OVERVIEW OF THE DEVELOPMENT OF CERAMIC ARMOR TECHNOLOGY- PAST, PRESENT AND THE FUTURE

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ARMOR CERAMIC WORKSHOP

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Paper Objective

THIS PAPER PROVIDES AN OVERVIEW OF THE DEVELOPMENT OF CERAMIC ARMOR TECHNOLOGY OVER THE LAST 40 YEARS WITH AN EMPHASIS ON THE MAJOR DEVELOPMENTS, PRESENT DESIGN FACTORS AND FUTURE DIRECTION AND ISSUES IN THE APPLICATION OF CERAMIC ARMOR TECHNOLGY TO GROUND, AIR AND SEA PLATFORMS

SCOPE

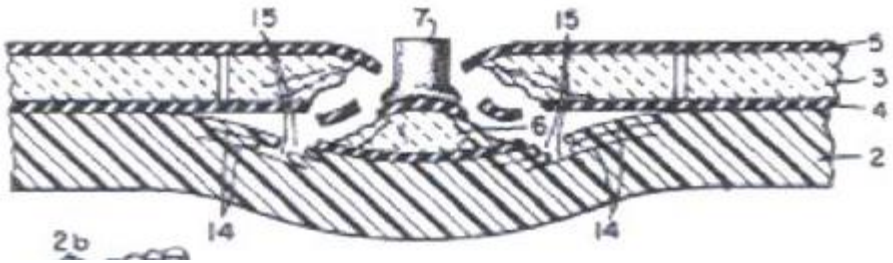
- **CHRONOLOGY OF THE HISTORY OF THE APPLICATION OF CERAMICS FOR COMBAT SYSTEMS: 1965-2005**
- **THE CHANGING THREAT ENVIRONMENT**
- **CERAMIC ARMOR DESIGN REQUIREMENTS**
- **APPLICATION OF CERAMIC ARMOR TO COMBAT SYSTEMS**

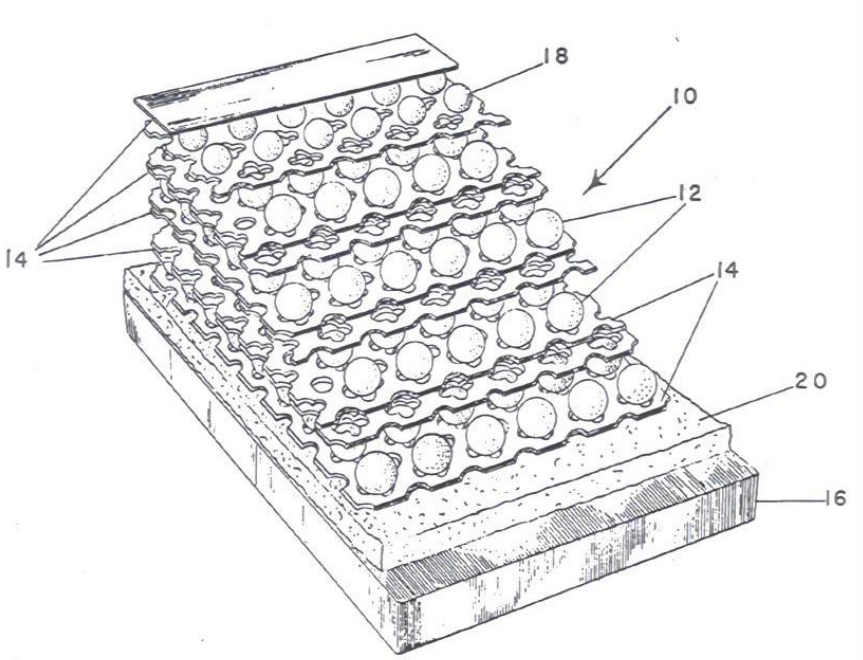
Early Ceramic Armor Research And Development

- This abbreviated chronology presents only the highlights of the extensive research work conducted on ceramic technology at DoD, DoE, Industry and academic centers.
- The main emphasis is on the development of ceramic armor technology for military application and is not a complete record of work.
- The chronology is as viewed from my standpoint and is somewhat subjective with my entry into these technology programs in 1970.
- I have interacted with many of the principals involved prior to and during this period.
- The intent is to examine the historical basis and current knowledge of ceramic armor systems to allow further increases in ballistic performance.

Patents of Goodyear Aerospace Company 1965 and earlier

- The earliest patented ceramic armor technology identified to date was by Goodyear Aerospace and took various forms.
- Shown here are two patents for 1) alumina balls in a polyurethane foam or 2) 85% alumina plates, both with woven/roven backings





Patent 3,509,833, Filed March 28, 1963, Issued May 5, 1970

Patent 4,179,979, Filed May 10, 1967, Issued December 25, 1979

Advanced Research Projects Agency Funding at Lawrence Radiation Laboratory 1967 - 1970

The work conducted by Wilkins, Landingham, Honodel and Cline on light weight armor is still considered a fundamental study today and should be reviewed periodically.

- Development of test facilities and extensive ballistic testing of a wide range of ceramic and cermet materials
- Effective application of then state-of-the-art diagnostic techniques for studying impact/penetration phenomena
- Development of theoretical models of material behavior and incorporation into a 2-D elastic-plastic computer code (HEMP)
- Development of a physical model to describe how a brittle-faced ceramic-faced armor defeats a hard projectile
- Extensive use of hydrocode calculations to support the design and analysis of experiments
- Pre- and post-test materials characterization
- Mechanical properties of armor ceramics at high pressures
- New materials (graded materials, BeO and Be-B compounds)

Vietnam Era Protective Vests 1965 - 1970

- The first fielded protective vests were for aircrews where weight was not a major issue:
  - 1965 - Reflective Laminates AD85 Alumina on woven/roven backing for helicopters
  - 1967 - Norton hot-pressed B_4C plates on woven/roven backing
- In 1968, the Natick Laboratory contracted with Carborundum for reaction bonded B_4C plates on a roven/woven backing for first ground force use
- The cancellation of the 30K vest order in 1970 underscores the cyclic military interest in body armor

Cobra Ceramic Helicopter Seat Armor 1969

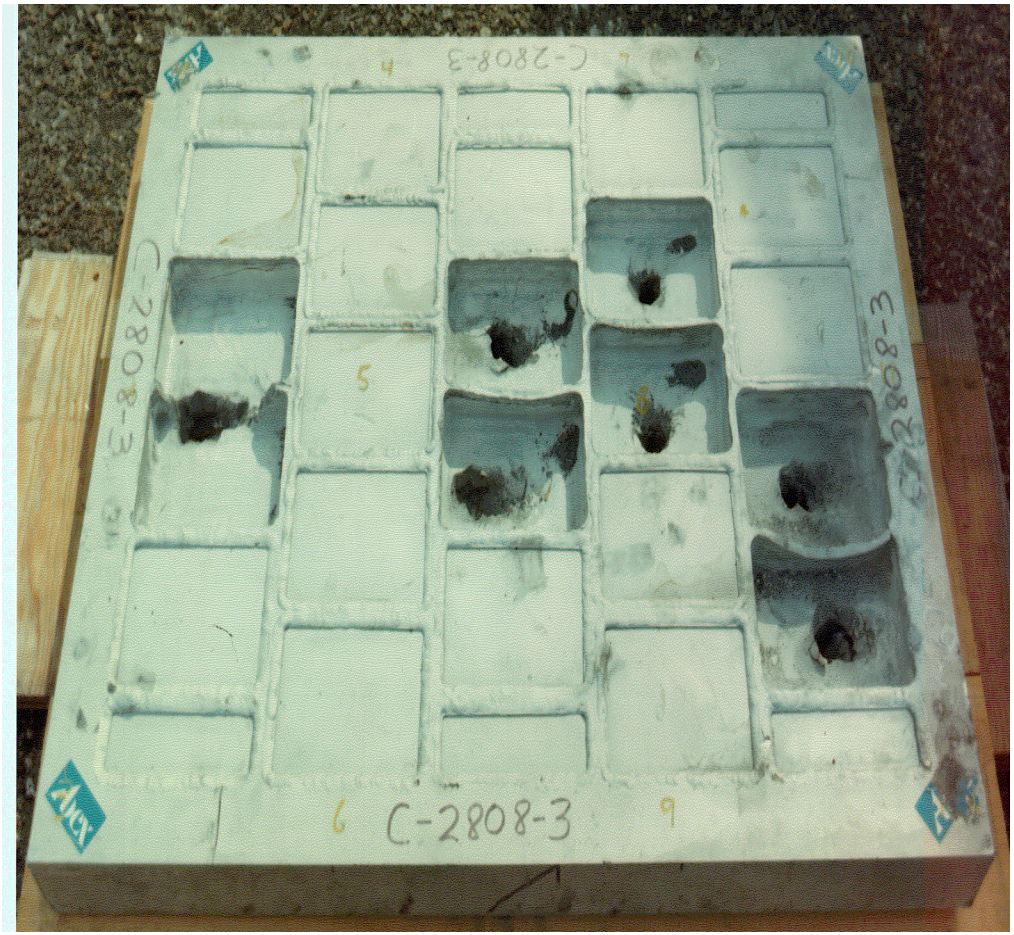
- The first true helicopter ballistic seats utilized Norton hot pressed B_4C on Kevlar 29 (1969)
- Ceradyne eventually bought out Norton armor ceramics and continues to produce hot pressed B_4C on Kevlar for the Cobra
- The armor design consists of large bonded and chamfered ceramic plates

