PUMICE LAYERED WITH PROJECTILE-RESISTANT MATERIALS FOR BULLET IMPACT MITIGATION OCTOBER 2007

Jared Grover

Mechanical Engineer

760-939-7131, jared.grover@navy.mil

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Objective

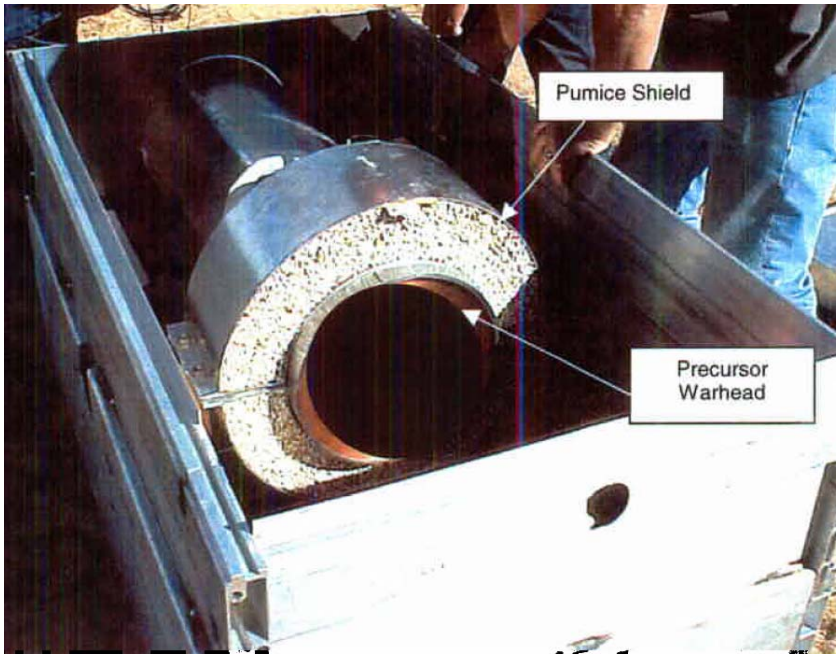
- Design and evaluate panels in which pumice is layered with projectile-resistant materials to quantitatively gauge the panels' ability to mitigate projectile impact threats
  - Panels to be used for protection of weapon systems during transportation within the United States

Collaborative work performed under NCRADA-NAWCWDCL-06-149 between Raytheon Missile Systems and NAWCWD

Background

- For 20 years, NAWCWD China Lake has developed the use of pumice to mitigate blast and sympathetic detonation

- Pumice technology successfully used in current weapon system containers
  - SLAM-ER
  - JSOW
- Pumice matrix comprised of 3/8-inch-diameter pieces glued together
- Pumice binder not effective mechanism in absorbing energy
- Crushing the pumice absorbs blast energy
- New application of old pumice technology



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Project Scope

Approach:

• Identify six (6) candidate materials to be layered with pumice to mitigate specific bullet impact threats

• Design/fabricate a simple, repeatable subscale test to evaluate layered pumice test panels

Down Select:

• Choose the best performing designs and provide scaled-up panels for testing at Aerojet's facility against commercially available ballistic panels

Materials Layered w/Pumice

Raytheon

Six (6) different bullet-resistant materials were layered with pumice

- Aramid Fibers–Kevlar
  - Bullet-resistant vests
- Gel Spun Polyethylene (GSP)–Dynema, Spectra
  - Automotive protection panels
- Ceramics–SiN, BC, AlO
  - Bullet trauma plates
- Steel–S-5 Tool Steel, Armor Plate
  - Industrial and military applications
- Aluminum
  - Ductile material slows velocity
- Nitinol
  - New bullet-resistant material

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Design Requirements and Test Instrumentation

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Design Requirements:

- Identified threats
  - 7.62- x 51-mm round (.30 cal)
  - .50-cal round–specified in MIL-STD 2105
- Range–most realistic distance during logistic lifecycle
- 90-deg impact–worst-case condition
- Standard, as manufactured, projectile velocity
- Panel must stop round from penetrating shipping container

Test Instrumentation

- High-speed camera coverage
- Simulated shipping container (witness plate)
- Velocity screen
  - At muzzle, after witness plate

