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-Develop Modeling and Simulation tools, use Depth of Penetration (DOP) as metric, 7.62 APM2
-Evaluate SiC tile on Aluminum with material properties from literature
-Develop seam designs to improve performance, demonstrate with DOP experiments (tiles from Supplier, sintered SiC)

15. SUBJECT TERMS
Adhesive Layer Effect, .30cal AP M2 Projectile, 762x39 PS Projectile, SPH, Aluminum 5083, SiC, DoP Expeminets, AutoDyn Sin

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ONR ARMOR-GRANT FINAL REPORT 2013-2014

Grant No. N00014-13-1-0219

Date: April 30, 2014

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MODELING AND SIMULATION OF CERAMIC ARRAYS TO IMPROVE BALLISTIC PERFORMANCE

OUTLINE

- Program Overview
- Technical Approach
- Material Properties
- Research Summary February 2013 - August 2013
- Research Summary September 2013 – March 2014
- Future Work

PROGRAM OVERVIEW

TWO PHASE PROGRAM:

- **Grant (15 mos)**
  - Develop Modeling and Simulation tools, use Depth of Penetration (DOP) as metric, 7.62 APM2
  - Evaluate SiC tile on Aluminum with material properties from literature
  - Develop seam designs to improve performance, demonstrate with DOP experiments (tiles from Supplier, sintered SiC)
- **Contract (2 years)**
  - Establish baseline seam and corner performance based on tests with 2 ft x 2 ft panels
  - Tile designs identified in grant – verify performance, provide panels for independent testing
  - Use modeling and simulation tools to assess corner (triple point) performance with seam designs – modifications as needed
    - Evaluate new designs – designs must be manufacturable!
  - Adapt modeling and simulation tools for lightweight backings (composite)
  - Verify designs with DOP and full panel tests
  - Fabricate panels with seam and corner designs and demonstrate improvements
  - Provide panels to Navy for independent verification

TECHNICAL APPROACH

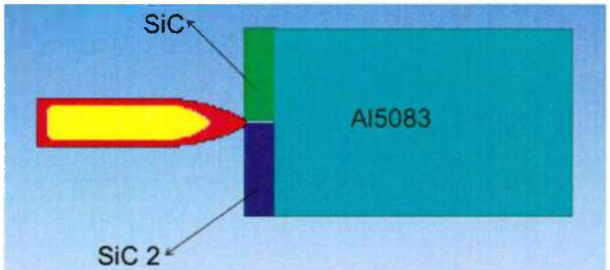
- The University of Delaware Center for Composite Materials (UD-CCM) is developing the next generation of lightweight hybrid ceramic/composite armor kits for Marine Corps tactical and combat vehicles
- The focus is on simulating and modeling the performance of ceramic/composite lightweight armor at seams and corners, and improving the armor's performance in these regions
- The ceramic/composite armor is comprised of composite backings, adhesives, ceramics and covers
- The tiles will be restricted to the sintered ceramics (SiC) due to the ability to fabricate SiC into complex geometries and cost analysis conducted in previous research
- Model ballistic experiments will validate the modeling done in simulation

TECHNICAL APPROACH

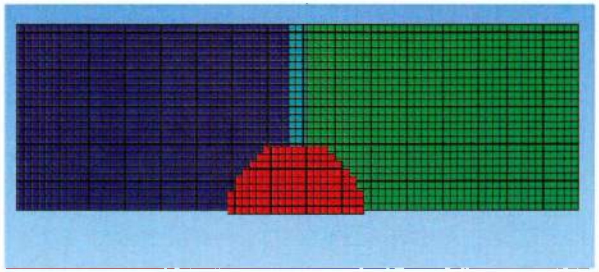
- Half-symmetric model is used in AutoDyn to simulate Depth of Penetration (DOP) experiments on SiC tile with and without a gap supported by solid Aluminum (Al5083)
- Impacts by .30cal AP-M2 projectile and are modeled using SPH elements in AutoDyn
- Center strike model validation runs with SiC tiles are conducted based on the DOP experiments described in reference - ARL-TR-2219, 2000
- Tile gap is found to increase the DOP as compared to baseline center impact
- Simulations were run on gap sizes 0.508 (20 mil) and 1.061 mm (40 mil) at the standard muzzle speed of 850 m/s
- DOP is the main measurement used to determine which geometry and configuration yield the best results.

TECHNICAL APPROACH

Side View



Front View

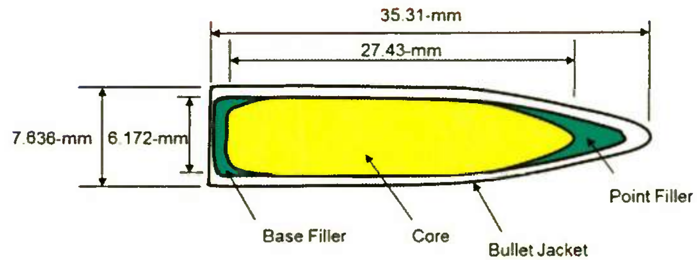


- Smoothed-particle hydrodynamics (SPH) used for all parts
  - SPH Size 0.4 used initially
  - SPH Size 0.2 used to capture smaller damaged particles
- SiC and SiC 2 are identical in properties and dimensions
  - Differentiated to show damage in each tile
- Clamp boundary condition used