The Down Cycle for Ceramic Production 1970-1983

- Little production of helicopter or ground force ceramic equipment after Vietnam era
- In 1979-1982, renewed interest by the Defense Advanced Research Projects Agency led to significant funding under what came to be know as the Roof Point ceramic program
- Significant DoD, DoE and Private Sector funding
- Many ceramic technologies had their origins during this period, some disappeared and some are with us today.
- The following five slides highlight developments still impacting current work

Aeronautical Research Associates of Princeton Technology on Ceramic Encapsulation - 1978

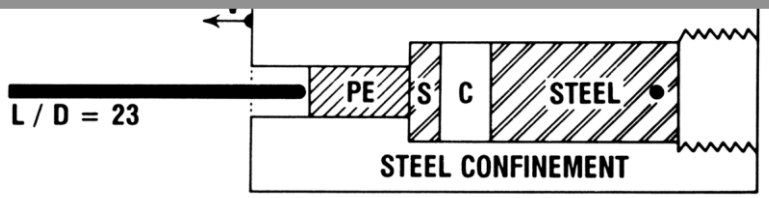
ARAP TECHNOLOGY TRANSFERED TO NORTON/ABEX
NORTON PRECISION HOT-PRESSED SILICON CARBIDE
ABEX PRECISION CAST ALUMINUM MATRIX

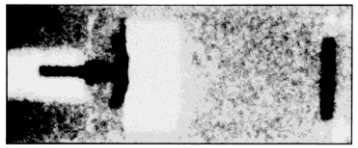


George Hauver at BRL Initial work on Ceramic Dwell Phenomena -1979

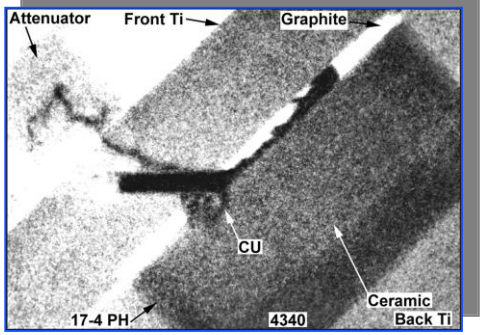
Laboratory Discovery :

penetrator defeat *without* penetration

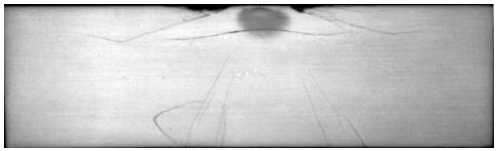




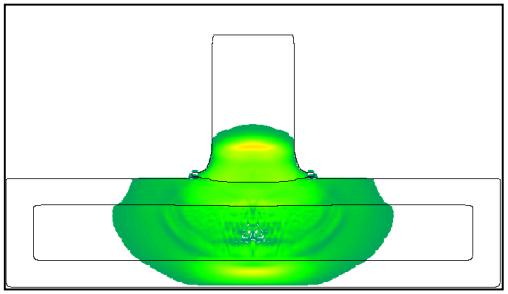
Exploratory Development

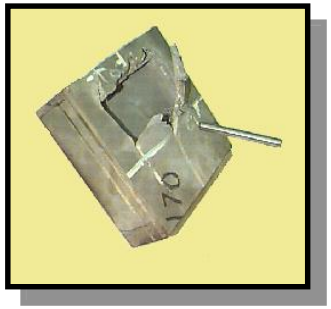


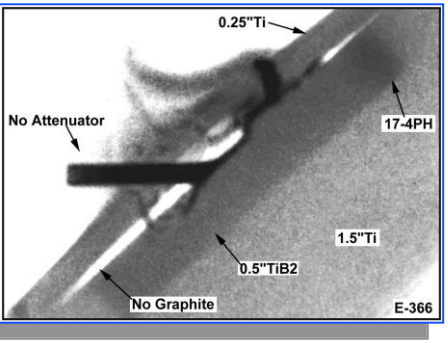
Experiment



Numerical Simulation







Encapsulated Ceramic Armor Product

US/UK/FR/GE Four Power Senior National Representatives Target Working Group 1979-Present

- International Working Group established by the DoD/MoD of each country to develop common targets for antiarmor development.
- The members are drawn from the research agencies of each country that were also responsible for development of each countries combat systems
- Many threat targets were ceramic, glass and composite based and resulted in a significant exchange of firing test data continuing to the present with > 4000 full scale tests
- The SNR Integrated Target Group is now a five power group with the addition of Italy

Army Materials and Mechanics Research Center 1979-1983

- **AMMRC emphasized the development of light weight armor materials that resulted in further commercialization in the private sector, particularly B_4C, SiC, TiB_2 and high purity AL_2O_3.**
- **AMMRC TR 81 "Ballistic Technology of Light Armor", last published in 1981, is still considered the primary data base for metal and ceramic composite test data.**

AH64 Apache Armored Helicopter Seat 1983

Simula Incorporated (Armor Holdings)
Cercom (BAE Advanced Materials)
Hot-pressed B_4C/Kevlar 49

DARPA Armor/Antiarmor Program 1985-1992

- DARPA initiated a major program to develop lightweight and heavy armor technology in industry and the DoE.
- This program injected large funding into many new programs
- New ceramic companies or technologies were started up to meet demands of program:
  - Cercom Incorporated started in 1985 producing B_4C, SiC, TiB_2, and WC by pressure assisted densification
  - Lanxide Corporation started in 1986 producing Dimox AS and AT by the Directed Metal Oxidation process
  - Dow Chemical developed aluminum nitride as an armor material
  - Coors Ceramics developed AD995 CAP3 high purity alumina
- DoD funding also increased significantly to Army laboratories and the understanding of the design requirements for ceramic armor technology advanced

Ceramic Armor Design Requirements
Main Ceramic Types (U.S.)

