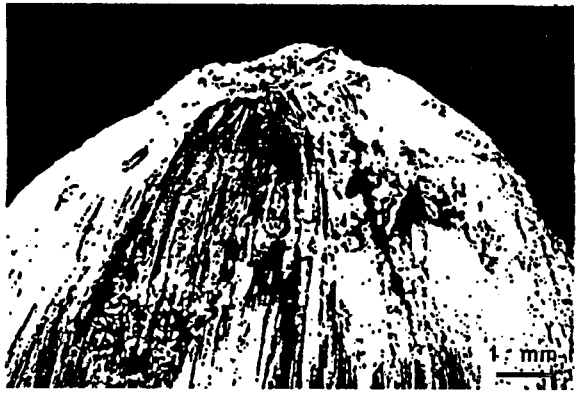
EPW Technology

AISI E4340 SAQ Steel Projectiles into SAC-5 Concrete



1-0335 (450 m/s)

1-0336 (612 m/s)



1-0337 (821 m/s)

1-0341 (926 m/s)

1-0346 (987 m/s)

1-0345 (985 m/s)

EPW Technology

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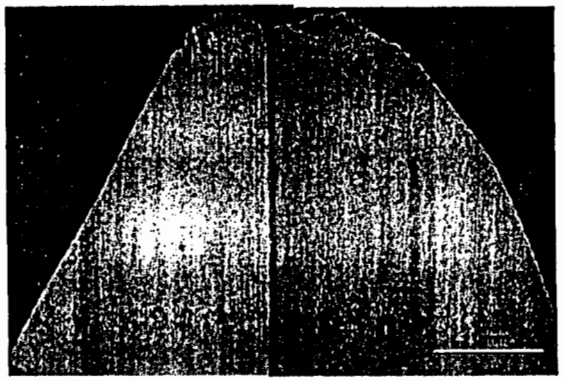

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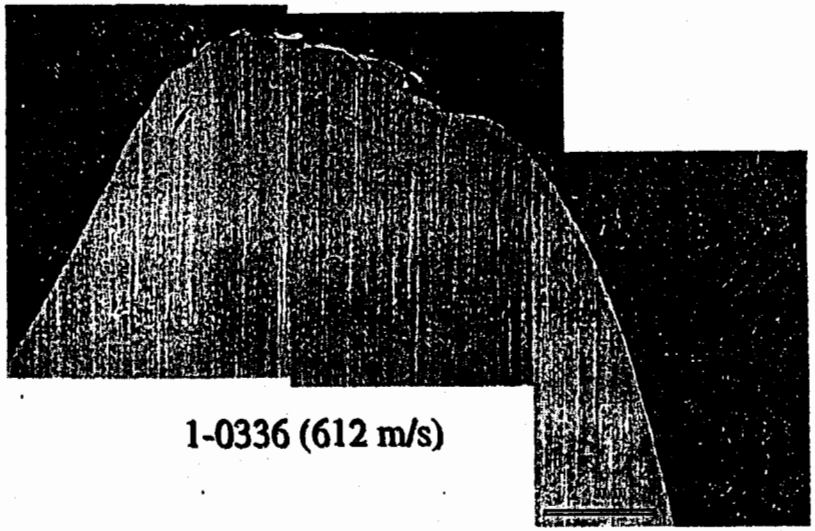

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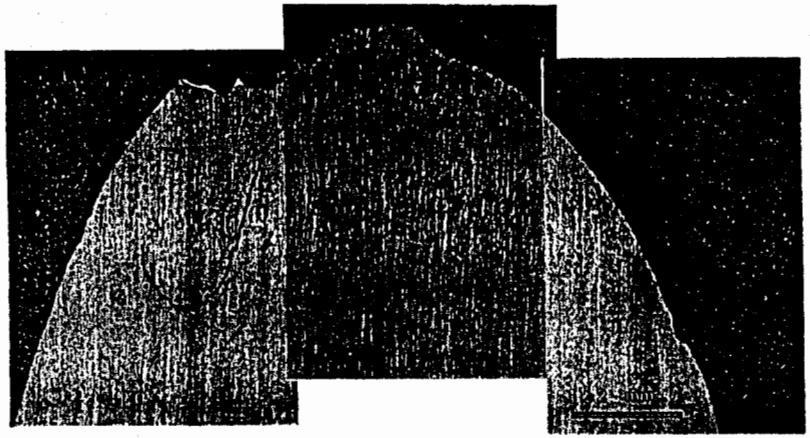

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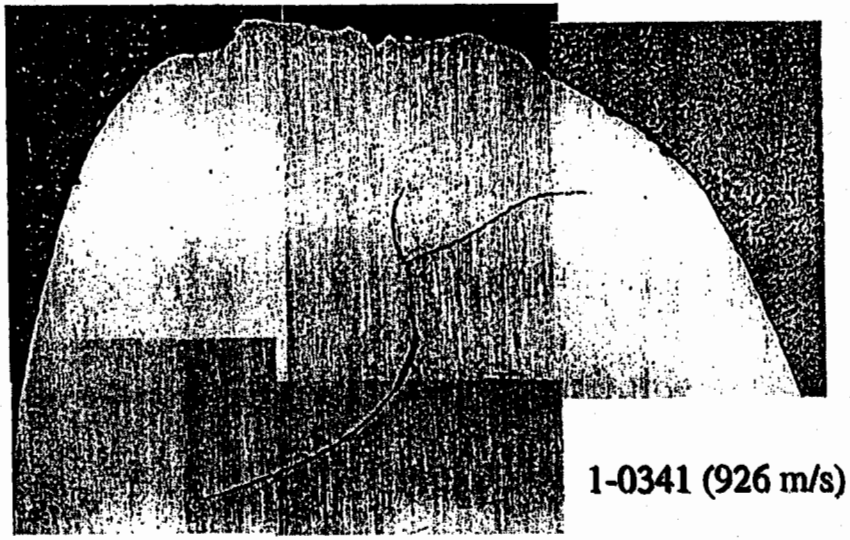


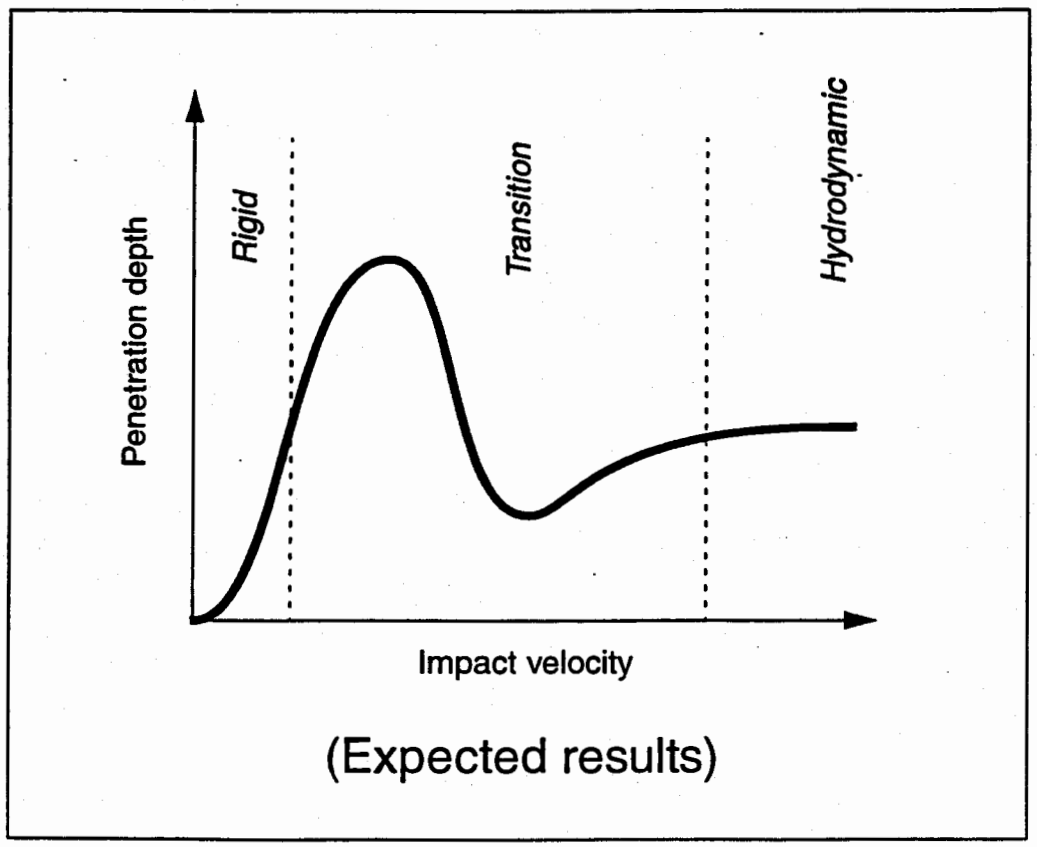
1-0341 (926 m/s)

Technical accomplishments: Experimental data up to 3 km/s

Sandia National Laboratories

Computational Physics & Mechanics Department

- Existing data on high velocity penetration is fragmentary.
- Obtain a consistent set of data over a wide range of velocity.
  - Steel rods into aluminum blocks, 1-3 km/s.
  - For use in model validation.
    - ♦ Can we predict the expected maximum and minimum in the penetration depth curve as a function of velocity?
  - To be completed in FY96.



(Expected results)

FY96-97 planned work

- Improve and validate penetrator-target coupling algorithm, implement in ALEGRA.
- Get data for and thoroughly understand penetrator depth curve in transition region (steel -> aluminum).
  - Reproduce computationally.
- Incorporate into models what is learned from micrographic analysis and penetration data.
  - Physical models can be incorporated into any applicable code.

Table 1: LDRD Milestones/Accomplishments (R&D Activities)

Major Milestones	Date	Accomplishments
Tabulate existing data Select computational method	12/94	Existing data tabulated Modeling approach selected
Select benchmark dataset Run benchmark calculations	7/95	Data deficiency identified Developed ballistic experiment plan Initiated scoping calculations
Transition velocity regime studies	12/95	Micrograph analysis of penetrator nosetips Completed scoping calculations
Model development and testing	7/96	Abrasion model developed Calculations performed to exercise/ assess model Initiate(d) ballistic experiment series
Complete test series Assess/refine erosion model Validate computational methods Evaluate design tradeoffs		Work in progress

Resource Utilization

FY96	*5400 (Rogers)*	*9200 (Yarrington)*	*2100 (Hansen)*
	186,354	*233,478*	*223,839*
Labor	*165,000*	*164,000*	*150,000*
DC	*9,000 Travel*	*34,000 Contract*	*34,000 Tests*
SC	*0*	*20,000 Computer*	*25,000 Shop*
			($30,000 Kelley)
			($80,000 Forrestal)
FY97	*230,000*	*225,000*	*221,000*
	45K Additional	*same*	*same*
	for test & travel		

LDRD Products - End FY97

1. *SNL/DIA Publication on Hard Target Characterization*
2. *Report on Military Mission Considerations for EPW Use*
3. *Report on Nose-Tip Enhancements for Increased Penetration*
4. *Summary of Scale Model Test Results*
5. *An Abrasion/Erosion Model that can be incorporated in Hybrid Numerical Codes for Penetration Analysis*

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Response to MAWG Questions (U)

EXISTING NUCLEAR STOCKPILE OPTIONS VARIABLE YIELD NUCLEAR EPW WEAPON

J.F.Cuderman, Steve Schaefer, Al Baker-- Sandia National Laboratories

John St Ledger-- Los Alamos National Laboratory

Michael Schwab--Lawrence Livermore National Laboratory

(3)

M Buchwald 10/24/00

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August 6-8, 1996

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Lawrence Livermore National Laboratory

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Response to MAWG Questions

EXISTING NUCLEAR STOCKPILE OPTIONS
VARIABLE YIELD NUCLEAR EPW WEAPON

- **Design Information**
- **Weapons Output Information**
- **Effects/Effectivness**
  - **Fireball Effects**
  - **Groundshock**
  - **Fallout**
- **Collateral Damage**

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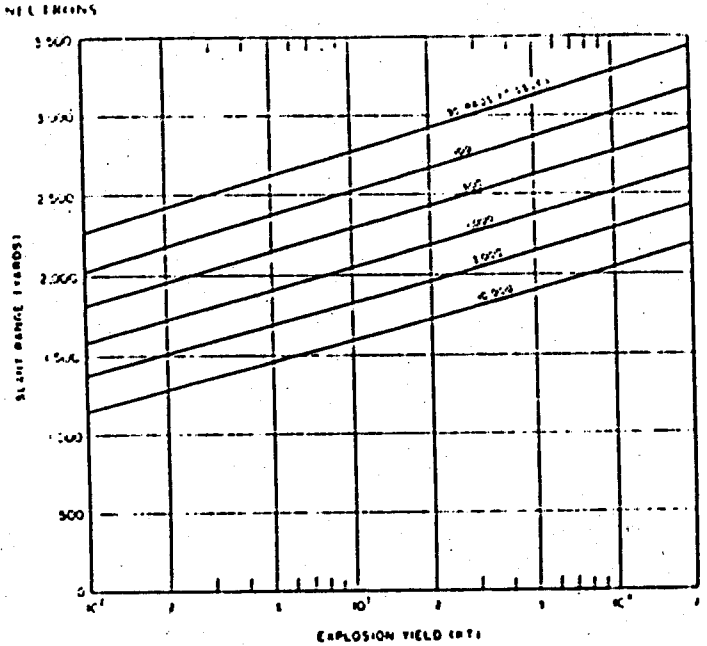
3