Material Models

MATERIAL	EOS	STRENGTH MODEL	FAILURE MODEL
Steel Core	Polynomial	Johnson & Cook	Johnson & Cook
Lead Filler	Gruneisen	Piecewise Johnson & Cook	N/A
Copper Jacket	Linear	Piecewise Johnson & Cook	N/A
SiC Ceramic	Polynomial	JH-2	JH-2
Aluminum	Polynomial	Johnson & Cook	Johnson & Cook
S-Glass/Phenolic	Linear	LS-DYNA MAT162	LS-DYNA MAT162
Polymeric Foam	Linear	Non-linear Elastic	N/A
Adhesives & Interlayers	N/A	Cohesive Laws	Cohesive Laws

.30cal AP-M2 Projectile



Component	Material	Weight (g)
Jacket	Gilding Metal	4.2
Core	Hardened Steel - RC 63	5.3
Point Filler	Lead	0.8
Base Filler	Lead	0.5
Total Weight		**10.8**

MATERIAL PROPERTIES: Al 5083 AND SiC

Experimental Al 5083

Density (g/cm^3)	2.65
Tensile Strength (MPa)	377.1
Yield Strength (MPa)	318.5
Elongation (%)	9.3

Experimental SiC

Density (g/cm^3)	3.20
Elastic Modulus (GPa)	455
Shear Modulus (GPa)	195
Longitudinal Wave Velocity (km/s)	12.3
Poisson's Ratio	0.14
Hardness (kg/mm^2)	2700
Compressive Strength (MPa)	3410

Ref:

MTL TR-86-14, 1986.

ARL-TR-2219, 2000.

AutoDyn SiC

Equation of State	**Polynomial**
Reference density	3.21500E+00 (g/cm3)
Bulk Modulus A1	2.20000E+12 (ubar)
Parameter A2	3.61000E+12 (ubar)
Parameter A3	0.00000E+00 (ubar)
Parameter B0	0.00000E+00 (none)
Parameter B1	0.00000E+00 (none)
Parameter T1	2.20000E+12 (ubar)
Parameter T2	0.00000E+00 (ubar)
Reference Temperature	2.93000E+02 (K)
Specific Heat	0.00000E+00 (erg/gK)
Thermal Conductivity	0.00000E+00 ( )
Strength	**Johnson-Holmquist**
Shear Modulus	1.93500E+12 (ubar)
Model Type	Segmented (JH1)
Hugoniot Elastic Limit, HEL	1.17000E+11 (ubar)
Intact Strength Constant, S1	7.10000E+10 (ubar)
Intact Strength Constant, P1	2.50000E+10 (ubar)
Intact Strength Constant, S2	1.22000E+11 (ubar)
Intact Strength Constant, P2	1.00000E+11 (ubar)
Strain Rate Constant, C	9.00000E-03 (none)
Max. Fracture Strength, SFMAX	1.30000E+10 (ubar)
Failed Strength Constant, ALPHA	4.00000E-01 (none)
Failure	**Johnson Holmquist**
Hydro Tensile Limit	-7.50000E+09 (ubar)
Model Type	Segmented (JH1)
Damage Constant, EFMAX	1.20000E+00 (none)
Damage Constant, P3	9.97500E+11 (ubar)
Bulking Constant, Beta	1.00000E+00 (none)
Damage Type	Instantaneous (JH1)
Tensile Failure	Hydro (Pmin)

AutoDyn Al 5083

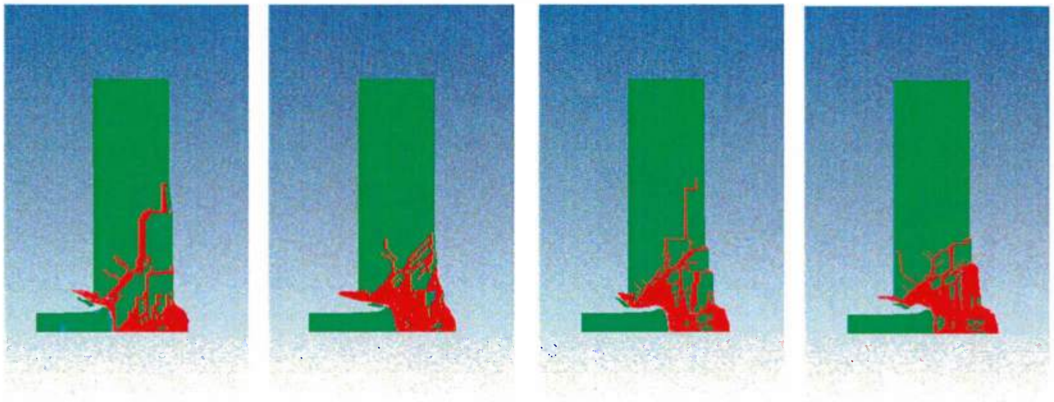
Equation of State	**Linear**
Reference density	2.70000E+00 (g/cm3)
Bulk Modulus	5.83300E+11 (ubar)
Reference Temperature	2.93000E+02 (K)
Specific Heat	9.10000E+06 (erg/gK)
Thermal Conductivity	0.00000E+00 ( )
Strength	**Johnson Cook**
Shear Modulus	2.69200E+11 (ubar)
Yield Stress	1.67000E+09 (ubar)
Hardening Constant	5.96000E+09 (ubar)
Hardening Exponent	5.51000E-01 (none)
Strain Rate Constant	1.00000E-03 (none)
Thermal Softening Exponent	8.59000E-01 (none)
Melting Temperature	8.93000E+02 (K)
Ref. Strain Rate (/s)	1.00000E+00 (none)
Strain Rate Correction	1st Order
Failure	**None**
Erosion	**None**
Material Cutoffs	-
Maximum Expansion	1.00000E-01 (none)
Minimum Density Factor	1.00000E-05 (none)
Minimum Density Factor (SPH)	2.00000E-01 (none)
Maximum Density Factor (SPH)	3.00000E+00 (none)
Minimum Soundspeed	1.00000E-04 (cm/s)
Maximum Soundspeed (SPH)	1.01000E+20 (cm/s)
Maximum Temperature	1.00000E+16 (K)