- **Sintered Ceramics**
  - Coors Cap-3 99.5% Alumina
  - Saint Gobain Alumina
- **Reaction-bonded Ceramics**
  - M-Cubed (Simula) RB SiC
  - Ceradyne RB SiC
- **Metal Matrix Composites**
  - Lanxide Dimox-AS
  - Lanxide Dimox-HT
- **Hot-pressed Ceramics**
  - BAE Advanced Materials B_4C, TiB_2, SiC, WC
  - Ceradyne B_4C, TiB_2, SiC

Ceramic Armor Design Requirements
Bonding/Impedance Effects

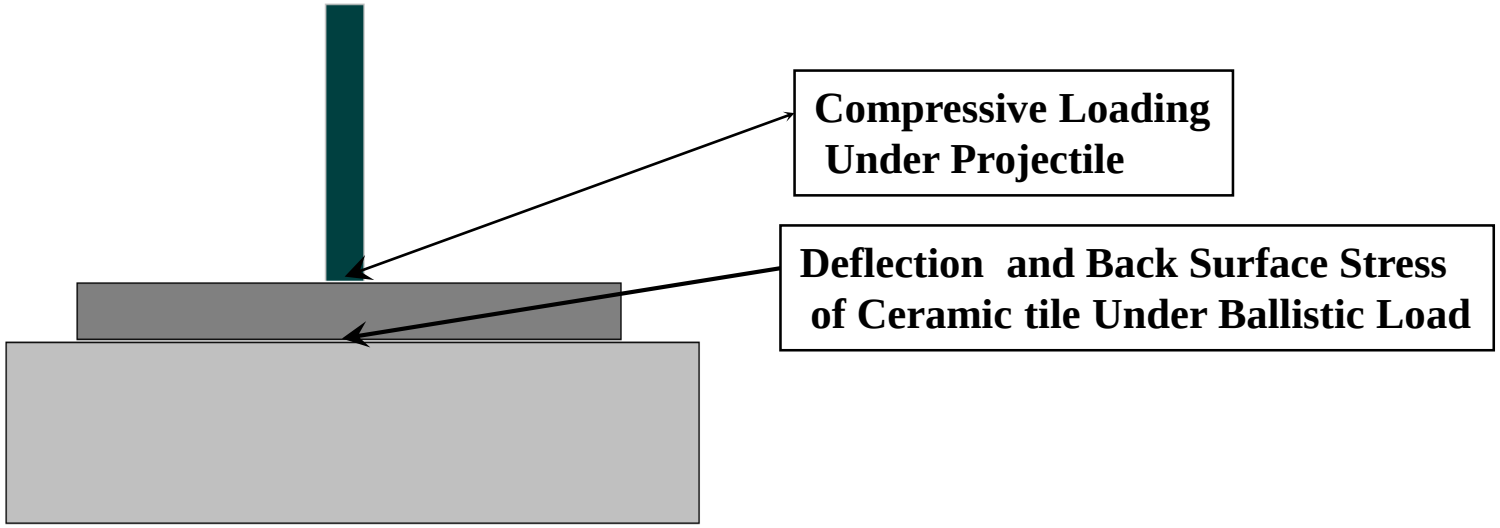
- Most Ceramic Composite Armors Are Adhesively Bonded Systems
- These Bonds Are Typified By Low-density, Low-impedance And Low-shear Coupled Interfaces
- In 1993, Furlong Presented An Exact Solution For The Transmission Of Spherical Waves Across A Planar Surface For Three Conditions:
  - Free Surface (Air)
  - No Shear Coupling (Two Unbonded Plates)
  - Shear Coupled/no Slip (Good Adhesion Allowing Transmission Of Stress And Motion)
- Shear Coupled Bonds Provided Best Interface

Ceramic Armor Design Requirements
Adhesive Thickness And Uniformity

- In 1995, Burkins Conducted A Taguchi Variance Analysis On DOP Tests With Three Variables:
  - Rear Interface Bond Thickness
  - Lateral Confinement Interface Thickness
  - Presence Of Cover Plate
- The Least Variance Occurred When The Bond Thickness And Confinement Gap Were Minimums
- ARL DOP Tests Were Modified To Incorporate Constant 0.127-mm (0.005”) Interfaces With Uniformity Controlled By Spacers In Adhesive

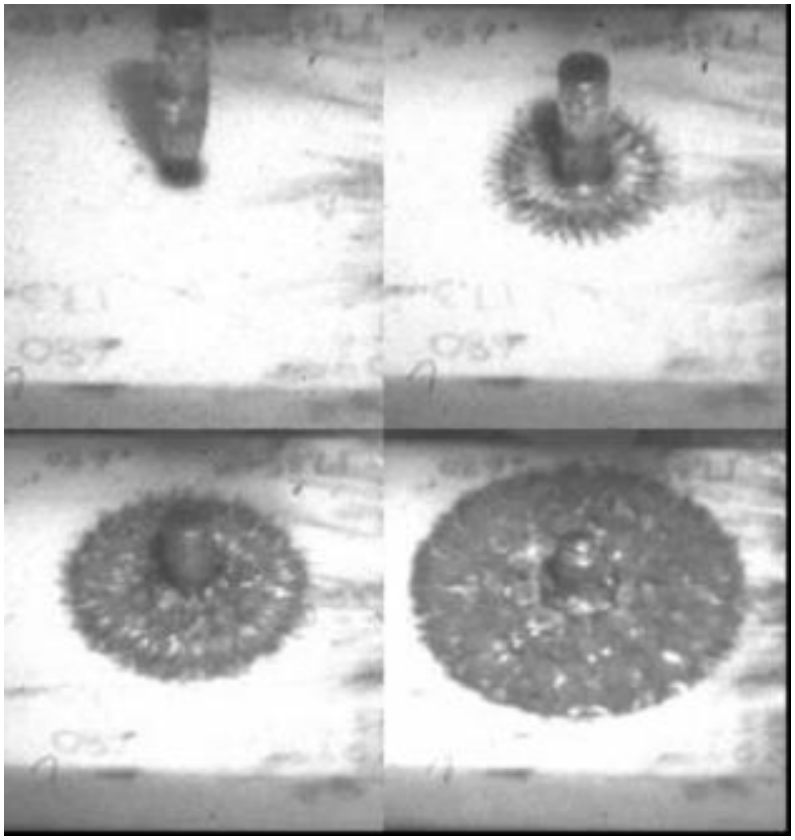
Ceramic Armor Design Requirements Confinement And Stiffness

- Failure of a ceramic tile is dependant on:
  - Compressional loading of the ceramic directly under the penetrator
  - Maximum flexure of ceramic plate and tensile stress/strain at the ceramic rear surface
- These factors are heavily influenced by the side and rear confinement material and stiffness



Ceramic Armor Design Requirements
Confinement And Stiffness

Dwell of hard-steel core APM2 bullet on an unconfined thick alumina tile. Photos courtesy of Southwest Research Institute (SwRI), San Antonio, TX



Ceramic Armor Design Requirements
Multi-hit, Edge And Joint Impacts

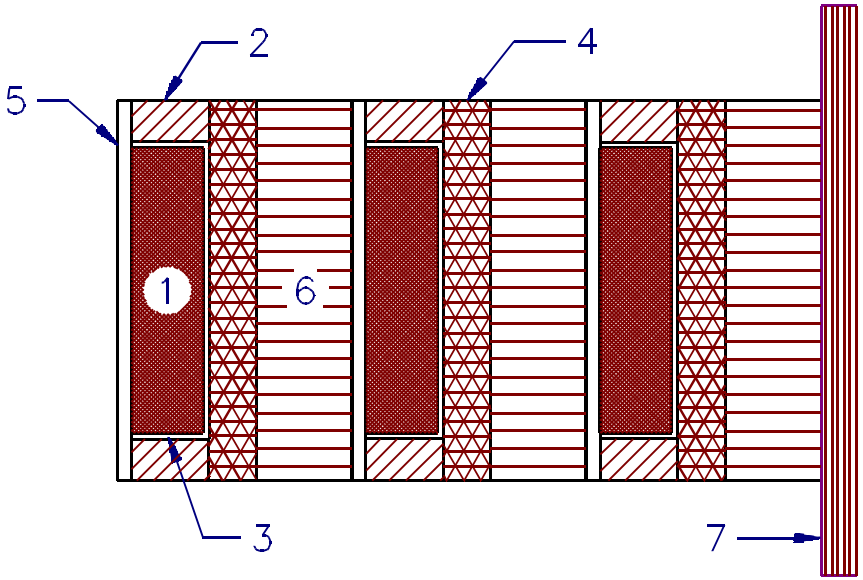
Multi-hit Requirements Are A Driving Design Factor As Tile Size Is Dependant On Impact Locations

WEAPON CALIBER	METALS AND METAL LAMINATES* (mm)	CERAMIC LAMINATES* (mm)
7.62-mm	27	54
12.7-mm	45	90
14.5-mm	51	102
20-mm	70	140
23- to 25-mm	75	145
30- to 50-mm	76 (105)**	152