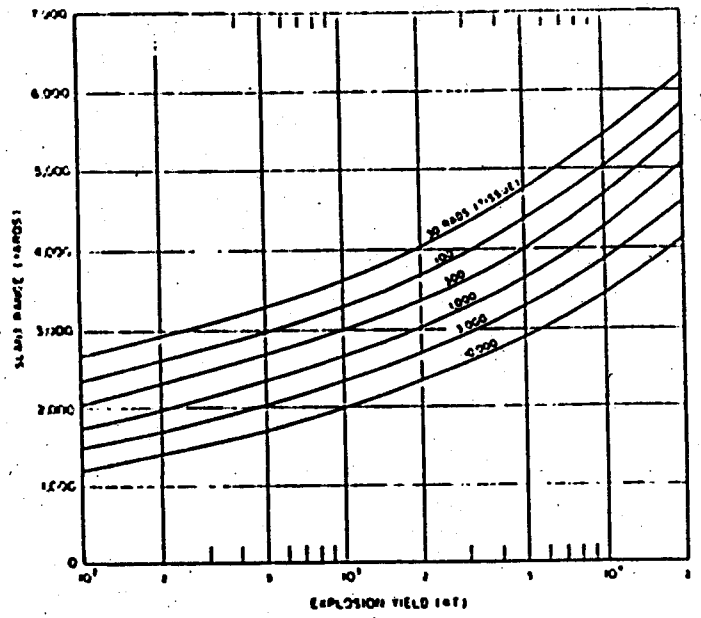
Fireball Effects/Effectivness

- Within some fraction of the radius of a fireball, all C/B agents will be destroyed
  - Steve Schaefer Presentation
- Proposed Fireball Kill Radius

$$R = 145(kt)^{0.4}$$



Slant ranges for specified neutron doses for targets near the ground as a function of energy yield of air-burst thermonuclear weapons based on 0.9 sea-level air density (Reliability factor 0.25 to 1.5 for most thermonuclear weapons)



Slant ranges for specified gamma-ray doses for targets near the ground as a function of energy yield of air-burst thermonuclear weapons with 50 percent fission yield, based on 0.9 sea-level air density (Reliability factor from 0.25 to 1.5 for most thermonuclear weapons)

Characteristics of Expected Radiation Field

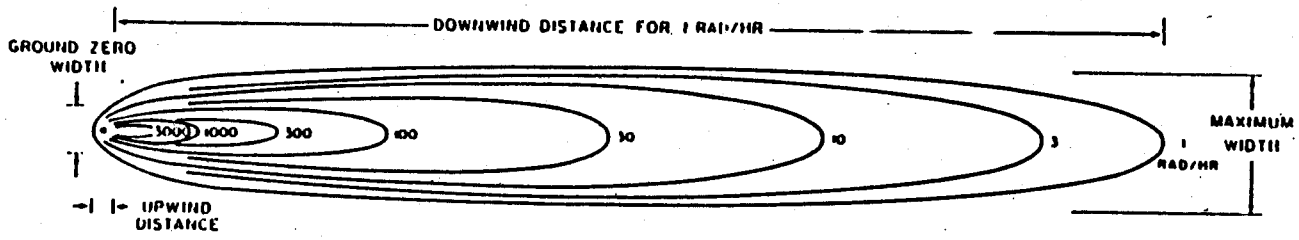


Illustration of idealized unit-time dose-rate pattern for early fallout from a surface burst (The contour dimensions are indicated for a dose rate of 1 rad/hr)

SCALING RELATIONSHIPS FOR UNIT-TIME REFERENCE DOSE-RATE CONTOURS FOR A CONTACT SURFACE BURST WITH A YIELD OF *W* KILOTONS AND A 15 MPH WIND

Reference dose rate (rad/hr)	Downwind distance (statute miles)	Maximum width (statute miles)	Ground zero width (statute miles)
3,000	0.95 $W^{0.4}$	0.0076 $W^{0.4}$	0.026 $W^{0.4}$
1,000	1.8 $W^{0.4}$	0.036 $W^{0.4}$	0.060 $W^{0.4}$
300	4.5 $W^{0.4}$	0.13 $W^{0.4}$	0.20 $W^{0.4}$
100	8.9 $W^{0.4}$	0.38 $W^{0.4}$	0.39 $W^{0.4}$
30	16 $W^{0.4}$	0.76 $W^{0.4}$	0.53 $W^{0.4}$
10	24 $W^{0.4}$	1.4 $W^{0.4}$	0.68 $W^{0.4}$
3	30 $W^{0.4}$	2.2 $W^{0.4}$	0.89 $W^{0.4}$
1	40 $W^{0.4}$	3.1 $W^{0.4}$	1.5 $W^{0.4}$

Fallout Criteria and Data

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Impact Velocity (ft/sec)

B61-11 Flight Characteristics

Sandia National Laboratory

Los Alamos National Laboratory

DLM 7/1/96

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OPTION 3

SMALL PARACHUTE/BALLUTE
REPLACES CURRENT RETARDATION SYSTEM

RNE 9/28/94

Ground Shock Propagation (U)

DOE (b)(3)

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Nuclear Penetrator Performance at a Specific Site

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DoD 6(1)

Summary

- **On These Two Concepts Groups**
  - Design data are well developed, available
  - Weapon outputs, effects documented, modeled
    - Temperature history
    - Radiation outputs and spectra
    - Shock production
  - Major effort required is in area of
    - Estimating collateral damage/agent release
    - What is required for denial
    - What are consequences of agent release

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Agent Defeat Weapon Nuclear Baseline Assessment (U)

John St. Ledger
Steve Schafer
Chris Cunningham

November 19, 1996

M Burkwald 10/23/00

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CONCEPT EXPLORATION AGENT DEFEAT WEAPON

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Attn: Mr Todd F

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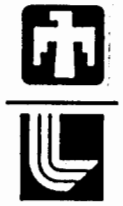
Overview

- Baseline analysis roadmap
- Damage and collateral criteria
- Baseline weapons
- Physical vulnerability system
- Above ground targets
- Buried targets
- Conclusions



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Baseline Analysis Roadmap

- Targets with additions
- Baseline weapons
- Codes
  - PDCALC6
  - CORES
  - SAMPLL & DUG 1C
  - KDFOC & NEMESIS
  - Agent release
  - SCIPUFF
  - QUICKSTRIKE & CTEM
- Target damage and collateral damage

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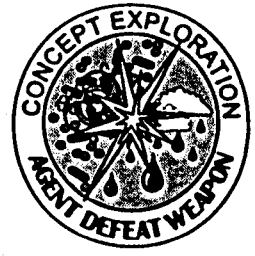

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FY 97 PROPOSED ACTIVITIES FOR AGENT DEFEAT WARHEAD STUDY (a)

DOE (b)(3)

[redacted] At this point we don't know which or how many of them will be selected for further development.

For the concepts selected, calculations of the performance and collateral effects of the nuclear candidates against the Agent Defeat Weapon target set will be required. A few of the nuclear concepts will also require additional weaponization effort. This would consist of preliminary concept layouts and packaging studies.

[redacted] What would be required for those proposals is presented in more detail on the next page.

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Mel Buchwald 10/23/00
MB

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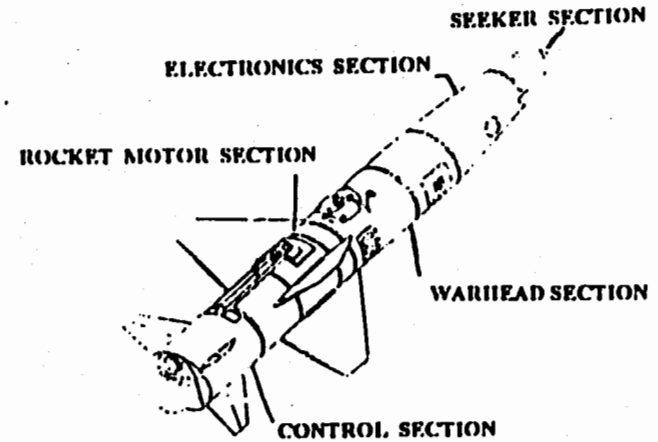
PLYWD TYPE

Concept Description

- Low-yield nuclear weapon
- Precision guidance
- Standoff capability
- AB/SB/EPW capability



AGM-142-Like Concept

Technical Issues

- pit production/use
- nuclear material production
- warhead certification
- nuclear tests

Benefits

- Neutralization of Bio/Chem agents
- facility and weapon destruction
- Long-term denial
- can defeat area targets
- mitigates target/critical element location uncertainty
- potential collateral damage reduction
- high confidence BDA
- compatible with current and proposed AF weapon systems
- can engage weapons in all stages from manufacture to deployment on delivery platforms

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Steven A. Wright, March 12, 1996

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DEPARTMENT OF THE AIR FORCE
AIR FORCE MATERIEL COMMAND (AFMC)
NUCLEAR WEAPONS INTEGRATION DIVISION

28 June 1996

MEMORANDUM FOR SEE DISTRIBUTION

FROM: SA-ALC/NWIE
1651 First Street SE, B-20360
Kirtland AFB NM 87117-5617

SUBJECT: Agent Defeat Weapon (ADW) Concepts Working Group (CWG) Action Items CWG-6 and CWG-7

1. CWG #6 was held at Eglin AFB, FL on 7 May 96. At this meeting Action Items CWG-6 and CWG-7 were generated. CWG-6 tasks the Mission Analysis Working Group (MAWG) to review the ADW concepts and provide specific questions. The MAWG reviewed the concepts during 17-20 Jun 96. The specific questions from this review are included in the attachment. Response is requested by 31 Jul 96. Although some of the concept questions are unclassified, many of the responses will be classified. Please classify response accordingly with the ADW Concept Exploration Security Classification Guide.

2. Action Item CWG-7 tasks the CWG and MAWG Chairs to schedule a joint meeting to discuss the results from the effort identified in paragraph 1. Concept providers will be required to brief their responses to the questions during this meeting. The joint meeting is scheduled for 6-7 Aug 96 with an ADW Program Review scheduled on 8 Aug 96. Details for these meetings are forthcoming.

3. If you have additional questions please contact Don Erdmann, (505) 846-4001 x206, DSN: 246-4001 x206, FAX: (505) 846-4618.

DONALD R. ERDMANN
ADW CWG Chairperson

Attachment:
Specific Concept Questions (S)

M Buchwald 10/23/00

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ADW CONCEPT QUESTIONS
CONCEPT 27
Existing Nuclear Stockpile Options.

1. (U) QUESTIONS REGARDING PHYSICAL CHARACTERISTICS:

   a. (U) What are the external dimensions?

   b. (U) What is the case thickness?

   c. (U) What are quantity & characteristics of ADW materials?

   d. (U) What is the toxicity of the by-products?

   e. (U) What are the mass moments of inertia?

   f. (U) How much HE, if any, and what type?

   g. (U) What type of propellant is used?

   h. (U) What is the overall weight?

2. (U) QUESTIONS REGARDING FUNCTIONAL CHARACTERISTICS:

   a. (U) What volume or area is effected by the weapon?

   b. (U) How will dust, debris and other contaminants effect the system?

   c. (U) What weapon outputs should be associated with each weapon and yield combination?

   d. (U) What are the CEP's for each weapon?

   e. (U) What are the available fuse settings for each weapon?

3. (U) QUESTIONS REGARDING LOGISTICAL CHARACTERISTICS:

   a. (U) What restrictions will different weather conditions pose upon the concept?

   b. (U) What intelligence dependencies does the concept need (agent type, target structure, BDA)?

   c. (U) Does the concept need any special handling?

ADW CONCEPT QUESTIONS
CONCEPT 27
Existing Nuclear Stockpile Options.

d. (U) What is the shelf life of the system?

e. (U) What is the time needed to prepare the concept for a launch?

f. (U) What are the VN and GVN numbers for the targets?

4. (U) QUESTIONS REGARDING COST:

a. (U) What is the life cycle cost?

b. (U) What is the average unit cost?

c. (U) What is the disposal cost?

5. (U) QUESTIONS REGARDING PROGRAM MANAGEMENT:

6. (U) GENERAL COMMENTS:

a. (U) What type of testing has been completed?

b. (U) What is the availability of defeat mechanism raw material?

c. (U) Is there any reference material available?

d. (U) What is the impact of missing the target on weapon function?

e. (U) What are the characteristics of the expected radiation field?

f. (U) What delivery accuracy will be required?

g. (U) For any system or subsystem performance specifics, justify or substantiate how these claims were arrived at. Was it due to a system level test, subsystem level test, or was it simulated or analysis performed (i.e. DARPA, contracted, in-house).

h. (U) What would the agent defeat mechanism footprint look like for this weapon (i.e., how large an area can one weapon be expected to effectively neutralize agent?