- Mesh sensitivity analyses were preformed to show fracture and determine particle size
- Initial AutoDyn Models were developed

RESEARCH SUMMARY FEBRUARY 2013 - AUGUST 2013

MESH SIZE ANALYSIS

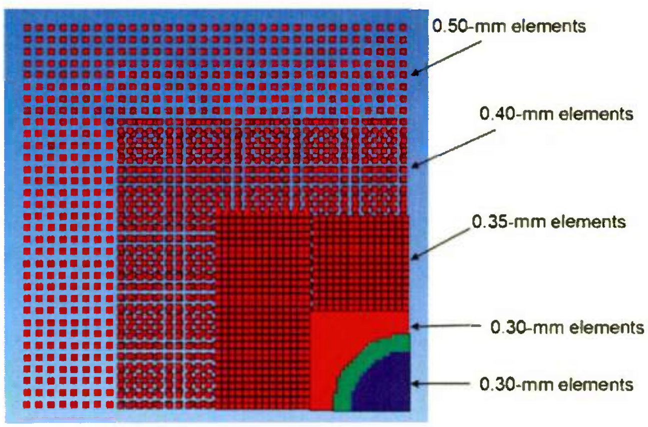
Fracture at Varying Mesh Size

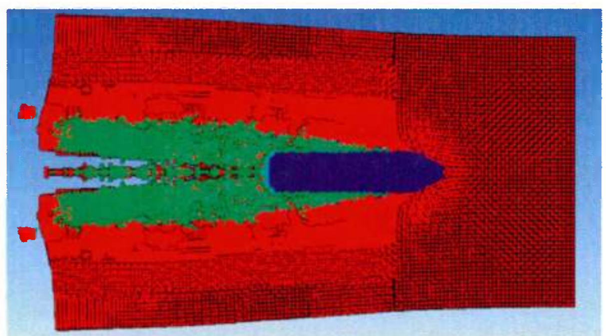


0.50-mm **0.40-mm** **0.30-mm** **0.20-mm**

- ❑ SPH particle size of 0.4 mm determined to be sufficient in capturing the damage of the ceramic tile
  - ❑ Later simulations SPH size is changed to 0.2 mm to capture more of the damaged particles

Multiple Mesh Size Failure

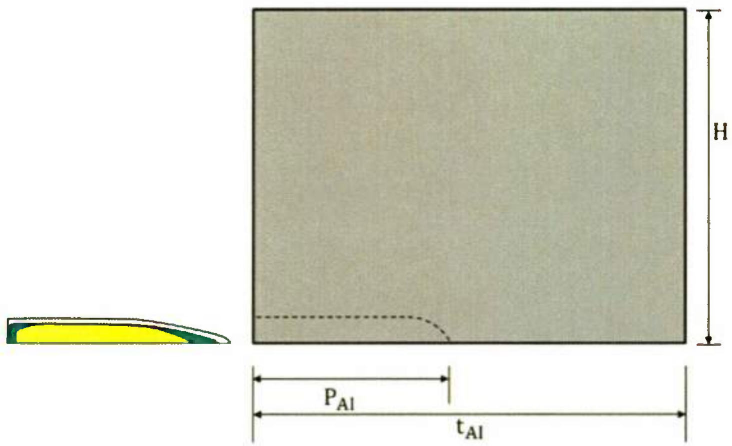




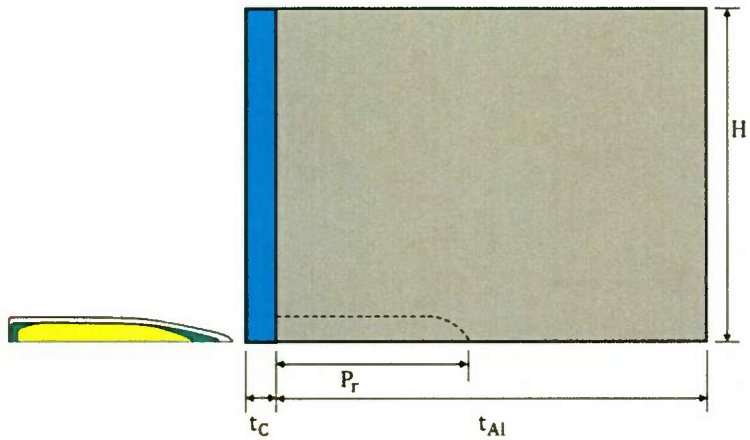
- ❑ Combining multiple mesh sizes in one simulation fails
  - ❑ Due to stress wave propagation causing deflection
  - ❑ Softening and damage modes that are occurring differently in the different mesh sizes