*** Minimum spacing between impacts as measured from center to center of impacts in vertical plane**

**** Full bore AP bullets only**

Army Developments
ARL Tandem Ceramic Armor - 1990



TANDEM ARMOR SYSTEM

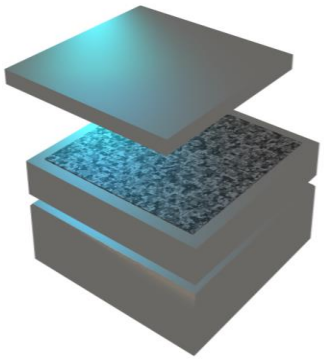
1. CERAMIC TILE
2. CONFINEMENT FRAME
3. POLYMERIC ADHESIVE
4. SUPPORTING PLATE (METAL/COMPOSITE)
5. THIN GRP SECTION (OPTIONAL)
6. HONEYCOMB/ISOLATION MATERIAL
7. VEHICLE HULL

- **Tandem ceramic armor overcomes ceramic failure limitations by limiting damage**
- **Optimum ceramic design is determined and repeated in tandem allowing the performance to be additive**
- **Significant energy absorption is possible**

Army Developments
Encapsulated Ceramics - 1992

WEAPONS AND MATERIALS RESEARCH DIRECTORATE

TERMINAL EFFECTS DIVISION



ARL continued research to move the dwell phenomena from the laboratory to application

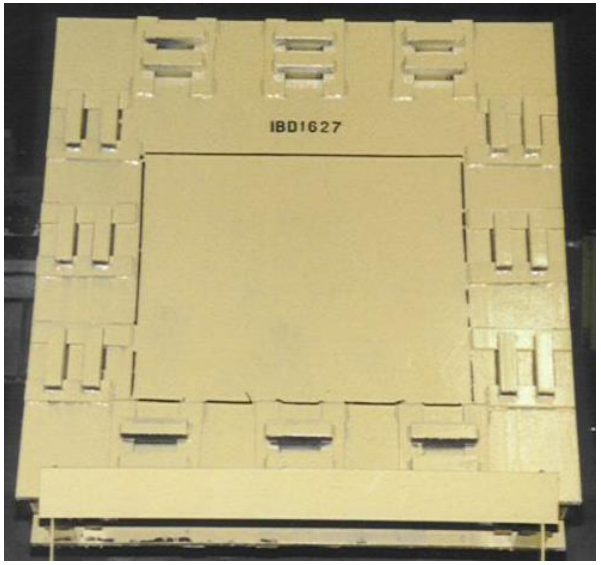
NO PENETRATION INTO TITANIUM BACK PLATE

REAR SURFACE OF TITANIUM COVER PLATE

Army Developments
ARL Full Scale Ceramic/glass Tests 1988-1991

- Full scale ceramic tests conducted with German firm of Ingenieurbüro Deisenroth (IBD)
- Full scale ceramic/glass targets tested at ARL
- Long term purchases of large ceramic tiles:
  - 450mmX450mmX100/200mm Coors CAP3 Alumina
  - 450mm X450mm X100mm Cercom SiC-B
  - 450mm X450mm X100mm Cercom TiB2

ARL ceramic/glass composite target

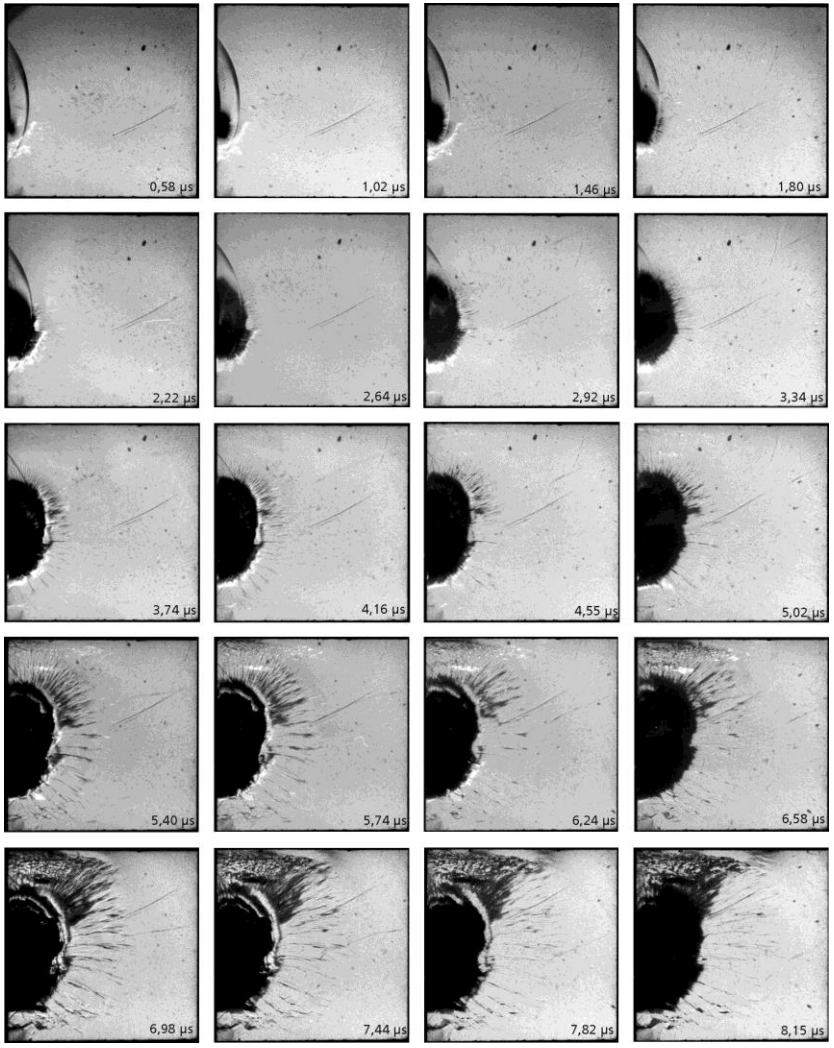


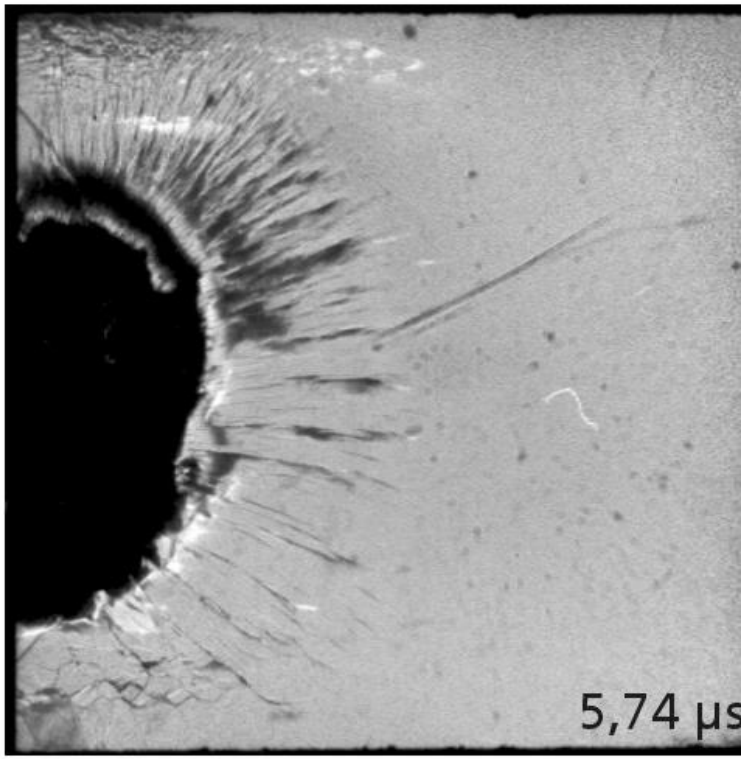
IBD ceramic composite target

Army Developments
ARL/German Ernst Mach Institute edge-on impact tests for analysis of crack propagation-1992