ADW CONCEPT QUESTIONS
CONCEPT 27
Existing Nuclear Stockpile Options.

i. (U) Please relate a concepts effectiveness to the ADW consolidated target list? For the ADW consolidated target list, how many sorts of a given concept are needed to defeat or deny access to that target?

j. (U) Can you provide energy spectra that should be used for transport calculations in bunkers with shielding? Or will you do the calculations or the threat scenarios? (radiation concepts only)

k. (U) Quantify collateral effects. Estimate effects - are containers vaporized, ruptured, thrown about, etc? Give some specific examples.

l. (U) We need more data to substantiate the kill mechanisms from these concepts. The radiation contours can be assessed in a straight forward manner - but thermal kill is a very difficult area. Provide the details that lead you to state the fireball will kill all agents. Since heat kill is a time and temperature criteria, how much dispersed agent is pushed out by the shock wave before the fireball temperature kills it. The lethality estimates call for about 2000 degrees for several milliseconds. Can you detail how the material is entrained and show that a conservative analysis kills most agent.

m. (U) Vaporization is certainly a kill criteria. But if you loft globs of spore the heat will kill spore on the outside but given the low thermal diffusivity of spore, the agent in the center may still be viable.

n. (U) Provide some sure-thermal-kill radius based on hydrocode calculations of the shock wave from weapon detonation and fireball temperature.

o. (U) Need to address agent in containers that may be ruptured outside of this sure-kill zone. Please estimate the probability of container rupture.

p. (U) Please provide detailed fallout data on this concept to use as a measure of collateral damage.

ADW CONCEPT ANSWERS
CONCEPT 27 (U)
Existing Nuclear Stockpile Options
J. F. Cuderman, Steve Schafer, Al Baker—Sandia National Laboratories

1. (U) PHYSICAL CHARACTERISTICS

   a. (U) External Dimensions:
   B61-7: 142"long, 13.3" OD; B83: 145"long, 18"OD;
   W80 CM Warhead: 31.5 "long, 12.75" OD.

   b. (U) Case Thickness:
   Not Applicable to non-penetrator systems

   c. (U) Quantity and characteristics of ADW materials:
   Nuclear Package

   d. (U) What is toxicity of the by-products:
   Radiation

   e. (U) What are moments of inertia:
   B61-7: Pitch and Yaw: 819 lb-in^2; Spin: 15,000 lb-in^2
   B83: See Fig. 1

   f. (U) How much HE, if any, and what type:
   Not applicable to nuclear systems since it is not significant part of the ADW material

   g. (U What type of propellant is used:
   Not applicable to these nuclear systems

   h. (U) Overall weight:
   B61-7: 765 lb
   B83: 2467
   W80 CM Payload: 300 lb

2. (U) FUNCTIONAL CHARACTERISTICS

   a (U) Volume or area affected by weapon:
   Depends on yield, height of burst

   b. (U) Effect of dust, debris, and other contaminants:
   Little or none

   c. (U) Weapon outputs associated with each weapon and yield combination:

DERIVATIVE CLASSIFIER:
R. B. COX 2161, Adv. Sys. Development
Date: 8/1/96
Sources: SAND 79 - 2452, 7/81
SAND 77 - 0173, 2/78
CGW-5 Class. Pol. Guide 11/8

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Unauthorized disclosure subject to
Administrative and Criminal Sanctions. Handle
in Restricted Data in Foreign Dissemination
Section 144.b., Atomic Energy Act, 1954.

Radiation, heat, blast , shock—will be provided in effects calculations

[redacted]

DoD
6(3)

a. (U) Restrictions imposed by different weather conditions:
Only those which affect delivery system.

b. (U) Required intelligence:
Target structure, BDA

c. (U) Special handling requirements
Approval by National Command Authority, Nuclear weapon handling procedures.

d. (U) Shelf life of the system :
Indefinite—intent is to maintain stockpile as long as necessary

e. (U) Time required to prepare for launch:
Depends on approval time, state of readiness of weapons and delivery systems.

f. (S) VN and GVN numbers for targets:
See **Attachment 1**

4. (U) Questions Regarding Cost:
These systems are already in stockpile. Therefore there are no development costs involved. In any event, costing is a DOE, not a laboratory, function.

5. (U) Questions Regarding Program Management
There are no questions regarding program management since the weapons are already in stockpile. Any program management issues are handled by the appropriate POG.

6. (U) GENERAL COMMENTS
a. (U) Weapons Testing Completed:
All tests required for certification of the weapons "pre-Test Ban".
b. (U) Availability of defeat mechanism raw material:
In stockpile

c. (U) Reference material availability:
In Stockpile.

d. (U) Impact of missing target on weapon function:
None.

e. (U) Characteristics of expected radiation field.
See **Attachment 2** and Cris Cunningham's presentations

f. [redacted] DoD 6L31

g. (U) How were delivery accuracy's determined?
Full systems tests:

h. (U) Agent defeat mechanism footprint for effective neutralization:
A kill radius is proposed for open or "soft" containers above ground which is given by:

$$R = 145(kt)^{0.4}.$$

i. (U) Please relate a concepts effectiveness to ADW consolidated target list.
How many sorts of a given concept are needed to defeat or deny access to that target?
Effectiveness is a function of yield, HOB, and target characteristics. **Attachment 1** addresses effectiveness for the consolidated list. No need is seen to use more than one sort of a given concept/configuration on a given target. Under some circumstances, such as above ground missiles, ready for launch, a single weapon might take out more than one target.

j. (U) Energy spectra for calculations of effects in shielded bunkers:

k. (U) Collateral effects quantification:
Outside of the kill volume, whether above ground, or from ground shock, there exists no credible analysis to estimate collateral damage. There are just too many variables. It appears likely that it would be severe.

l. (U) Additional data on kill mechanisms for nuclear concepts:
See presentation by Steve Schafer

m. (U) Vaporization is a criteria, but spores heat resistant.....
See answer to 6-k., above.

n. (U) Provide some sure-thermal-kill radius based on the shock wave from weapon detonation and fireball temperature.
See 6-h.

o. (U) Estimated probability of container rupture outside of "sure kill zone":
Unity

p. (U) Detailed fallout data as a measure of collateral damage:
See Attachment 3 and Cris Cunningham's presentation.

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MASS PROPERTIES

		4 FIN	3 FIN
IXX	SLUG FT²	24.59	24.39
IYY	SLUG FT²	640.76	634.28
IZZ	SLUG FT²	640.76	634.28
CG	(IN)	56.12	55.97
WEIGHT	(LBS)	2464.43	2459.93

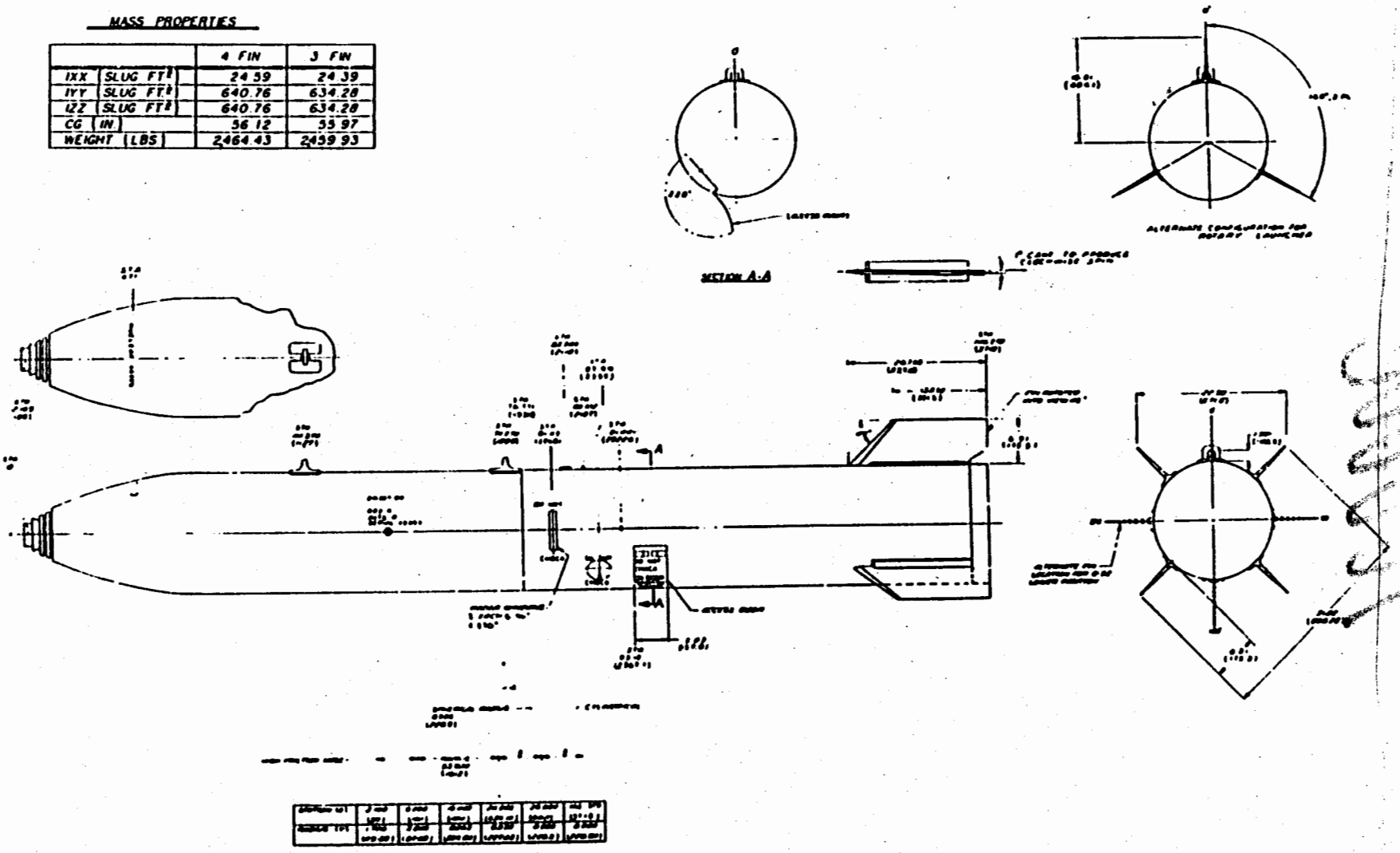

Fig.1 B83 Physical Characteristics

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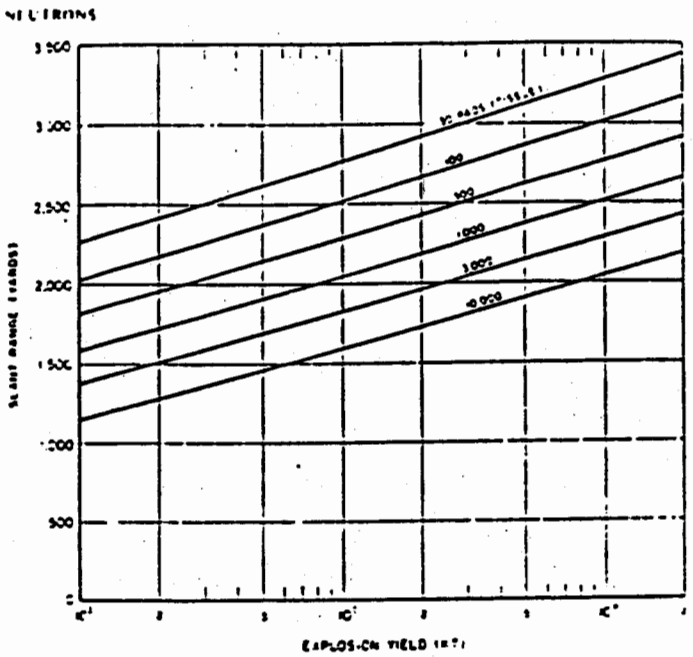
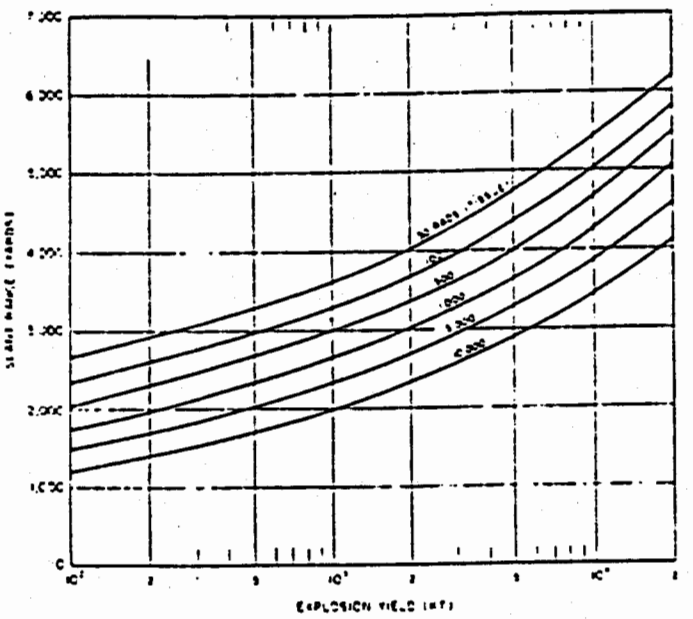
ATTACHMENT 2: Characteristics of Expected Radiation Field



Slant ranges for specified neutron doses for targets near the ground as a function of energy yield of air-burst thermonuclear weapons based on 0.9 sea-level air density (Reliability factor 0.25 to 1.5 for most thermonuclear weapons.)