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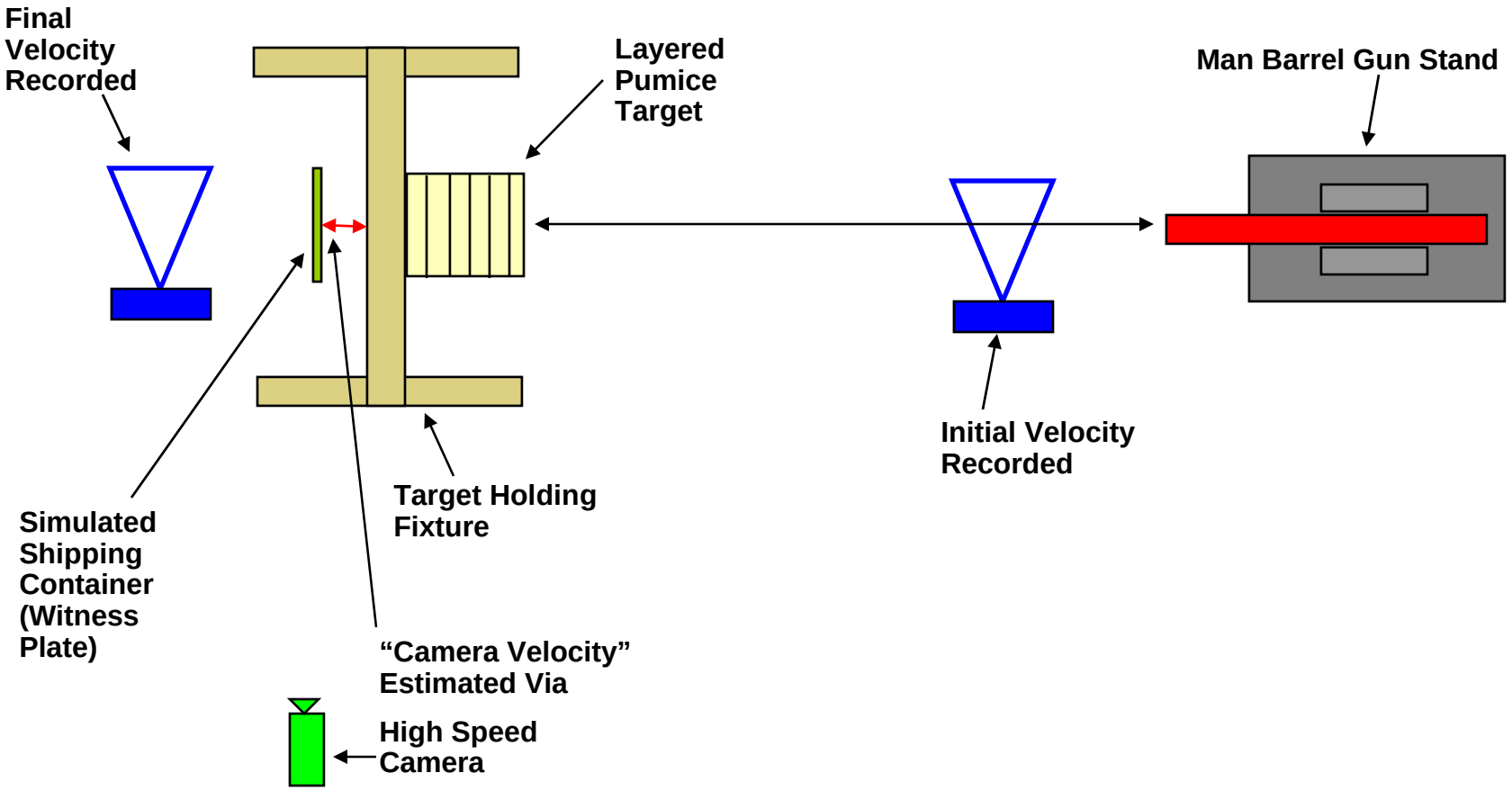
Test Layout



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Test Matrix

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- **Many configurations built and tested**
- **Nearly all configurations tested against both the .50-cal and .30-cal projectiles**