WEAPONS AND MATERIALS RESEARCH DIRECTORATE

DIVISION





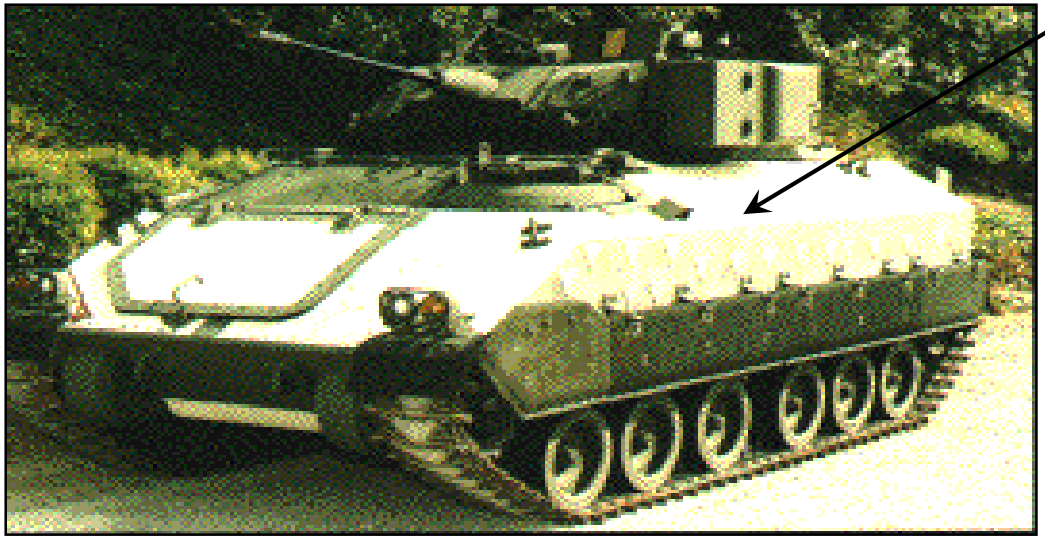
- 20 Station high speed Cranz-Shradin spark cameras
- Examined SiC, Al_2O_3, TiB2, WC, B_4C, glass, sapphire
- Recent testing of ALON

Army Developments
Composite Infantry Combat Vehicle - 1991

United Defense Limited Partnership (now BAE Systems Land Systems NA)

S2 Glass composite vehicle structure

TiB_2 Tiles for small arms protection



Ceramic Development 1992-2001

- **After the fall of the Soviet Union and the end of the first Iraq war, significant downsizing in research programs, manpower, funding and procurement occurred.**
- **This effect repeated the down turn seen at the end of the Viet Nam war.**
- **The Composite Armored Vehicle technology demonstrator was developed.**
- **One area of research and procurement that expanded was body armor.**
- **The Interceptor Body Armor program with the Special Armored Protective Insert (SAPI) started in 1996-1997 by Natick and multiple vendors were qualified in 1998.**

COMPOSITE ARMORED VEHICLE (CAV)

United Defense Limited Partnership
(now BAE Land Systems NA)

Ceramic Body Armor Inserts
1995-1999

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TERMINAL EFFECTS DIVISION

Ceradyne Incorporated

Interceptor Body Armor with SAPI 1996

Simula Incorporated (Armor Holdings)

VEST SYSTEM AND HARDFACE CERAMIC INSERTS

REACTION BONDED SILICON CARBIDE FROM M-CUBED WITH COMPOSITE BACKING

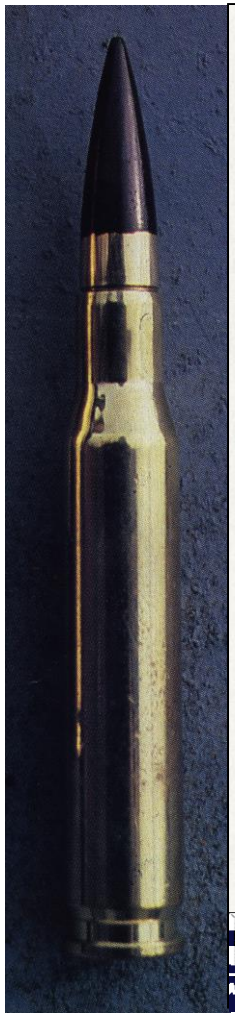
Multi-tile And One-piece Body Armor Plates 1995-1996

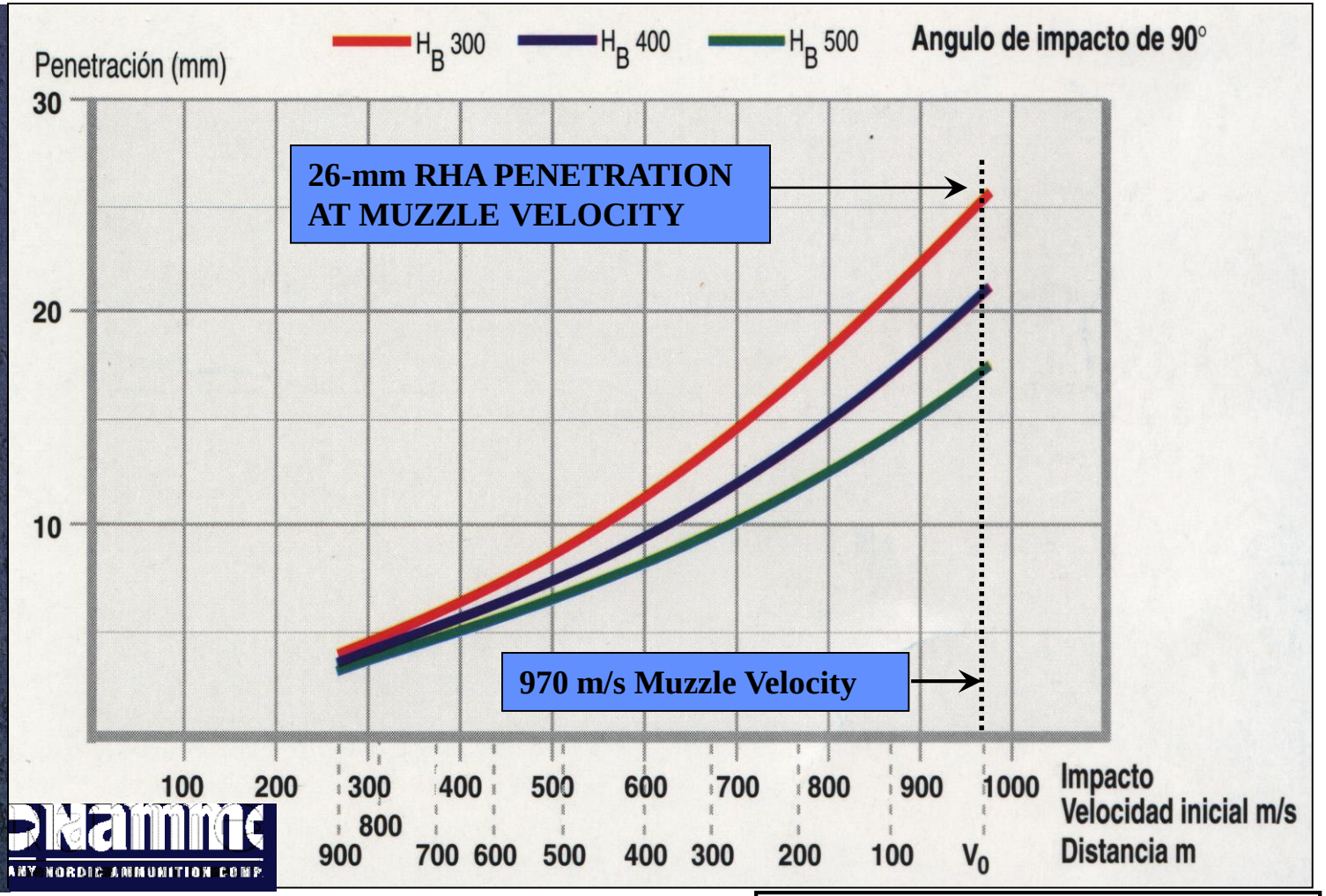
Cercom Incorporated
(Formerly United Defense, now BAE Advanced Materials)

Ceramic Development 2002-Present

- Future Army transformation is centered on the development of the Future Combat System (FCS) family of vehicles
- The military response after 9/11 with the Afghanistan and Second Iraqi wars significantly increased the research and procurement of improved body armors and armors for light tactical vehicles.
- Both these factors have greatly increased the demands for ceramic armors and production still lags demand.
- The Special Armored Protective Insert (SAPI) for the Interceptor Body Armor is being replaced by the Enhanced Special Armored Protective Insert (E-SAPI) to provide greater protection and is also increasing the demand for ceramics
- Changes in the threat environment will impact the future development of ceramic composite systems
- Researchers are using increased analytical and computational assets with higher performance computer systems