IDENTIFICATION OF THE PROBLEM

MONOLITHIC Al5083



SiC TILE SUPPORTED BY Al5083



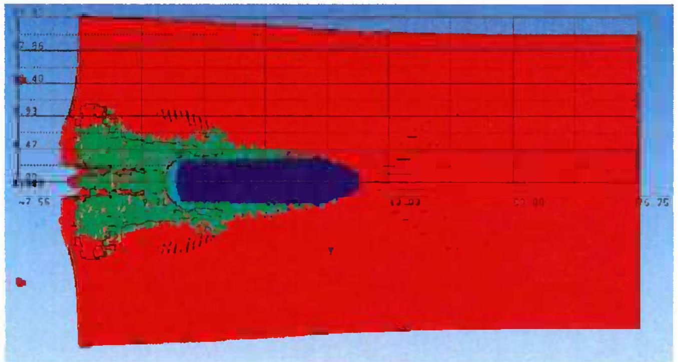
- ❑ Two projectile IGES geometry files are provided by ONR.
- ❑ Quarter-symmetric model is used in AutoDyn to simulate DOP experiments on aluminum targets and ceramic-faced aluminum targets with .30cal AP-M2 projectile using SPH

AUTODYN QUARTER-SYMMETRIC MODEL

- ❑ SPH used for all parts
- ❑ Particle size = 0.30-mm totaling 351k elements
- ❑ Static boundary condition used at end of aluminum to secure the target
- ❑ Material strength and damage properties will be varied to validate ARL DOP data in future

SIMULATION OF ARL DOP EXPERIMENTS

MONOLITHIC Al5083

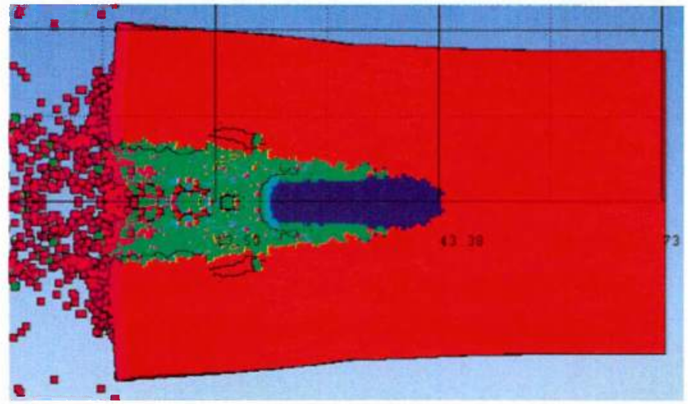


AutoDyn DOP $= 37.8$ mm

Experimental DOP $= 33.8$ mm

Difference $= 11.8\%$

SiC TILE SUPPORTED BY Al5083



AutoDyn DOP $= 42.4$ mm

Experimental DOP $= 40.1$ mm

Difference $= 5.7\%$

- Simulate DOP experiments in AutoDyn to compare to ARL data
- Conclusion: Reasonable results since yaw and pitch are not considered in AutoDyn or ARL
- Stress wave propagation in the target causes the target to split
  - To control for this a static boundary condition is added to all walls of the target

- Simulation details
- Baseline monolithic Al5083
- Improved seam design simulations

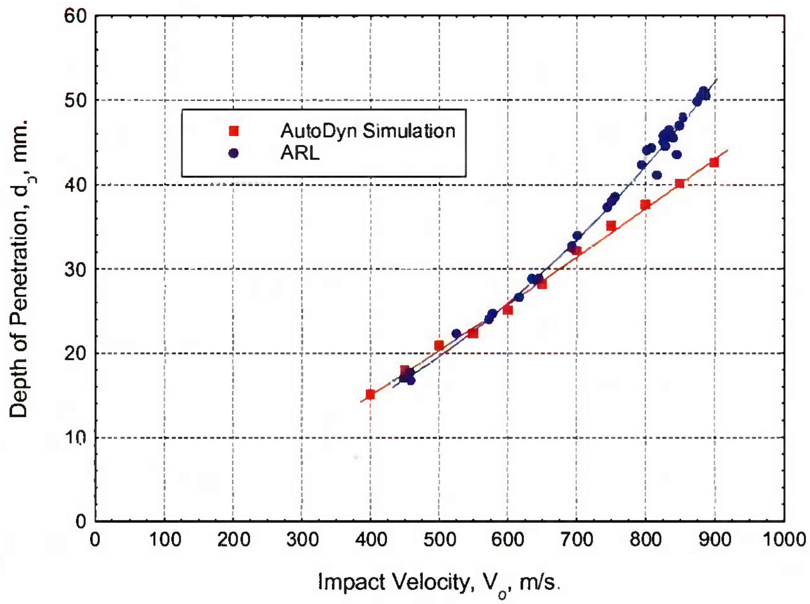
RESEARCH SUMMARY
SEPTEMBER 2013 – MARCH 2014