Slant ranges for specified gamma-ray doses for targets near the ground as a function of energy yield of air-burst thermonuclear weapons with 50 percent fission yield, based on 0.9 sea-level air density (Reliability factor from 0.25 to 1.5 for most thermonuclear weapons.)

ATTACHMENT3: Fallout Data

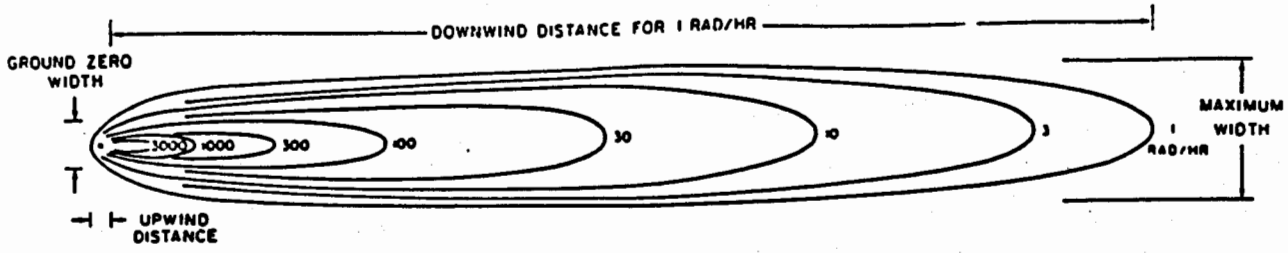


Illustration of idealized unit-time dose-rate pattern for early fallout from a surface burst (The contour dimensions are indicated for a dose rate of 1 rad/hr.)

SCALING RELATIONSHIPS FOR UNIT-TIME REFERENCE DOSE-RATE CONTOURS FOR A CONTACT SURFACE BURST WITH A YIELD OF W KILOTONS AND A 15 MPH WIND

Reference dose rate (rad/hr)	Downwind distance (statute miles)	Maximum width (statute miles)	Ground zero width (statute miles)
3,000	0.95 $W^{[illegible]}$	0.0076 $W^{[illegible]}$	0.026 $W^{[illegible]}$
1,000	1.8 $W^{[illegible]}$	0.036 $W^{[illegible]}$	0.060 $W^{[illegible]}$
300	4.5 $W^{[illegible]}$	0.13 $W^{[illegible]}$	0.20 $W^{[illegible]}$
100	8.9 $W^{[illegible]}$	0.38 $W^{[illegible]}$	0.39 $W^{[illegible]}$
30	16 $W^{[illegible]}$	0.76 $W^{[illegible]}$	0.53 $W^{[illegible]}$
10	24 $W^{[illegible]}$	1.4 $W^{[illegible]}$	0.68 $W^{[illegible]}$
3	30 $W^{[illegible]}$	2.2 $W^{[illegible]}$	0.89 $W^{[illegible]}$
1	40 $W^{[illegible]}$	3.3 $W^{[illegible]}$	1.5 $W^{[illegible]}$

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Detecting, Locating and Attacking Theater Ballistic Missiles During Boost Phase (U)

Derek A. Snyder, Retired
Raymond M. Zazworsky

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

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Detecting, Locating And Attacking Theater Ballistic Missiles During Boost Phase (U)

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Strategic Studies Center
Sandia National Laboratories
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ABSTRACT (U)

This report describes the results of a study that was funded under a Laboratory Directed Research and Development (LDRD) project to assess the capability of selected sensor-to-shooter architectures designed to detect, locate, and destroy enemy missiles during the boost phase portion of their flight. The basic architecture consists of arrays of seismic sensors that are deployed within suspected enemy launch areas to detect missile launches at long range, accurately estimate launch location and transmit this information to either ground or air platforms for subsequent intercept operations against the in-flight missile. Modifications to the computer model SENSEM (SENSor Evaluation Model) were made to simulate the complete process from detection to destruction. The sensitivity of mission effectiveness was evaluated for a number of important parameter variants such as sensor array size, detection range, and reaction time.

[redacted] intercept operations were found to be successful only when sensor location data were transmitted in a timely manner.

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Contents

Introduction 5
Scenario Development 5
Sensor Deployment Strategy 6
Sensor Requirements for Launch Detection and Location 8
Sensitivity of Sensor Requirements to Detection Range 10
Attack Options for Boost Phase Intercept 12
Ground Interceptor Results 14
Air-to-Air Interceptor 17
Conclusions 20

References 23

APPENDIX 24

Figures
1. SCUD Hide and Launch Areas 6
2. Offline Analysis - % Covered vs. Sensor Array Size 7
3. Deployment Patterns for 8 Sensor Array 8
4. Number of Sensor Detections vs. % Launches Detected 9
5. Distribution of Position Estimation Errors 10
6. Maximum Detection Range Sensitivity 11
7. TOA vs. Range to Sensor 12
8. Maximum Arrival Times - 16 Sensor Array 13
9. SCUD B Trajectory Performance 13
10. Ground Interceptor Protected Area 15

12. Ground Interceptor Capability vs. SCUD 17
13. AMRAAM Protected Areas 18
14. Aircraft Tracks 19
15. Air-to-Air Capability vs. SCUD 20
A1. Three Layer Model, TOA and Depth versus Range 24
A2. Launch Point Estimate 25
A3. Multiple Minima on Cost Function 26
A4. LPE Sensitivity - 10 km Case 29
A5. LPE Sensitivity - 2 km Case 29

Tables
1. Geology Inputs 9

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(U) INTRODUCTION

(U) Desert Storm experience alerted U.S. theater commanders to the fact that major deficiencies exist in our ability to detect and locate critical mobile targets on the tactical battlefield. Possible ways to reduce these deficiencies include the use of sensors of various types to detect and identify SCUDs (or other missiles) with enough timeliness and precision to cue effective counter-attacks before the missiles are launched. Issues pertaining to sensor capabilities and deployment in this situation were analyzed in Reference 1. Another possible defense is to use sensors to detect missile launch and communicate launch time and location information to missile defense systems that can intercept and destroy the missile in-flight. The effectiveness of this defense will depend on sensor and interceptor performance and deployment parameters. The path from concept to a fielded, effective system is arduous, but a simulation analysis, such as is reported here, can provide ballpark figures that will be useful to system designers and operational planners.

(U) This report, as indicated, describes the results of a simulation analysis to evaluate a sensor-to-shooter architecture designed to detect and destroy tactical ballistic missiles (TBMs) during their boost phase. To perform the analysis, the previously-developed SENsor Evaluation Model (SENSEM) code[2], which was written to simulate the detection and identification of critical mobile targets, such as SCUD launchers in transit, was extended to simulate launch detection and boost-phase intercept.

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nterceptor ability was estimated as a function of the time delay from missile-launch to interceptor cue.

(U) SCENARIO DEVELOPMENT

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(U) SENSOR DEPLOYMENT STRATEGY

(U) Seismic sensors that have been used in the past to detect and locate Lance missile launches at White Sands Missile Range (WSMR) typically use accelerometers and geophones to measure the low frequency signature of the acoustically-coupled seismic energy associated with the first burn of the rocket motor. Although propagation times are a function of terrain type, detection ranges of 8-10 kilometers have been demonstrated[4]

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in some of the tests conducted at WSMR. Based upon discussions with sensor hardware experts, a detection probability of 0.9 was assumed for launches within the maximum detection range of the sensor. Launches outside this range were given a detection probability of 0. A value of 10 km was used as the base case maximum detection range but was varied in subsequent cases in order to evaluate the sensitivity of sensor array performance to detection range.

(U) Although each sensor has a high probability of detecting a launch within its maximum detection range, detection by at least 3 sensors is required in order to obtain an estimate of the launch location. The magnitude of the position estimate error can be reduced significantly as more and more sensors are within range of the launch site.

(U) In an attempt to place the seismic sensors in the most optimum position on the battlefield, an off-line analysis was done to examine the percent of area covered by sensor fields of various numbers. The total launch area was divided into 100 m x 100 m grids and various patterns of sensors (characterized as circles with 10 km radii) were deployed and the percent of the grids covered by 3 or more sensors was calculated for each sensor array size and type of pattern. Arrays of 4, 8, 16 and 24 sensors were assumed for the analysis. The types of patterns (uniform, concentric circles, chain link, etc.) that were examined should not be considered exhaustive by any means, but represent a first order approach to improve deployment efficiency. The results of the off-line analysis are shown in Figure 2.

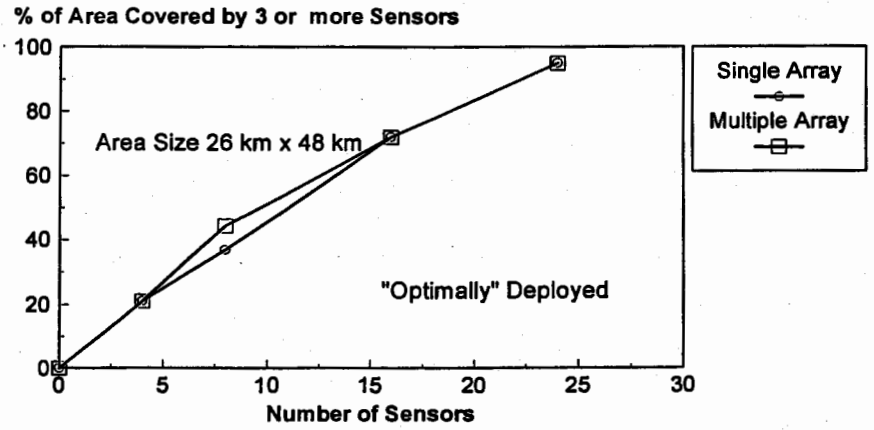

Figure 2. Offline Analysis - % Area Covered vs. Sensor Array Size (U)

(U) Of the patterns considered, the types that resulted in the maximum area covered are shown in Figure 3 for the 8 sensor array. For the 8 sensor array case, it was found that there was benefit in deploying the sensors in multiple arrays, i.e., two groups of 4 vs. one group of 8 (an 8 % increase in percent of area covered as shown in Figure 2). As the number of sensors in the array increases, both single and multiple patterns performed comparably in regard to percent of launches detected. The optimum spacing between

though, that while coverage may be enhanced by closely spaced sensors, such spacing could degrade launch location estimation. This is an area for future study.

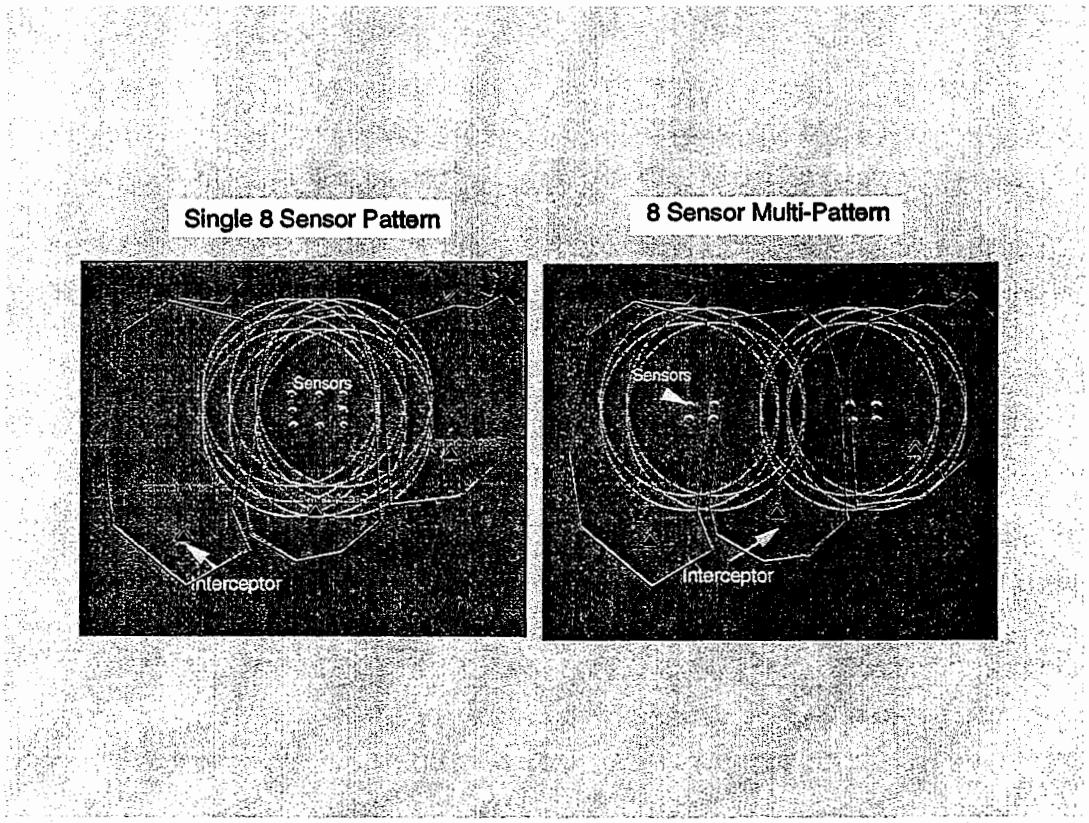

Figure 3. Deployment Patterns for 8 Sensor Array (U)

(U) SENSOR REQUIREMENTS FOR LAUNCH DETECTION AND LOCATION

(U) Sensor arrays were deployed across the three launch areas using the patterns discussed above and SCUD launcher tracks were generated using the SENSEM simulation. Multiple replications (50) were performed for a total of 200 launches and the percent of launches detected by 1,2,3,4,...., or 8 sensors was calculated. The base case results are shown in Figure 4 for a sensor maximum detection range of 10 km. No location solution is possible with less than 3 sensor detections, therefore the bar values for 0 (no detections) and 1 or 2 sensor reports represent detections only. The bars for 3,4,...., or 8 sensor reports represent the percent of launches for which detection and location estimates were made for the indicated array size. For example, for the 16 sensor array case, 19% percent of the launches were detected by only 2 sensors (no location solution) while 28% of the launches were detected by exactly 3 sensors and located after post-processing of the individual sensor data. The solid lines accompanying the bar charts sum the total percent of launches for which 3 or more and 4 or more sensors both detect and estimate launch location. As expected, the percent of launches for which position estimates are made increase as the number of sensors in the sensor array grows, e.g.

nearly 75% of launches are detected and located by 3 or more sensors for the 16 sensor case as opposed to 40% for the 8 sensor case. Note that increasing the sensor field from 16 to 24 sensors improves the detection/location percentage by only ~5% because the launch area is well covered(≥ 3 sensors) by the overlapping detection regions of the respective sensors. Regardless of the size of the sensor array, it was found that if 4 or more sensors detected a launch they almost always (99%) were able to estimate the launch location.