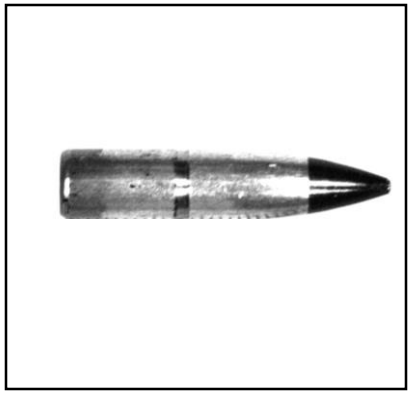
The Changing Threat Environment
Nammo 7.62-mm M993 WC Projectile

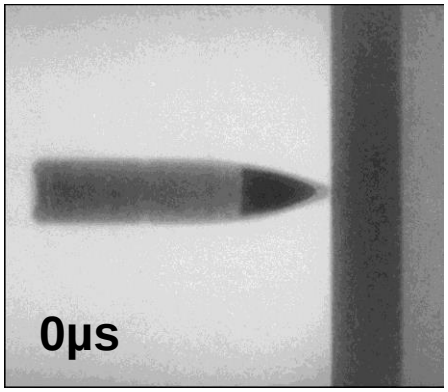


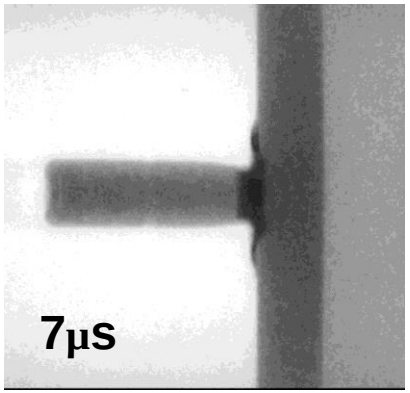


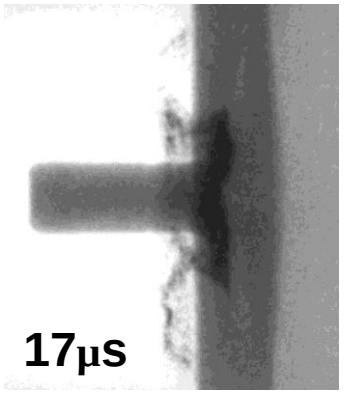
Courtesy of NAMMO

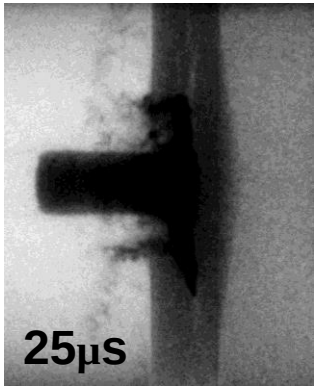
The Changing Threat Environment
7.62-mm APM2 Impact on B_4C

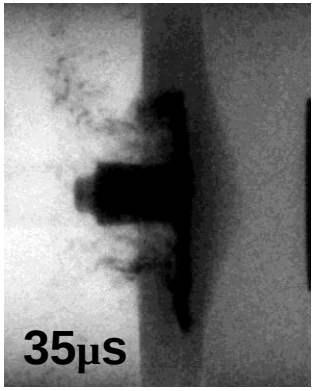


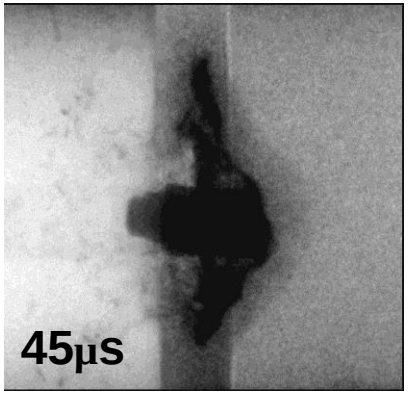


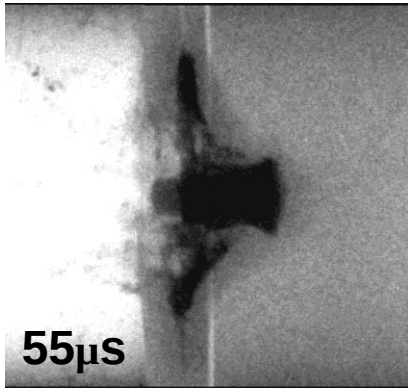




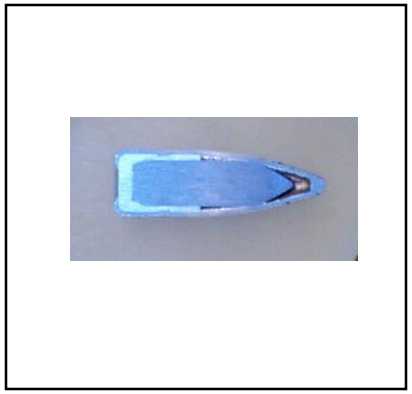


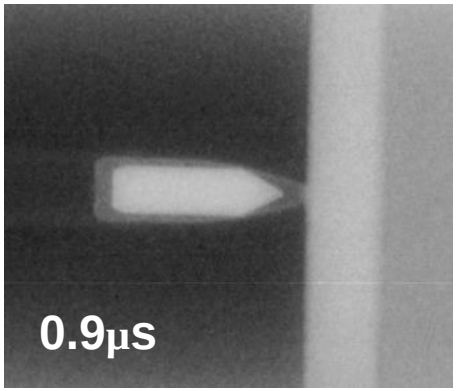


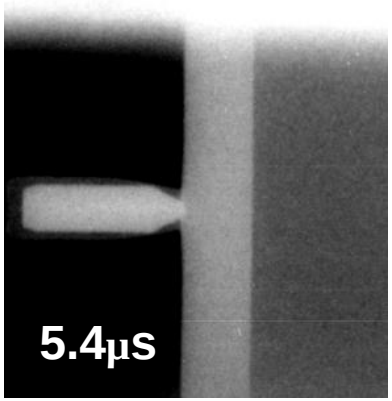


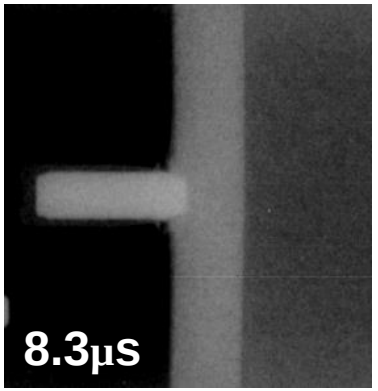


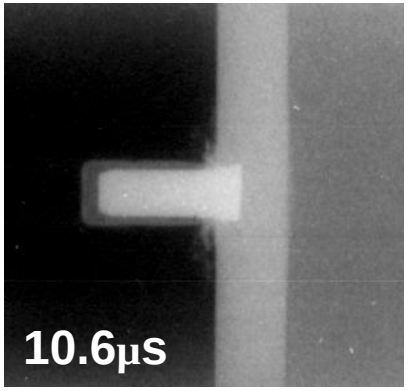
The Changing Threat Environment
7.62-mm M993 Impact on B_4C