	Kevlar and Pumice		Tool Steel and Pumice		Gel Spun Polyethylene and pumice		Aluminum and Pumice		Ceramics and Pumice		Nitnol and Pumice		Armor Plate and Pumice
KEV1	Kevlar	TS1	Aluminum	GSP1+	GSP	AL1	Aluminum	CER1+	BC Ceramic	NI1	Aluminum	AP2+*	Armor Plate
	Steel		Kevlar		Steel		Aluminum		Pumice		Nitnol		Pumice
	Pumice		Pumice		Pumice		Pumice		Kevlar		Pumice		Aluminum
	Aluminum		Tool Steel		Aluminum		Aluminum		Aluminum		Kevlar		Armor Plate
KEV2	Kevlar		Pumice		GSP		Pumice		Kevlar		Aluminum	AP3*	Armor Plate
	Pumice		Kevlar		GSP		Aluminum		Steel	NI2	Aluminum		Pumice
	Kevlar		Pumice		GSP		Pumice	CER2	BC Ceramic		Nitnol		Armor Plate
	Aluminum	TS2	Aluminum		GSP		Aluminum		Pumice		Pumice		Pumice
KEV3	Kevlar		Kevlar	GSP2+	Pumice		Pumice		BC Ceramic		Nitnol		Kevlar
	Pumice		Pumice		Aluminum	AL2	Aluminum		Pumice		Pumice		Aluminum
	Kevlar		Tool Steel		GSP		Aluminum		Aluminum		Aluminum		
	Pumice		Pumice	GSP3*	GSP		Aluminum	CER3	BC Ceramic	NI3	Aluminum		
	Aluminum		Aluminum		Pumice		Pumice		Pumice		Nitnol		
KEV4	Aluminum	TS3	Tool Steel		Aluminum		Aluminum		Aluminum		Pumice		
	Kevlar		Pumice		GSP		Pumice	CER4	BC Ceramic		Nitnol		
	Pumice		Tool Steel		Pumice		Aluminum		Pumice		Pumice		
	Kevlar		Pumice	GSP4	GSP		Pumice		BC Ceramic		Nitnol		
	Pumice		Tool Steel		Pumice		Aluminum		Pumice		Aluminum		
	Kevlar		Pumice		Aluminum		Aluminum		Kevlar				
	Pumice		Tool Steel		Pumice	AL3	Aluminum		Pumice				
	Kevlar		Pumice	H2O	Aluminum		Pumice		Aluminum				
	Pumice		Aluminum		Water		Aluminum	CER5	SiN Spheres				
	Aluminum	TS4	Aluminum		Aluminum		Pumice		SiN Spheres				
BONUS1*	Aluminum		Pumice		Pumice		Aluminum		SiN Spheres				
	Pumice		Tool Steel		Aluminum	AL4	Aluminum		Pumice				
	Kevlar		Pumice		Kevlar		Aluminum		Aluminum				
	Aluminum		Tool Steel	BASE3B	Aluminum		Pumice		Aluminum				
	Kevlar		Pumice		Pumice		Aluminum	CER6	Pumice				
	Aluminum		Aluminum		Mild steel		Pumice		AlO Rods				
	Pumice	TS5*	Aluminum		Aluminum		Aluminum		AlO Rods				
	Kevlar		Tool Steel	BASE3	Aluminum	BASE1	Pumice		AlO Rods				
	Aluminum		Pumice		Pumice		Aluminum		Pumice				
	Pumice		Tool Steel		Aluminum		Aluminum		Aluminum				
	Kevlar		Pumice				Pumice						
	Aluminum		Kevlar				Pumice						
	Pumice		Aluminum				Aluminum						
	Kevlar		Aluminum				Pumice						
	Aluminum		Tool Steel				Aluminum						
KevBonus	Aluminum		Pumice				Pumice						
	Pumice	TS6*	Tool Steel			AL6	Aluminum						
	Steel		Pumice				Pumice						
	Kevlar		Kevlar				Aluminum						
	Aluminum		Aluminum				Pumice						
	Pumice						Aluminum						
	Steel						Pumice						
	Kevlar				* .50 cal only		Aluminum						

.50-cal Test Data

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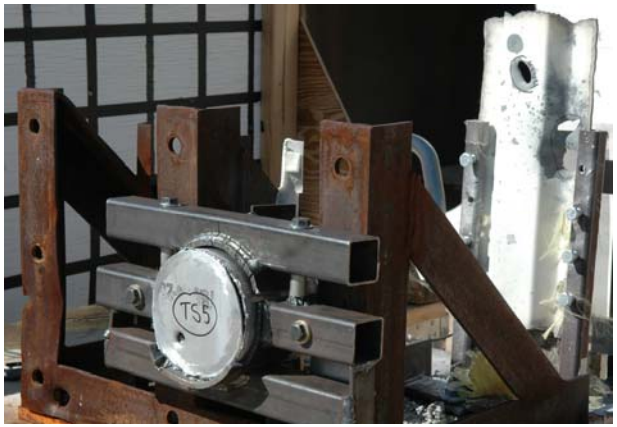
- **Target success not dependent on bulk density**
- **Four successful panel designs**