SIMULATION DETAILS

- Simulations are now incorporating gaps in the tiles to simulate cracks
- Both tiles are SiC but are modeled as two separate materials with the same properties to allow for easy differentiation of the damage
- DOP is calculated by : $DOP = L - L_{NP}$
- Where L is the length of the entire target, ceramic tiles and AL5083 backing
- L_{NP} is the length of the target left unpenetrated when the velocity and kinetic energy of the projectile core have reached zero

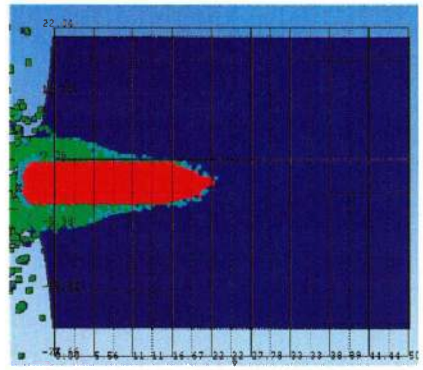
MONOLITHIC Al5083 DOP AT SPH SIZE 0.2 COMPARED WITH ARL DATA

Monolithic Al5083 DOP	
Velocity (m/s)	**DOP (mm)**
400	15.0
450	17.9
500	20.8
550	22.2
600	25.0
650	28.1
700	32.1
750	35.0
800	37.5
850	40.0
900	42.5

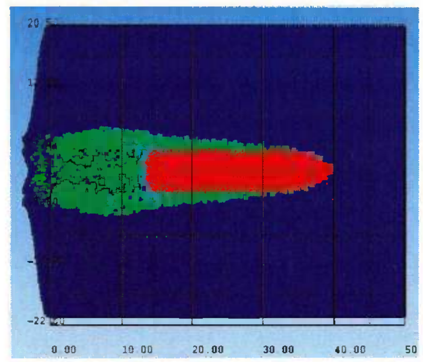


- ❑ Simulate monolithic Al5083 with the intent to compare to the ARL data and use as a baseline result
- ❑ Simulation results do not show the same trend as the ARL experimental data
- ❑ Simulations will be extended over a larger range of Impact Velocities
- ❑ Material properties may be edited if the properties do not match the material properties used in the ARL experiments