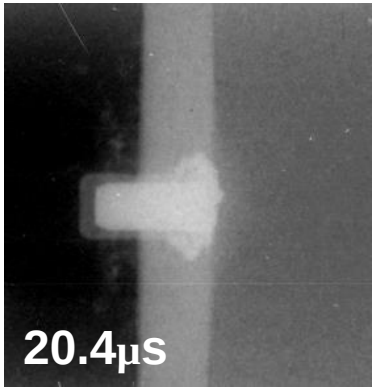


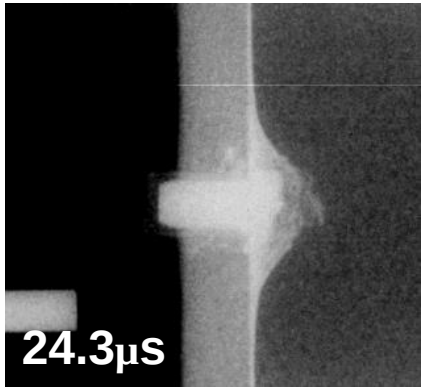


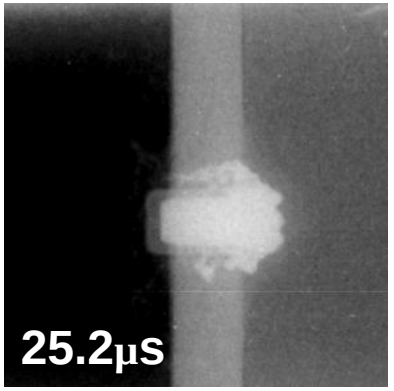




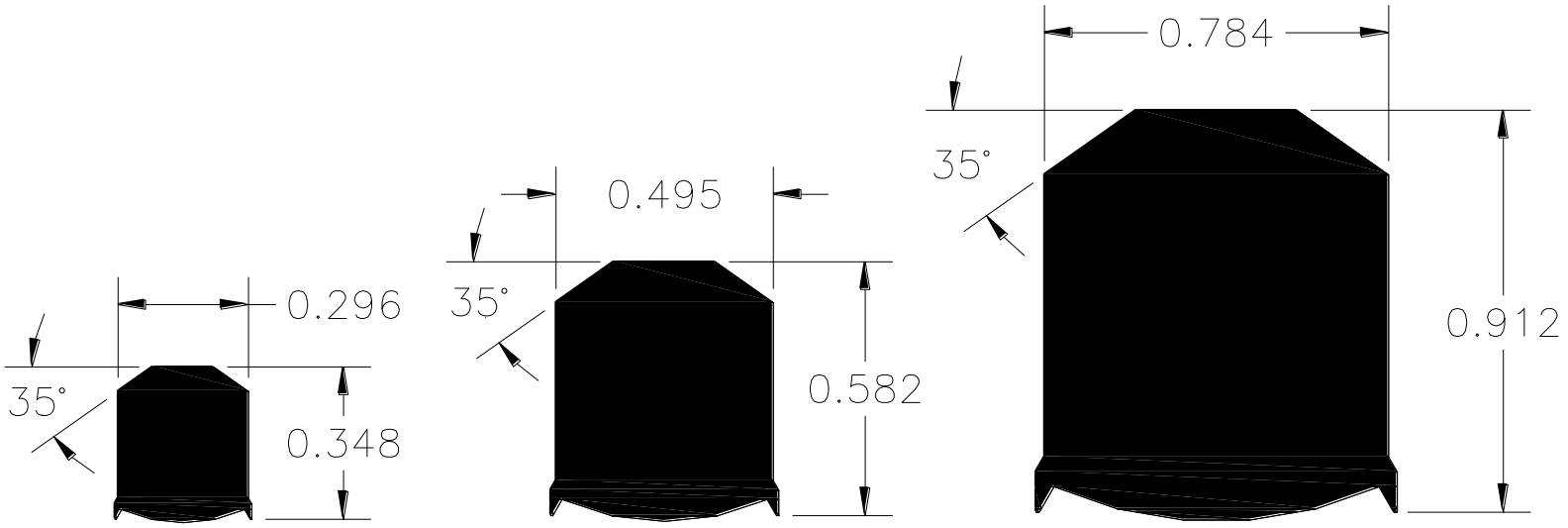








The Changing Threat Environment Fragments from Improved Explosive Devices



0.30 Caliber FSP
Rc 30±1 Steel
44 grains

0.50 Caliber FSP
Rc 30±1 Steel
207 grains

20mm FSP
Rc 30±1 Steel
830 grains

- **Blast and fragment loading from close range Improvised Explosive Devices (IED) have significantly changed protection concepts**
- **Blast loading, multi-hit and multi-threats are important design factors**
- **Armor arrays tested by single shot V_{50} testing with fragment simulating projectiles now have full scale confirmatory IED tests**
- **Ceramic armors have a more difficult task to meet design requirements over metals due to these increased loading effects**

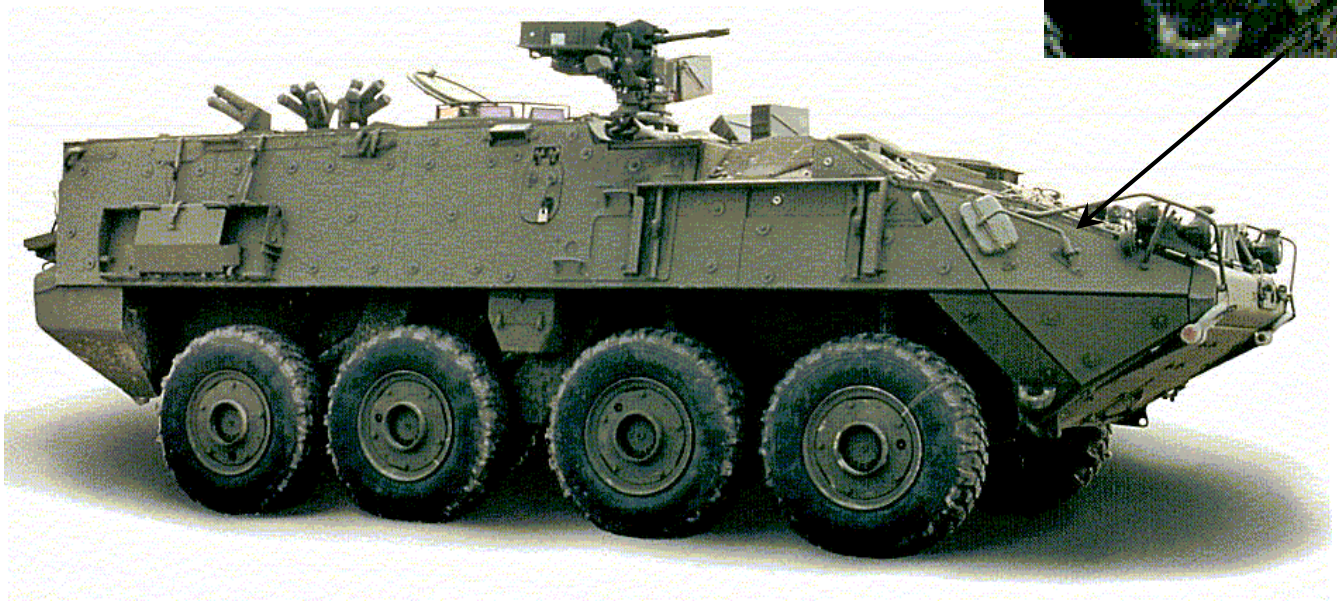
Current Fielded Vehicles with Ceramic Armor

WEAPONS AND MATERIALS RESEARCH DIRECTORATE

TERMINAL EFFECTS DIVISION

General Dynamics Land Systems

Stryker Infantry Carrier Vehicle
IBD MEXAS™ Composite Armor



Current Fielded Vehicles with Ceramic Armor

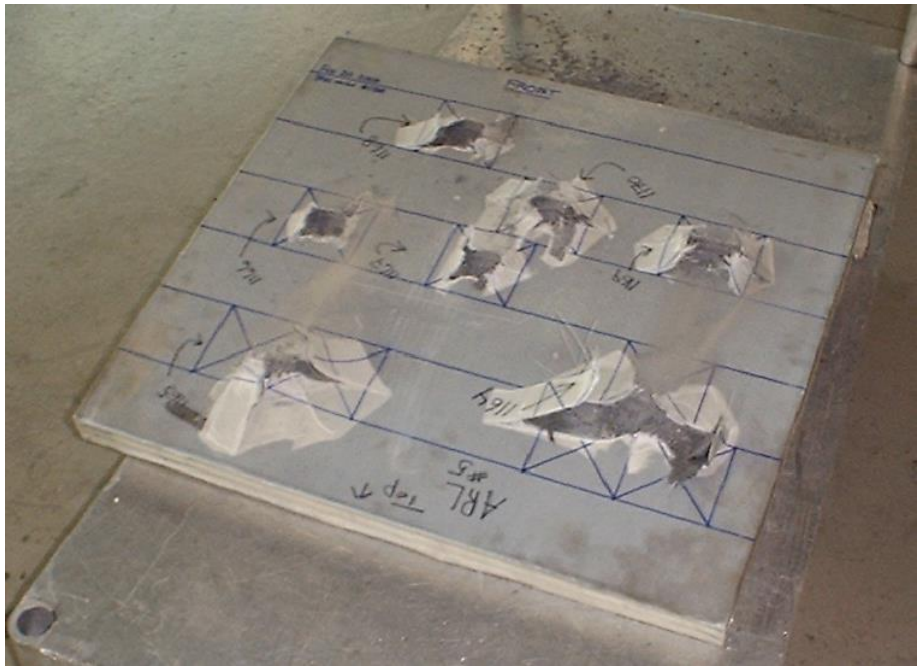
Textron Marine & Land Systems
Armored Security Vehicle
Initial Kits Produced by Simula Under Mexas ™ License From IBD