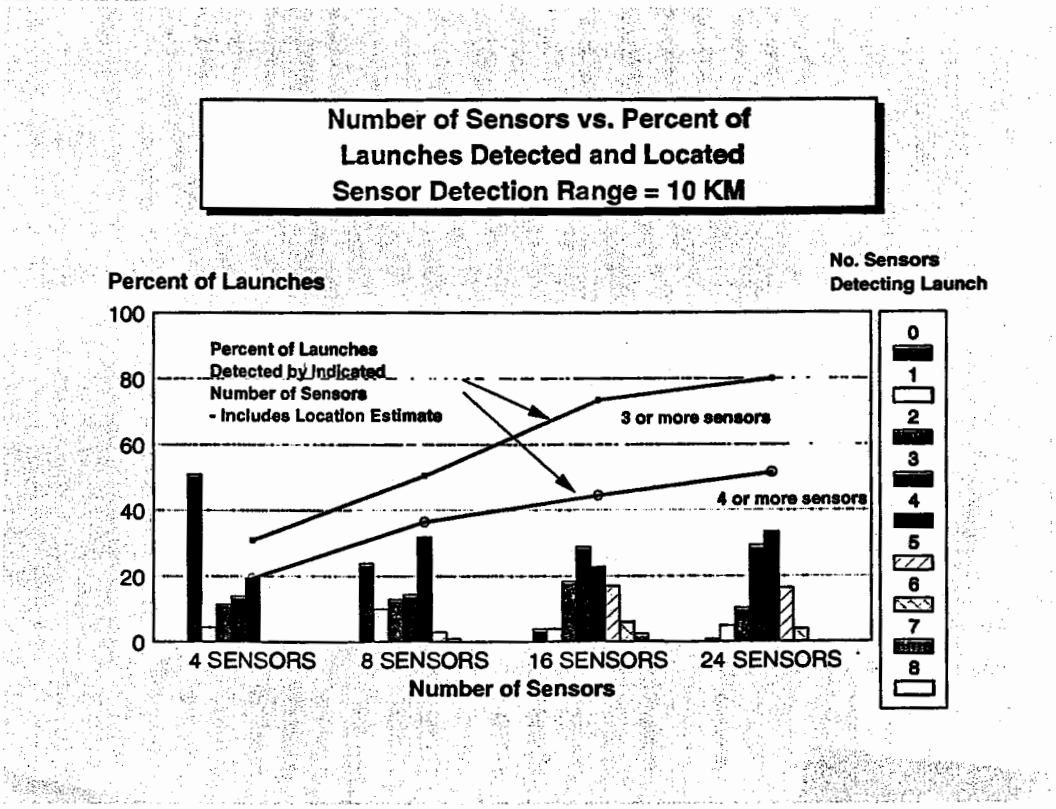

Figure 4. Number of Sensor Detections vs. % Launches Detected (U)

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(U) Increasing the number of sensors in the array has the beneficial effect of improving the accuracy of the launch location estimate. In Figure 5, for all the cases where a location estimate was made, the conditional cumulative distribution of position errors is shown for the different size arrays. The results show, e.g., that the median estimation error is 400 m for 4 sensors, 100 m for 8 sensors, and about 30 m for 16 sensors and 24 sensors. It should be noted that large position errors can occur, e.g., in excess of 3000 meters. These situations almost always occurred when only three sensors detected the launch and the launch point estimation algorithm failed to find a local minimum (see Appendix).

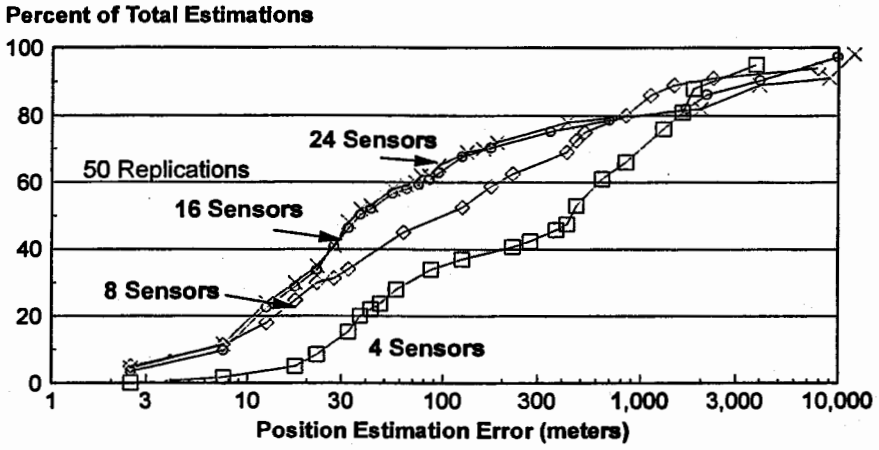

Figure 5. Distribution of Position Estimation Errors (U)

(U) SENSITIVITY OF SENSOR REQUIREMENTS TO DETECTION RANGE

(U) Additional calculations were made to assess the degradation in sensor array performance associated with smaller detection ranges. Although detection ranges of 8-10 km have been observed during test series, the base cases were rerun with a maximum detection range of only 5 km. The sensor deployment locations chosen for the base case (10 km detection range) were clearly not optimum for the 5 km case; therefore the off-line analysis was rerun for the latter case in order to determine more favorable sensor locations for use in the SENSEM model. The results of those calculations indicated that a deployment pattern similar to the base case was optimal for maximizing area covered by 3 or more sensors but modified by closer spacing between sensors.

(U) A comparison of sensor array effectiveness is shown in Figure 6 for both detection ranges. Sensor detection range is obviously a big driver in the performance of boost-phase sensor arrays. For example, with a detection range of 10 km, the 16 sensor array was able to detect and locate over 75% of the launches. However, when the sensor detection range was reduced to 5 km, only 20% of the launches were detected and located. Note that the area covered by a sensor is reduced by a factor of 4 when the detection range is halved, so, at least in the parameter region in which these calculations were done, there is a corresponding approximate factor of four decrease in the detect/locate probabilities.

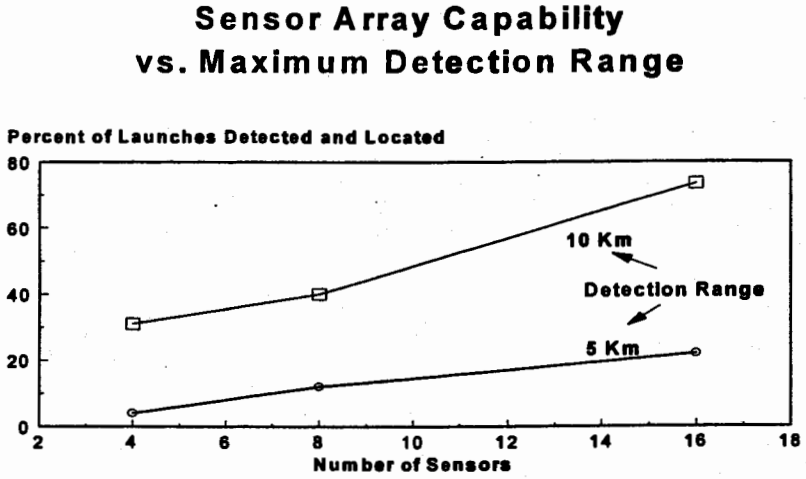

Figure 6. Maximum Detection Range Sensitivity (U)

(U) ATTACK OPTIONS FOR BOOST PHASE INTERCEPT

(U) The detection and location of enemy missile launches by seismic sensor arrays will be particuarly useful if they can be used to cue either ground or air platforms for subsequent intercept of the TBMs (Tactical Ballistic Missiles) while in the boost phase portion of their flight. Timeliness is crucial; therefore an analysis was done to determine the effect of time delay on interceptor effectiveness. One component of the time delay from TBM ignition until interceptor launch is the time of arrival (TOA) of the launch event signal at the sensor array. Figure 7 shows the TOA of the launch signal as a function of the range to the sensor for the geology assumed in this study.

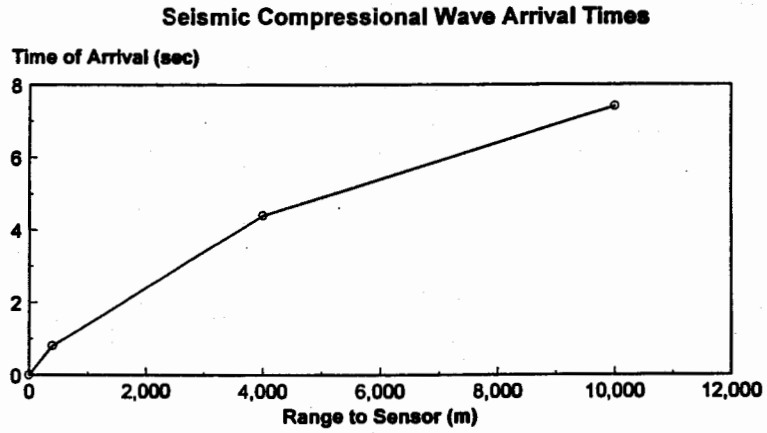

Figure 7. TOA vs. Range to Sensor (U)

(U) The observed cumulative distribution of arrival times (50 replications) for the 16 sensor, 10 km detection baseline case is shown in Figure 8. Since each sensor in an array that detects a launch event is located at a different range from the launch point, these arrival times in Figure 8 represent the TOA at the detecting sensor that is located at the maximum range. TOA curves for the baseline 8, and 24 sensor arrays are similar, i.e. launch event arrival times of 6-8 seconds were noted.

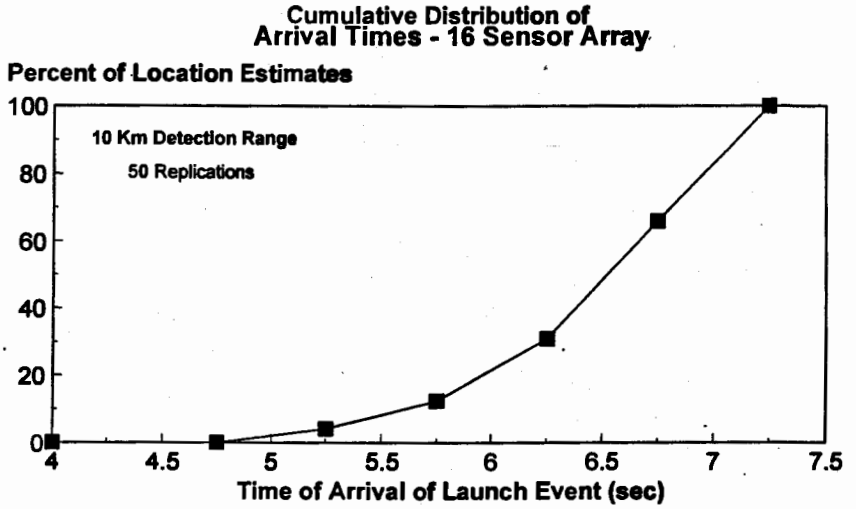

Figure 8. Maximum Arrival Times - 16 Sensor Array (U)

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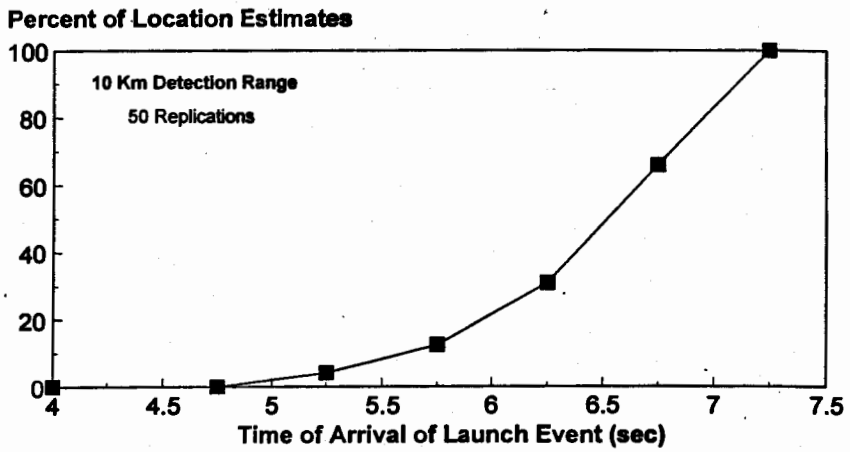
(U) Detailed Command, Control and Communication (C3) architecture requirements for data transmission between sensors and interceptor platform were not considered in this study. Rather, it was assumed that a seismic sensor array could receive the launch signal



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(U) Air-to-Air Interceptor

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(U) CONCLUSIONS

(U) The results of this study indicate that a moderately small number of capable, reliable, well-placed seismic sensors could successfully detect and locate enemy TBM launches.