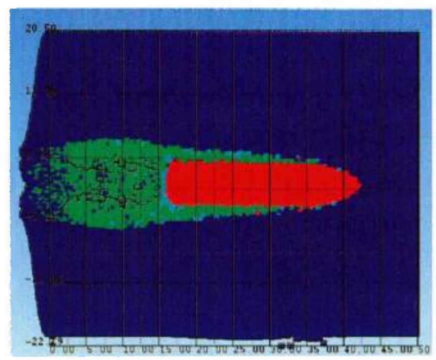
550 m/s



850 m/s

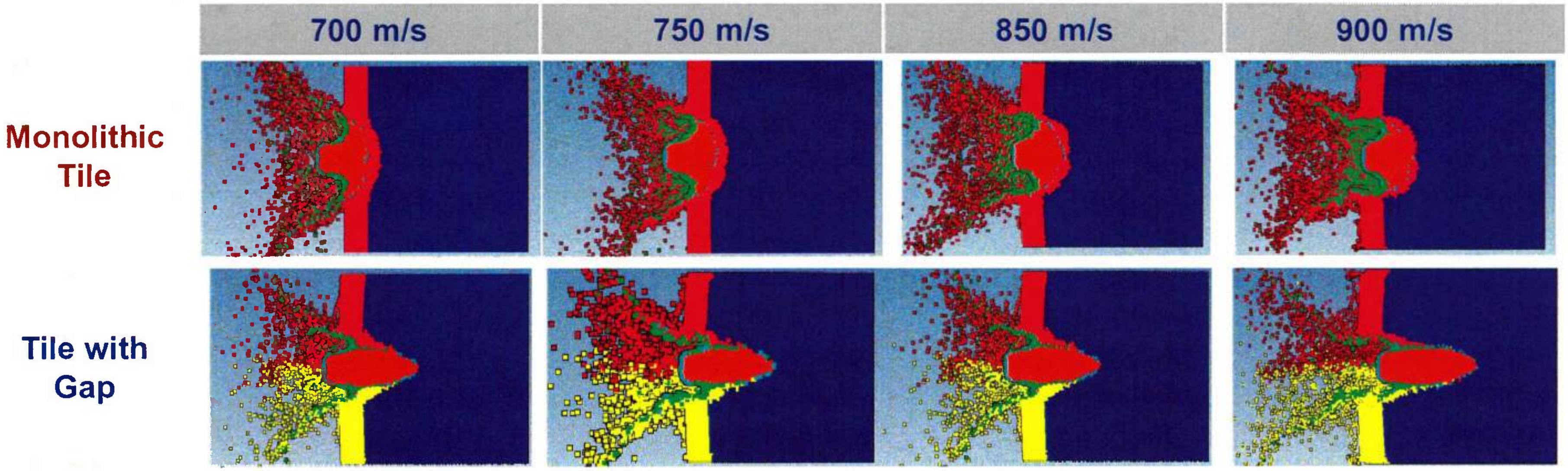


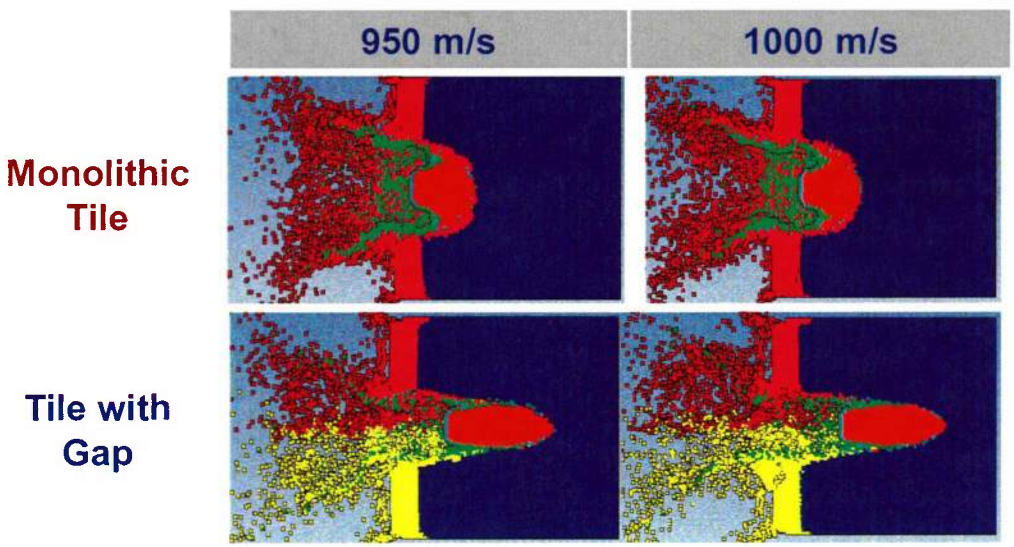
900 m/s



Moynihan, Thomas J., Shun Chin Chou, and Audrey L. Mihalcin. *Application of the Depth of Penetration Test Methodology to Characterize Ceramics for Personnel Protection.* Rep. Aberdeen Proving Ground, MD: Army Research Laboratory, April 2000. Print.