Current Fielded Vehicles with Ceramic Armor

General Dynamics Land Systems

Marine Corp Expeditionary Force Vehicle (EFV) With Surmax™ Armor

Future Combat System
Ceramic Armor Development



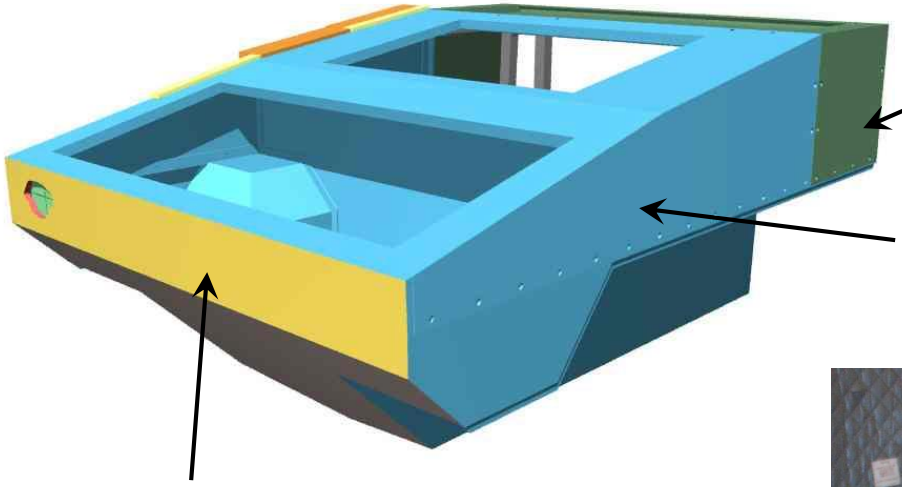
Material

Composite
Ceramic tile
Elastomer
Composite
Metal mesh
Glass / phenolic composite

Function

Low-velocity impact, abrasion protection
Ballistic protection
Structural integrity
Signature management
Fire, smoke, and toxicity protection

Future Combat System
FCS Technology Demonstrators



Space frame ceramic composites

Structural ceramic composites

Encapsulated ceramics

Modeling of Ceramic Impact

- A number of material models have been developed for modeling the high pressure response of ceramics:
  - Curran et al. (1990)
  - Johnson-Holmquist
    - JH-1 (1992)
    - JH-2 (1994)
  - Rajendran-Grove (1992)
  - Espinosa (1995)
  - Simha, Bless and Bedford (2002)

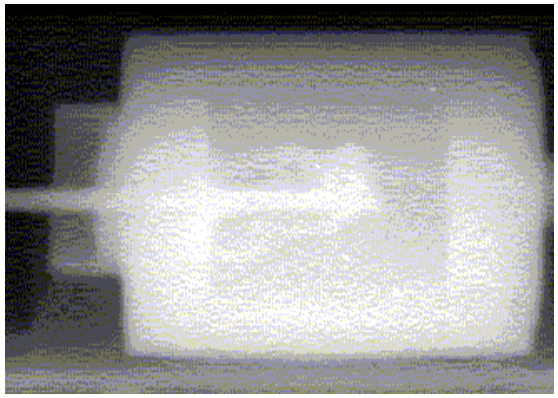
Issues with Modeling of Ceramics

- Determination of the material properties is not trivial.
- Penetration modeling with Lagrangian elements is difficult.

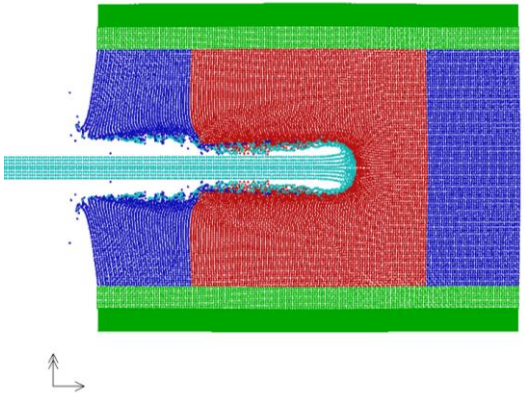
- The Johnson-Holmquist model(s) have been implemented in a number of finite element codes (CTH, ALEGRA, EPIC, AUTODYN, and DYNA) and have been characterized for a number of ceramics including float glass, aluminum oxide, boron carbide, aluminum nitride and silicon carbide.

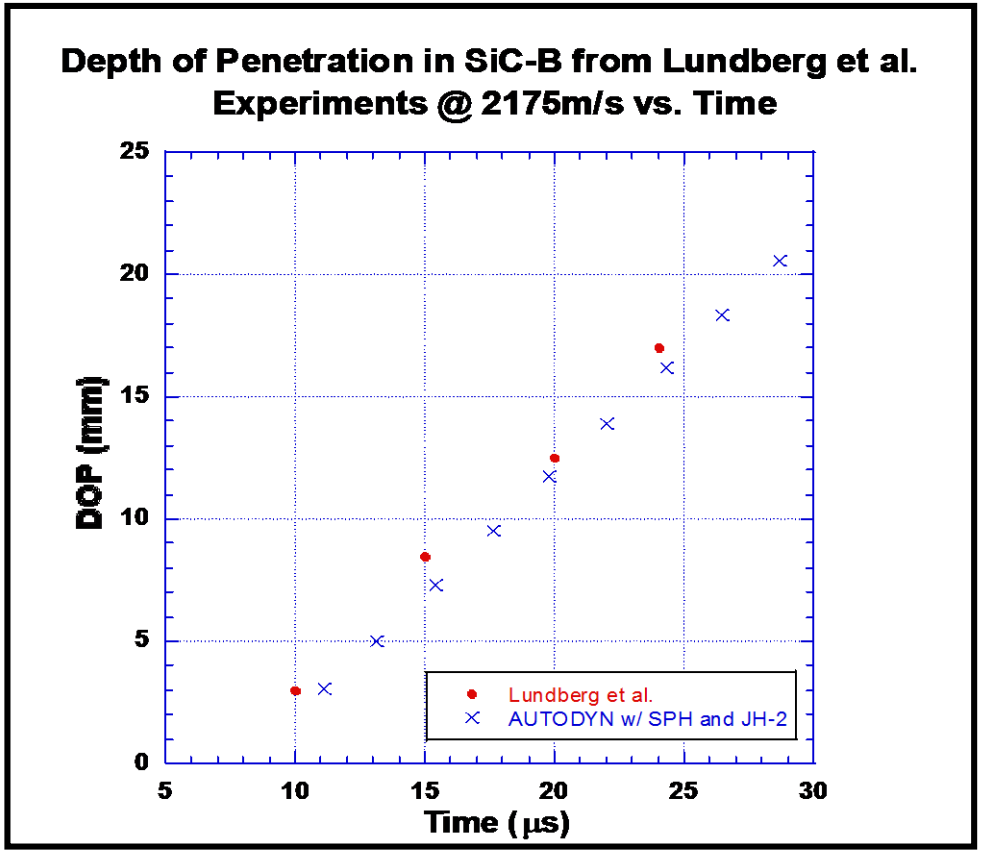
CERAMIC MODELING

AUTODYN with SPH and JH-2: Validate Lundberg experiments



From Lundberg et al., 2000





AUTODYN with SPH and JH-2 can accurately capture the behavior of rubble-ized ceramc

CONCLUSIONS

- This presentation has provided a short and abbreviated review of the development of ceramic armor technology over the last 40 years.

- I would like to acknowledge a number of people I talked to over the past weeks in preparation of this talk:
  - Richard Palicka
  - Bill Snowden
  - Carl Cline
  - Konrad Frank
  - Charles Anderson
  - Brian Scott