(U) The key assumptions underlying this conclusion area:

a. sensors can be suitably emplaced in the launch region and will be operational at the time of launch.
b. sensors will be able to identify TBM launches over the detection range and with the reliability modeled in the simulations.
c. the geology of the launch area is well-represented by the model used in estimating launch location.
d. there are no ambiguous signatures when near-simultaneous launches occur.

(U) In the baseline case, sensors with 10 km detection range and .9 reliability each covered about 25% of the launch area and a 16 sensor array was able to detect and locate ~75% of all launches. If the detection range is only 5 km, then only about 25% of the launches in the scenario studied can be detected and located. In general, launch detection

by four or more sensors is required to provide accurate location estimates, so the density and overlapping patterns of the sensors are important determinants of array performance. In this study, for 16 sensors the density is 16/(25*50)=1 sensor per 78 km^2, and this figure might be used to provide a rough estimate of sensor requirements in other launch scenarios. Neither the launches nor the sensors were uniformly distributed throughout the launch area in this study, so 'results may vary' in other applications.

(U) In summary, two components of this proposed boost-phase sensor-to-shooter architecture were analyzed. The detection and location phase seems promising although some risks are inherent, such as geology uncertainty, and a variety of issues pertaining to sensor emplacement, performance, and data processing would need to be resolved. On

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(U) In summary, two components of this proposed boost-phase sensor-to-shooter architecture were analyzed. The detection and location phase seems promising although some risks are inherent, such as geology uncertainty, and a variety of issues pertaining to sensor emplacement, performance, and data processing would need to be resolved. On

REFERENCES

1. Sensor Data Fusion for Location of Critical Mobile Targets (U), D.A. Snyder, J.I. Crowther, SAND94-0726, Secret, April 1994.

2. Sensor Evaluation Model (SENSEM) User Manual (U), Sandia National Laboratories, Nov 1996, Unclassified.

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4. Seismic and Acoustic Measurement of a Lance Missile Launch - WSMR, Aug 10-11,1992 (U), R.S.Harding, Sandia National Laboratories, November 25, 1992, Unclassified.

5. Ballistic Missile Threat Specification (U), BMDO, June 1994, Secret.

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APPENDIX

SENSEM Launch Point Estimation

A subroutine that estimates the launch point of a theater missile using unattended seismic/acoustic ground sensors was incorporated into the SENSEM model. The algorithm in the subroutine is based on a simple parallel plane geology model which assumes that the local geology can be represented by three parallel, homogeneous layers of soil or rock (Figure A1) with fixed sound speeds (c_1, c_2, c_3) and depths (d_1, d_2). The locations of the sensors (four are shown in Figure A1, and at least three are required) are assumed to be known (input by the user) within some given random error. A source location (the origin in Figure A1), also input by the user, is used with the geology model to calculate an "actual" arrival time at each sensor for the seismic signal generated by a missile launch. This arrival time is perturbed by a random measurement error to obtain a simulated measurement of the arrival time at each of the sensors. The measured time-of-arrivals (TOAs) are then used to estimate the source location by finding source locations which minimize the sum of the squared differences between the calculated and measured TOAs. Generally, there may be several potential source locations that give local minima of the sum of the squared TOA errors. The subroutine looks for these multiple minima by examining source locations on a grid whose size is determined by the maximum range of the sensors. The source location with the smallest local minimum is taken to be the most promising source location.

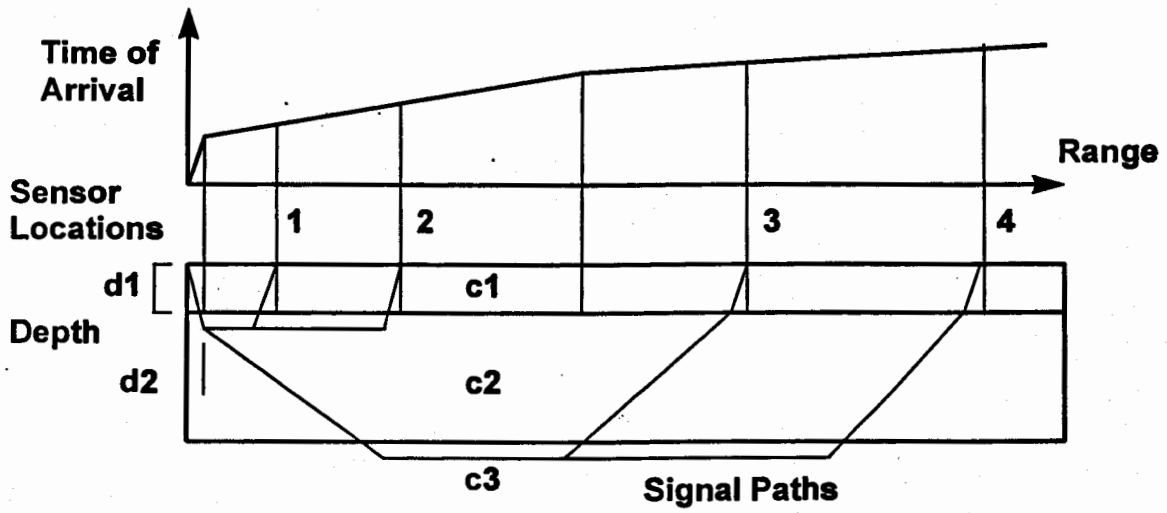

Figure A1. Three Layer Model, TOA and Depth versus Range

The process for locating the launch point is illustrated in Figure A2 where there are four sensors located (in meters) at (-1000,0) (red square), (0,1000) (dark blue square), (1000,0) (green square), and (0,-1000) (light blue square). Since the location of these sensors can only be known to a certain accuracy, a random error (a standard deviation of the distribution of random errors input by the user) is added to the sensor locations. The "actual" source location is (750,500) which is at the center of the small white circle. For the given depths (d_1=100m and d_2=1000m) and sound speeds (c_1=500m/s, c_2=1000m/s ,

of Figure A2. The smallest TOA is for the green sensor which is taken as the reference sensor. The dark blue region in the figure represents the set of all source locations which are consistent with the dark blue and green arrival times and a measurement error standard deviation of 0.15 seconds. The corresponding red and light blue regions give sets of source locations which are consistent with the red and light blue sensors respectively. The intersection of these regions is the set of all source locations which is consistent with all of the arrival times and a measurement error standard deviation of 0.15 seconds. The multicolored subsets located within this intersection represent the size of the intersection region if the measurement error had been less than 0.15 seconds as defined by the color code in the upper left corner of Figure A2.

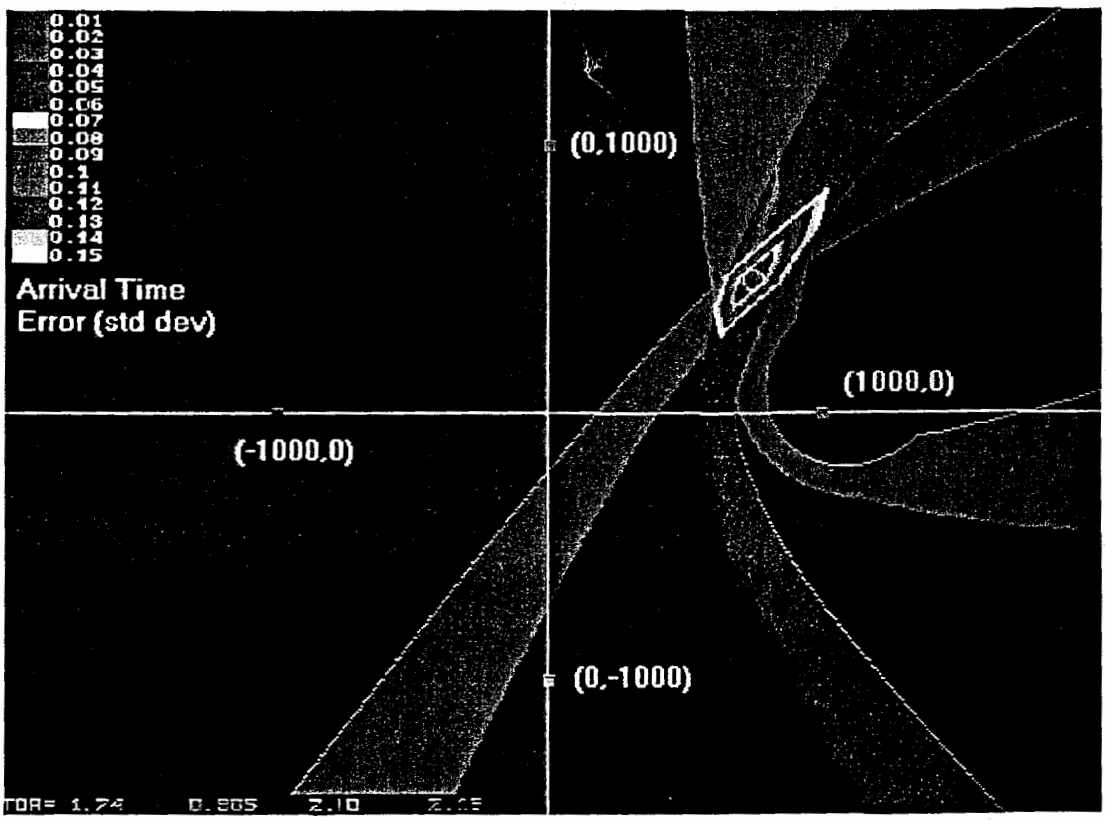

Figure A2. Launch Point Estimate

This example provides a deceivingly simple description for a situation that provides a unique local minimum that can be easily located using a convenient algorithm. However, this may not be the case for other sensor/source location combinations. Another example illustrated in Figure A3 uses the same three layer geology model, but places sensors at (-1000,1000), (-1000,-1000), (1000,1000), and (1000,-1000) and a source at (1400,1200). In this case, the red sensor is the reference sensor. The color coding is associated with the value of the sum of the squared TOA errors which shows two local minima. As mentioned above, the algorithm used in the launch point estimation subroutine will choose the minimum with the smallest squared error. It should be noted that, depending on the grid resolution and the separation of the minima, this may not correspond to the actual source location.

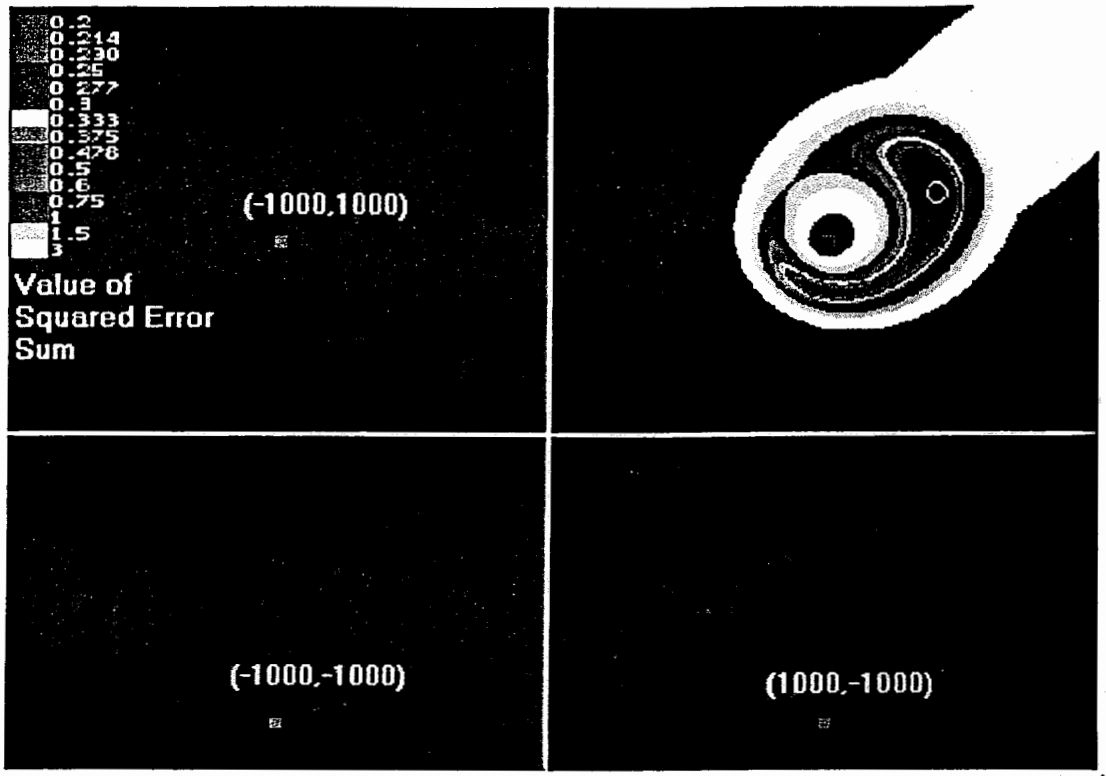

Figure A3. Multiple Minima on Cost Function

Launch Point Estimation for a Three Layer Model

Truth Model TOA:

The "actual" time of arrival (TOA) of the seismic signal at a sensor located a distance r from the source location is

$$\text{TOA} = t_{oa} = \frac{2d_1}{c_1 \cos\theta_1} + \frac{2d_2}{c_2 \cos\theta_2} + \frac{1}{c_3}\left[r - 2(d_1 \tan\theta_1 + d_2 \tan\theta_2)\right] \qquad (1)$$

where d is the thickness, c is the sound speed, and θ is the refraction angle at the respective layers.