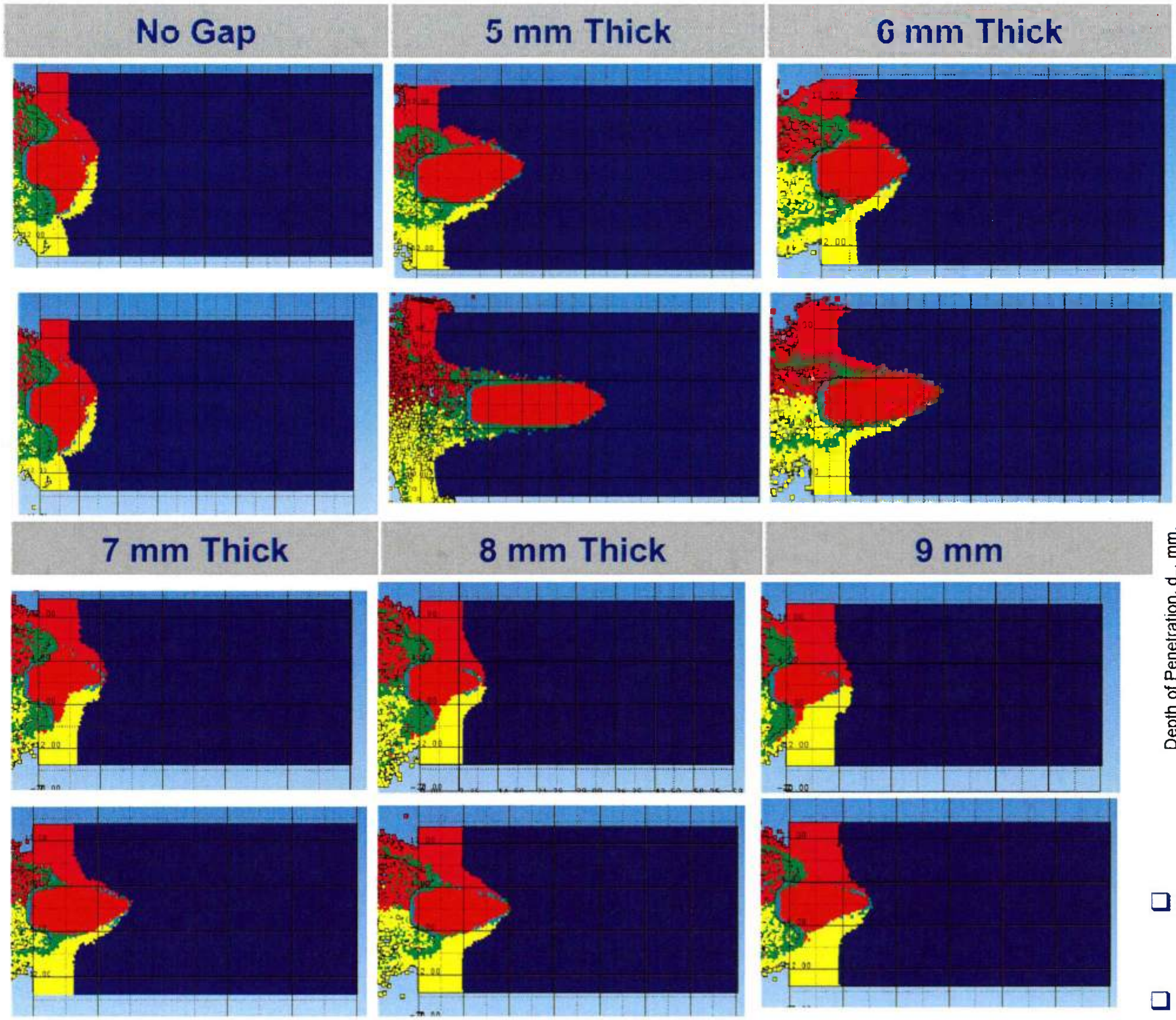
SIMULATING EFFECT OF TILE GAP ON DOP





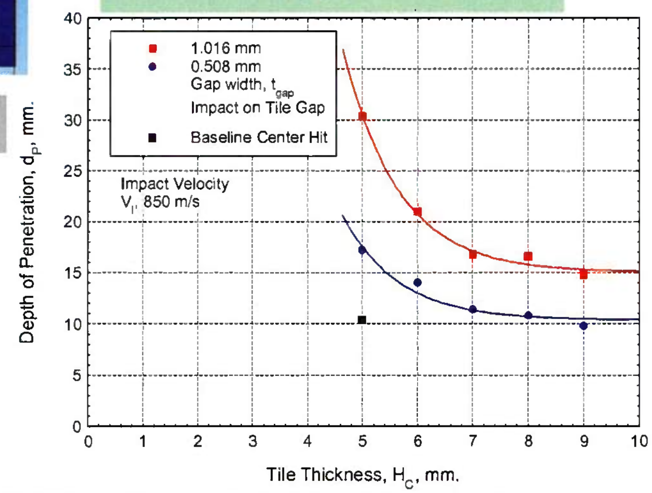
- ❑ See DOP of center impacted SiC tiles and effect on DOP of SiC tiles with gap
- ❑ Aluminum Backing
  - ❑ Length = 35.08 mm
- ❑ Ceramic Plate(s)
  - ❑ Length (t_c) = 5.08 mm
  - ❑ Gap size = 1.2 mm
- ❑ Total Length = 40.08 mm
- ❑ Velocity varying from 700-1000 m/s
- ❑ SPH Size 0.4
- ❑ As expected tile gap increases the DOP and improvements on this are needed

EFFECT OF TILE THICKNESS ON DOP AT 850m/s GAP SIZE 0.508mm AND 1.016mm



Depth of Penetration on Baseline Tiles and Modified Tiles at 850 m/s

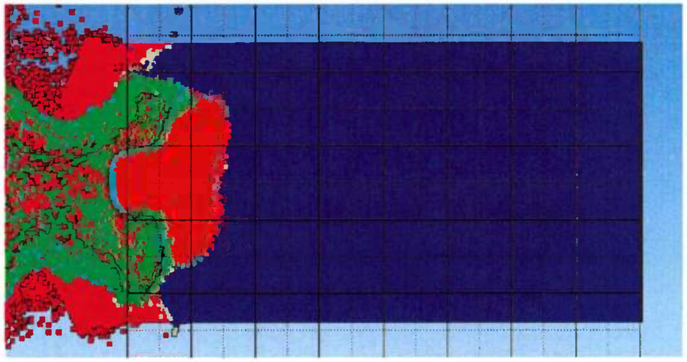
Tile Thickness H_c (mm)	Depth of Penetration, d_p, 0.508 mm Gap Size (mm)	Depth of Penetration, d_p, 1.061 mm Gap Size (mm)
5 (Baseline, No Gap)	10.3	10.3
5	17.2	30.3
6	14.0	21.0
7	11.4	16.8
8	10.8	16.6
9	9.8	14.8



- When the gap is held at 1.016 mm the baseline DOP of a center impacted tile cannot be effectively achieved
- A gap size of 0.508 mm allows the baseline to be achieved and gap size of 0.508 mm will be the gap size in use moving forward

ADHESIVE LAYER EFFECT IN AUTODYN

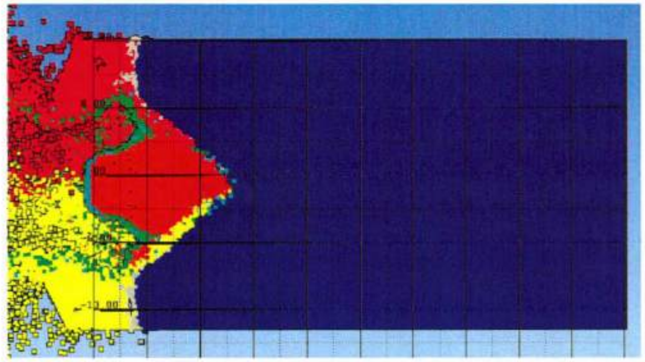
Center Impacted Single Tile



Adhesive Layer DOP Compared to No Adhesive Layer DOP, Gap 0.508 mm	
Adhesive Layer DOP (mm)	Baseline Center Impact with no Adhesive DOP (mm)
10.1	10.3