Let θ_{1m} and θ_{2m} be the refraction angles in layers 1 and 2 which minimize t_{oa}. Then

$$\sin\theta_{1m} = \frac{c_1}{c_3}$$
$$\sin\theta_{2m} = \frac{c_2}{c_3} \qquad (2)$$

If c_1 or c_2 is greater than c_3, the minimum time path will never be through layer 3. Also,

acoustic time of arrival = r/c_0 (3)

surface wave time of arrival = r/c_1 (4)

1st refracted wave TOA = $$\frac{2d_1}{c_1 \cos\theta_{1m}} + \frac{1}{c_2}\left[r - 2d_1 \tan\theta_{1m}\right] \quad (5)$$

2nd refracted wave TOA =

$$t_{oa} = \frac{2d_1}{c_1 \cos\theta_{1m}} + \frac{2d_2}{c_2 \cos\theta_{2m}} + \frac{1}{c_3}\left[r - 2(d_1 \tan\theta_{1m} + d_2 \tan\theta_{2m})\right] \quad (6)$$

If more than three layers are included in the model,

nth refracted wave TOA =

$$t_{oa} = \sum_{i=1}^{n-1} \frac{2d_i}{c_i \cos\theta_{im}} + \frac{1}{c_n}\left[r - 2\sum_{j=1}^{n-1} d_j \tan\theta_{jm}\right] \quad (7)$$

The actual TOA will be the minimum of the above TOAs.

Measured TOA:

The "measured" TOA, t_{oam}, is obtained for each of the sensors by taking the corresponding t_{oa} and adding a random measurement error (standard deviation input by user) that represents the accuracy of the sensor. The smallest of the measured TOAs is taken to be a reference and a relative measured TOA, rt_{oam}, is obtained. Corresponding to these relative measured TOAs there are relative actual TOAs, rt_{oa}. The sum of the squared differences between these two values will be used to determine a launch point estimate.

Launch Point Estimate (LPE):

Let $rt_{oa}(x,y)$ be the actual relative TOA obtained when the source is located at (x,y). Then a two dimensional search is performed over a region determined by the maximum range of the sensors looking for the local minima of the function

$$L(x,y) = \sum_{k=1}^{n_s}\left[rt_{oak}(x,y) - rt_{oamk}\right]^2 \quad (8)$$

where n_S is the number of sensors within range of the source. An error is issued if n_S is less than three.

For all of the local minima found in the region, the selected location estimate is the source location that gives the smallest value of L in the region. An error is issued if no local minima are found in the region which implies that the source may be at or outside the region's boundary.

Sensitivity of Launch Point Error to Model Parameters:

A potentially major source of error in the launch point estimate is uncertainty in the model of the underlying geology. A parallel layer model was used for the geology in all of the LPE calculations presented here. One part of the error is a result of deviations from the assumption that all layers in the underlying geology are parallel and homogeneous. Investigation of this type of error requires a much more sophisticated geology model and will not be examined in this analysis. Another part of the error is due to uncertainty of the values for layer depths and sound speeds. This is the focus of the following discussion.

The scenario involves four sensors with a 10 km range arranged in a box and separated by 10 km on each side of the box. Initially, a series of uniformly distributed random draws was made for the position of the launch point within this square. For each of the launch point draws, a second series of normally distributed random draws were made for the sound speed and layer depth deviations. These model parameter draws were defined by a three sigma percentage error (between 10 and 25%) and a mean value that were provided as part of the normal program input. Finally, for each speed and depth draw, a third series of draws was made for the normally distributed error in time of arrival (TOA). Then, a launch point estimate was obtained for each draw of launch point, layer parameters, and TOA. The mean and standard deviation of the LPE errors (distance from actual launch point) are illustrated in Figure A4 for the standard three layer model. The mean error with no model error is about 19 meters, but this increases by almost an order of magnitude as the three sigma error increases to 25 percent. It should be noted that a three sigma error of 25 percent implies a mean error of about 10 to 15 percent. Thus, geology uncertainties could have an appreciable effect on launch point estimation accuracy.

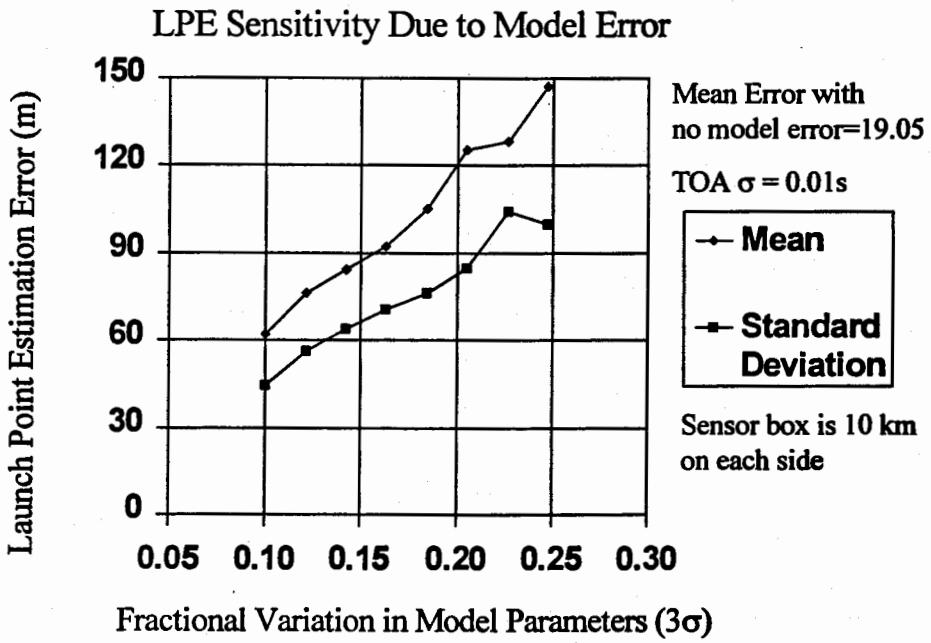

Figure A4. LPE Sensitivity - 10 km Case

A second case, with the sensors in a 2 km box, is provided in Figure A5 to illustrate the reduced sensitivity of the LPE when the sensors are more closely spaced.

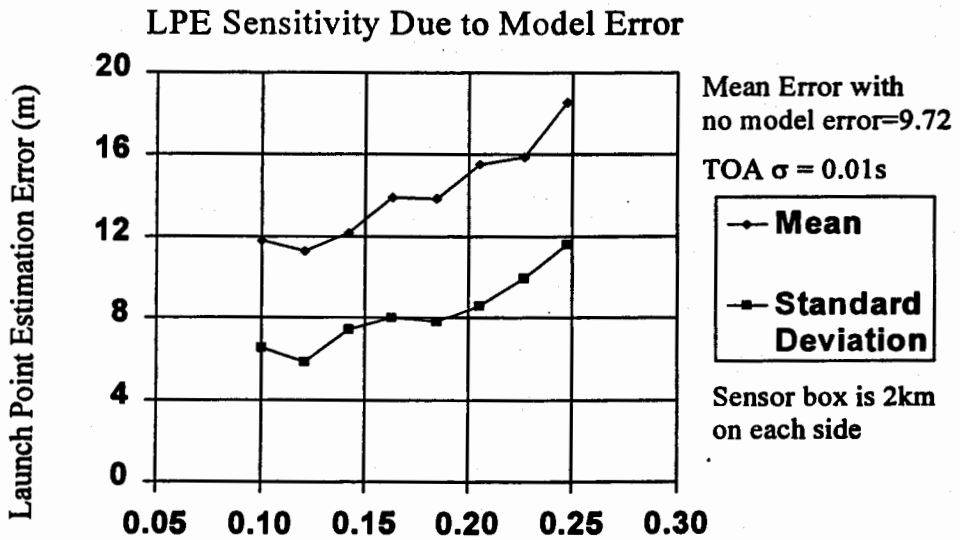

Figure A5. LPE Sensitivity - 2 km Case

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[redacted]

1. What initiatives are currently underway?

A. Tactical Unattended Ground Sensors (TUGS)

The TUGS program objective is to develop seismic, acoustic, and magnetic sensors for monitoring and characterizing underground facilities. Specific TUGS tasks are indications and warnings (detection of activity), equipment identification and location within the facility, and battle damage assessment. Hand emplaced sensor units will be developed for the Counterproliferation Advanced Concept Technology Demonstration (ACTD) in FY98. An air delivery capability will be developed in late FY98 and FY99.

Sponsor: Defense Nuclear Agency

POC: Brad Parks, (505)844-6883

B. Sensor Evaluation Model (SENSEM)

Sandia's SENSEM computer simulation model provides a means to investigate several important aspects of underground facilities. [redacted] Users also deploy packages of various types of ground-based sensors to collect intelligence on vehicle movements.

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Using SENSEM, users can represent operational activities of critical systems such as Multiple Rocket Launchers and tactical missiles as they move from underground hide sites to firing positions and return to hide sites. The utility of ground-based sensors can be evaluated in identifying and initiating the engagement of these targets during windows of vulnerability.

SENSEM can also be used to represent military and civilian traffic on the road network to include traffic patterns that might be characteristic of critical underground facilities. From these representations, investigations can be conducted of our ability to identify the location and operational status of important facilities through analysis of traffic patterns.

POC: Jim Crowther, (505)844-1206

C. Remote Induction of Signals into Power and Communication Lines

DOE-supported technology presently being developed addresses close-in survey to detect and characterize underground facilities. The present survey capability is very limited for covert operations. However, a closely associated capability has been demonstrated to be technically viable in the course of detecting and characterizing underground structures. This capability is remote signature coupling for two-way communication into and out of underground structures. The latter capability can support such intelligence needs as: (1) remote location of previously intercepted equipment acquired by a hostile operation and placed in service on the power grid at an unknown location; (2) covert transmission of operative messages or information from clandestinely installed sensors inside a facility; (3) intra-facility/sensor communication; (4) remote interrogation of a suspect power grid to estimate its linear extent to unknown termination points; and (5) (not yet demonstrated) remote imaging of the physical location and distribution of the power grid through induction of highly unique signals onto the suspect grid to facilitate remote tracking of segments of high interest.

POC: Dan Cress, (505)844-7182

D. Coherent Change Detection (CCD)

CCD is a technique that uses 2 complex radar images in a way that permits the detection of extremely subtle changes in the earth, e.g., vehicles traveling on dirt roads. This technique is currently being used to detect evidence of activity around sites such as chemical and biological facilities.

POC: Tom Prevender, (505)844-8768

E. Airborne Multisensor Pod System (AMPS)

AMPS consists of three pods carried on a P-3 Orion aircraft. AMPS Pod 1 contains a Synthetic Aperture Radar (SAR), AMPS Pod 2 contains a Multisensor Imaging system (MSI), and AMPS Pod 3 (in development) contains Effluent Species Identification (EFI) sensors. The data from the AMPS Pods can be used for Coherent Change Detection (CCD), or multisensor data fusion. The SAR Pod is being upgraded to an Interferometic SAR (IFSAR) using two antennas which will result in high-quality terrain elevation maps (3-D). AMPS has been used to observe underground facilities at the Nevada Test Site (NTS) through characterization of surface features such as ground subsidence, adit identification, and muck pile changes.

POC: Bob Huelskamp, (505)844-0496

F. Gravity Gradiometry

Variations in the local gravity field can be used as indicators of voids or structures underground. Measurement of the gravity field and its gradient can locate underground structures. Recent work has been directed toward both the improvement of the gravimeters used to measure the gravity field and the signal processing algorithms used to analyze the data.

POC: Bob Asher, (505)844-5900

2. What enhancements are needed?

[redacted]

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3. What special collection efforts need to be maintained/established/enhanced?

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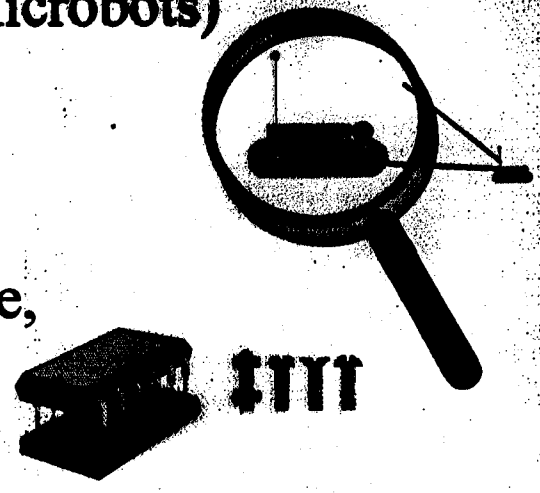
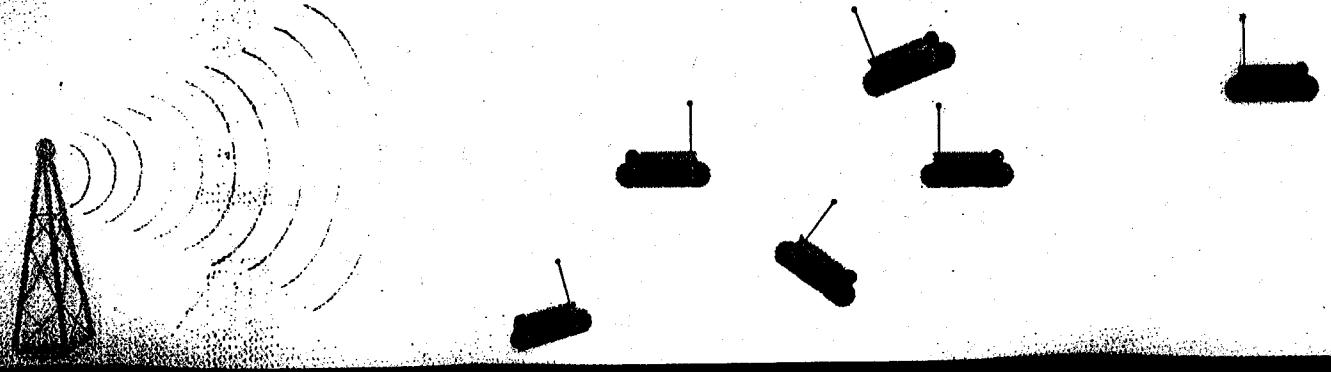
Microbots - Miniature Intelligent Robotic Vehicles

Miniature Intelligent Robotic Vehicles (Microbots) are mobile, intelligent, sensing platforms capable of performing such functions as: searching, following, target locating, detecting, target identification, intelligence, with stealth, miniaturization, remote control, remote transmission, and multi-agent cooperation as required.





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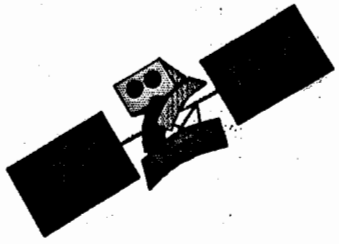
Micro Sensor Capabilities

- Imaging
- Seismic
- Acoustic
- Chemical
- Biological
- RF Tags
- Electromagnetic Field
- Radar
- Nuclear
- Accelerometer



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Microbot Missions - Phase I (cont'd)

- Other possible counterproliferation/intelligence applications
  - Determination of factory output (chemical, acoustic, electromagnetic, imaging, and biological sensors)
  - Location of underground structure air vents (imaging)
  - Attachment of microbot to TEL (chemical sensor, RF tags)
  - Location of high electrical power machinery (electromagnetic sensors)
  - Targeting of high value targets (imaging sensors, RF tags)
  - Locating and following communication lines (electromagnetic sensors)
  - Attachment of microbot to vehicles (RF tags, explosives)
  - Soil sample collection around secure sites
  - Counter intelligence perimeter control

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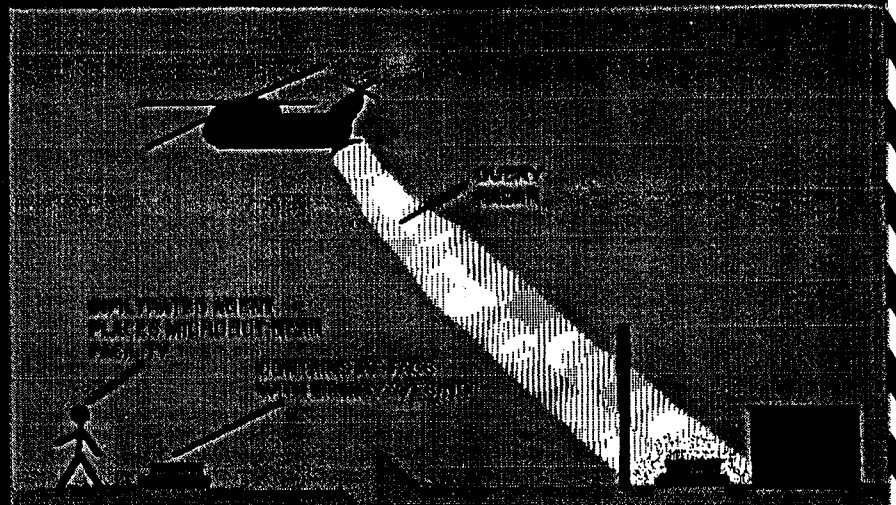
Microbot Concept of Operations



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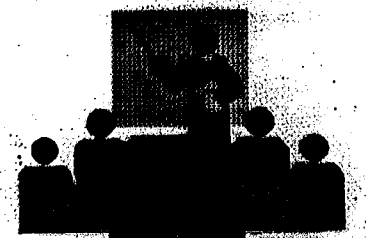
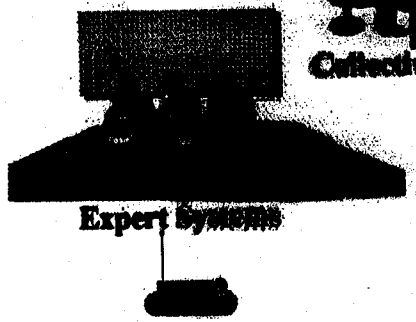
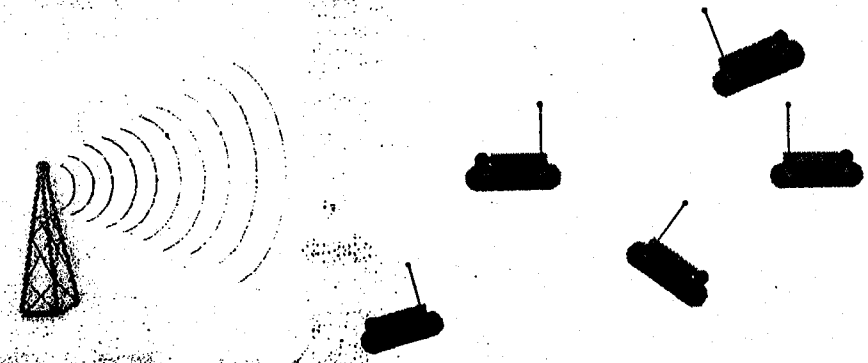
Behavior Algorithms

Simulations and systems have been developed which demonstrate group and cooperating algorithms using genetic programming, learning classifiers, neural networks, statistical hypothesis testing, fuzzy logic, and expert systems.







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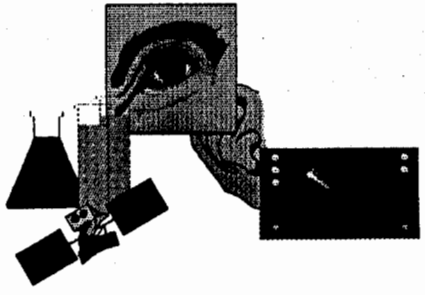
Sensor Fusion Process

Estimate Target Site Characteristics
Knowledge of Appropriate Sensor Measurands

→

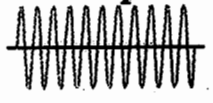
Risk Assessment
Sensor Data Acquisition Plan
(Sample Rate, Patterns, Filters, etc.)

↑ **New Estimates**



↓ **New Paths/ Sensing Locations**

Interpretation of Raw Data Using:



- **Expert Systems**
- **Physical Models**
- **Statistics**
- **Learning Algorithms**

(Neural Nets, Genetics, etc.)

←

Microbot Paths/Sensing Locations
Sensor Data Acquisition Control

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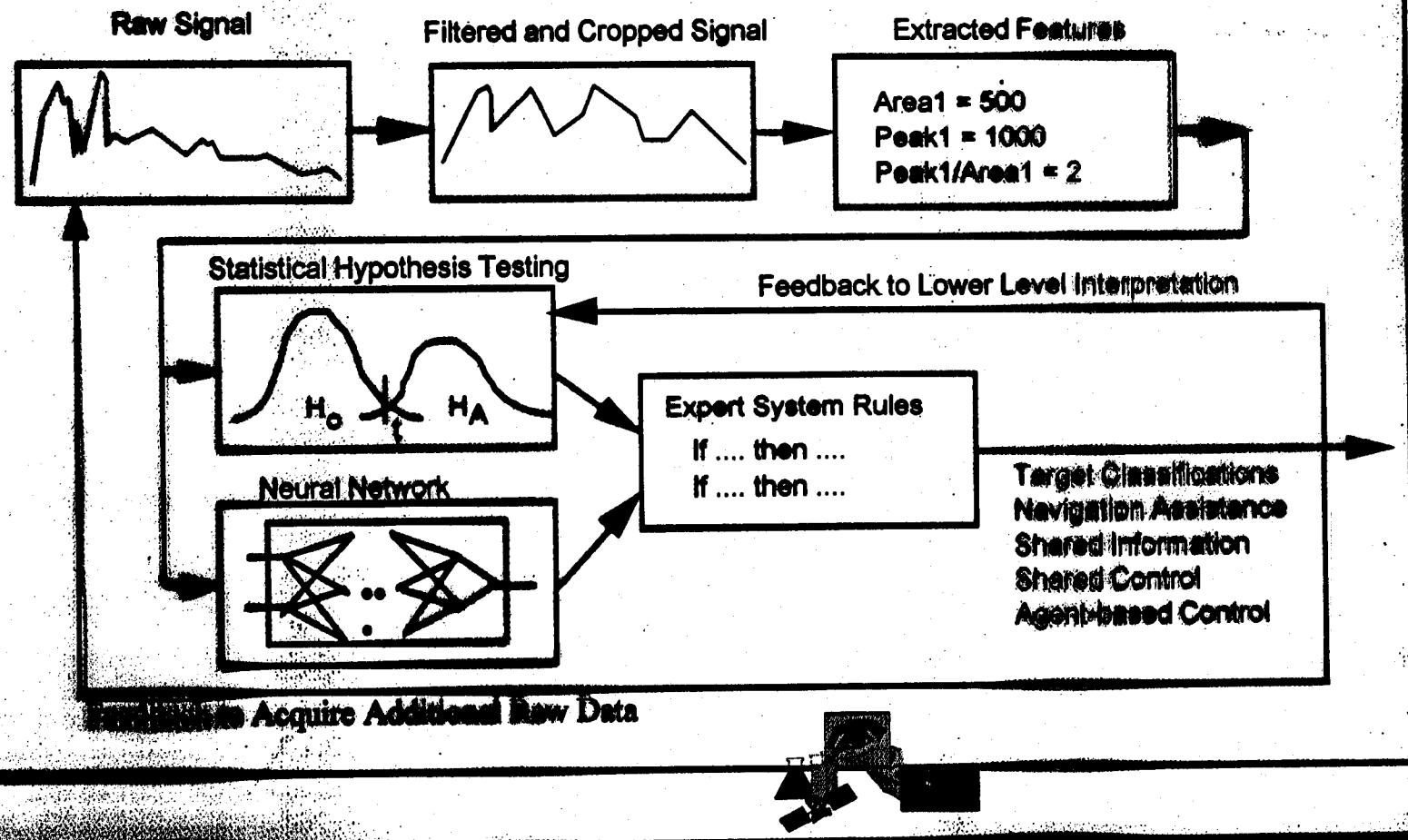
Data Fusion with Statistical, Learning, and Expert System Reasoning



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Miniature Intelligent Robotic Vehicle

- **Demonstrated experience in designing and building intelligent, miniature components**
  - **Miniature components machine shop**
    - **includes EDM (Electric Discharge Machine) and miniature machining facilities**
  - **Experience with neural networks, fuzzy logic, and genetic algorithm control systems**
- **Micromachining and microelectronics facilities**
  - **complete semiconductor fabrication facility**
  - **LIGA micromachine fabrication facility**

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Proposed Program

- Objectives
  - Systems study leading to arthitecture development which will include scenarios, concepts, design definition tradeoffs
  - Development of Phase I stealthed microbots - six each of the following:
    - 6 microbots with micro, imagers with low BW communications
    - 6 microbots with micro, chemical sensors and RF tags
    - 6 microbots with micro, seismic sensors and RF tags
    - 6 microbots with electromagnetic field sensors and RF tags
    - 6 microbots with micro, nuclear sensors and RF tags
    - 6 microbots with micro, acoustic sensors with low BW communications
  - Field tests of microbots
  - Further development of microsensors to include:
    - Micro, biological sensors (work is proceeding at SNL but project is underfunded)
    - Micro, low BW communications
    - Micro, acoustic sensors with low BW communications
  - Further development of micro fuel cells
  - Research and development of Phase II microbots

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2/8/96 One Page Total
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Proposed Program, cont'd.

- Cost/Schedule: Four year program at $2M/year
  - End of first year review and microbot demonstrations
  - End of third year - sensor development complete, delivery of 36 microbots
  - End of fourth year - demonstrate operational advanced concepts

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