- An adhesive layer of Epoxy Resin was added in between the SiC tile and the Al backing
- The tile remained 5 mm thick

Impact on a Tile with 0.508 mm Gap

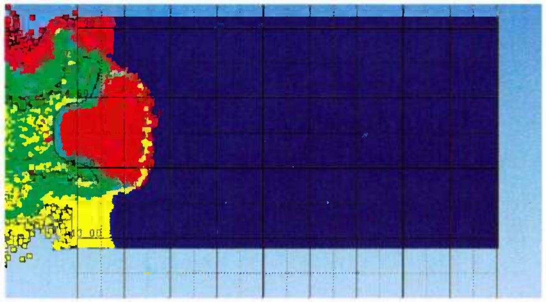


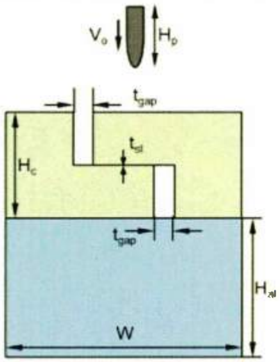
Adhesive Layer DOP Compared to 0.508 mm Gap with No Adhesive DOP	
Adhesive Layer DOP (mm)	Tile Gap 0.508 mm with No Adhesive DOP (mm)
13.9	17.2

- An adhesive layer of Epoxy Resin was added in between the SiC tile and the Al backing
- The tile remained 5 mm thick and the gap size at 0.508 mm to compare when no adhesive was added

STEP LADDER SEAM DESIGN

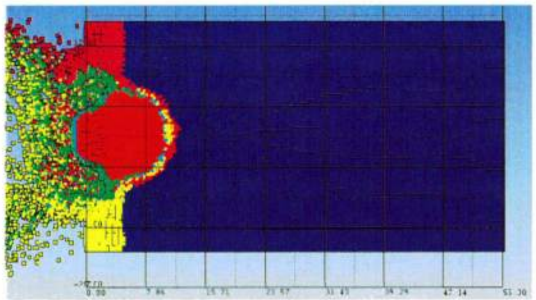
CENTER IMPACTED STEP LADDER
t_{sl}= 0

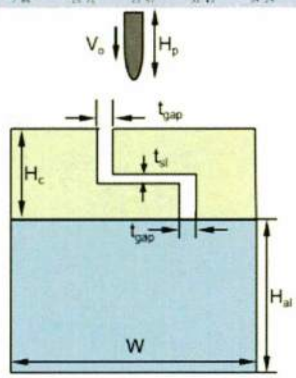




Part			
V_o	850 m/s	t_{sl}	0 mm
H_p	35.31 mm	H_{al}	50 mm
t_{gap}	0.508 mm	W	30 mm
H_c	5 mm		

CENTER IMPACTED STEP LADDER
t_{sl}= 0.2





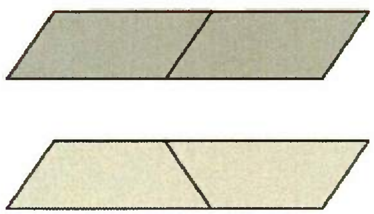
Part			
V_o	850 m/s	t_{sl}	0.2 mm
H_p	35.31 mm	H_{al}	50 mm
t_{gap}	0.508 mm	W	30 mm
H_c	5 mm		

Step Ladder DOP			
Step Ladder t_{sl} = 0 mm DOP (mm)	Step Ladder t_{sl} = 0.2 mm DOP (mm)	No Step Ladder DOP, Gap Size 0.508 mm (mm)	Baseline Center Impacted One Tile
9.2	11.8	17.2	10.3

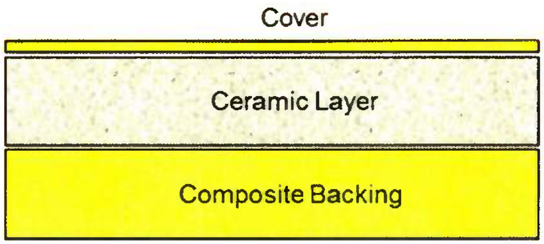
- An Step Ladders were created according to the schematics with presented specifications
- The tile remained 5 mm thick and the gap size at 0.508 mm to compare to the baseline results
- The DOP results are compare against center impacted single tile and standard 0.508 mm gap between two tiles

FUTURE WORK

- Angled Seams (a) and Cover plates (b) are proposed seam designs to be tested in the future
- Continued modeling and experimental tests will down select for the best solution and improvement to seam design
- Modeling will move from AutoDyn to LS-DYNA for increased computational power and the ability to model complex geometries
- Baseline performance seam assessment (2 ft x 2 ft panels)
  - Sintered 4'sq. SiC (Superior Graphite) on Kevlar/Phenolic with 2-ply cover



(a) Angled Seam



(b) Cover Plate