	Tested order	Round Used	Penetration (Y/N) ?	Target Bulk Density,lb/ft^3	Comments
AL1	7	.50 cal	yes	60.3	
AL2	3	.50 cal	yes	70.2	Exit velocity screen captured debris velocity
AL3	9	.50 cal	yes	66.4	
AL4	8	.50 cal	yes	73.2	No video
AL6	6	.50 cal	yes	53.5	Switched to 2 exit velocity screens
AP2+	35	.50 cal	no	201.3	Added .5" AP in front AP2
AP3	33	.50 cal	yes	131.8	Back half bullet stopped front half penetrated witness plate
BASE1	2	.50 cal	yes	49.6	
BASE3	1	.50 cal	yes	83.1	Bullet tumbled, exited sideways
BASE3B	32	.50 cal	no	97.9	Bullet tumbled, hit steel plate sideways, deflected up and away from witness plate
BONUS1	4	.50 cal	yes	N/A	
CER1+	29	.50 cal	yes	59.6	
CER2	25	.50 cal	yes	56.7	
CER3	26	.50 cal	yes	56.9	
CER4	23	.50 cal	no	56.0	Yes target, no witness plate, camera velocity of debris
CER5	31	.50 cal	yes	61.2	
CER6	21	.50 cal	yes	80.2	
GSP1+	36	.50 cal	yes	51.4	No velocities, instrumentation error
GSP2+	34	.50 cal	yes	46.7	Round deflected, didn't enter second velocity screen
GSP3	22	.50 cal	yes	48.4	
GSP4	21	.50 cal	yes	45.0	Spectra- GSP
H2O	30	.50 cal	yes	N/A	
KEV1	19	.50 cal	yes	77.6	
KEV2	20	.50 cal	yes	50.2	
KEV3	12	.50 cal	yes	53.5	Started using foil switches
KEV4	13	.50 cal	yes	50.6	
KEVBONUS	28	.50 cal	yes	N/A	Round deflected off stand on exit, exit velocity is suspect incorrect
NI1	10	.50 cal	yes	60.2	Removed all exit screens
NI2	11	.50 cal	yes	63.2	
NI3	27	.50 cal	yes	81.6	
TS1	14	.50 cal	yes	60.4	
TS2	18	.50 cal	yes	60.5	
TS3	5	.50 cal	yes	85.5	
TS4	17	.50 cal	yes	80.4	Barely thru witness plate
TS5	16	.50 cal	no	76.1	Yes target, no witness plate, camera velocity of debris
TS6	15	.50 cal	no	143.1	

TS5 Testing

- **Target TS5: Tool Steel**
  - .50-cal projectile
  - 24000 frames/second
  - Target bulk density: 76.1 lb/ft^3



TS5	Aluminum
	Tool Steel
	Pumice
	Tool Steel
	Pumice
	Kevlar
	Aluminum

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TS6 Testing

- **Target TS6: Tool Steel**
  - .50-cal projectile
  - 24000 frames/second
  - Target bulk density: 143.1 lb/ft^3

TS6	Aluminum
	Tool Steel
	Pumice
	Tool Steel
	Pumice
	Kevlar
	Aluminum

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CER4 Testing

- **Target CER4: Ceramic**
  - .50-cal projectile
  - 24000 frames/second
  - Target bulk density: 55.95 lb/ft^3

CER4	Aluminum
	BC Ceramic
	Pumice
	BC Ceramic
	Pumice
	Kevlar
	Pumice
	Aluminum

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AP2+ Testing

- **Target AP2+: Armor Plate**
  - .50-cal projectile
  - 24000 frames/second
  - Target bulk density: 201.3 lb/ft^3

AP2+	Armor Plate
	Pumice
	Aluminum
	Armor Plate

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.30-cal Testing

- **Performed in case a panel capable of stopping the .50-cal round is too heavy**
- **Verified all panels successful with .50 cal could stop the .30-cal round also**
- **Select other panels could stop the .30-cal round but not the .50-cal round**

Target ID	Tested order	Round used	Target Bulk Denisty (lb/ft^3)	Penetration (Y/N)	Comments
AL1	28	.30 cal	60.3	Yes	
AL2	13	.30 cal	70.2	Yes	
AL3	22	.30 cal	66.4	Yes	
AL4	14	.30 cal	73.2	Yes	
AL6	21	.30 cal	53.5	Yes	
BASE1	12	.30 cal	49.6	Deflected	Deflected right of witness plate
BASE3	23	.30 cal	83.1	Deflected	Deflected down into test stand
BASE3B	24	.30 cal	97.9	Deflected	Deflected right of witness plate
CER1	10	.30 cal	59.6	No	Penetrated target, not the witness plate
CER2	9	.30 cal	56.7	No	Projectile stuck in target
CER3	8	.30 cal	56.9	No	Projectile stuck in target
CER4	7	.30 cal	56.0	No	Projectile stuck in target
CER5	25	.30 cal	61.2	No	Projectile stuck in target
CER6	11	.30 cal	80.2	No	Projectile stuck in target
GSP1	4	.30 cal	51.4	Yes	
GSP2	5	.30 cal	46.7	Deflected	Deflected down into test stand
GSP4	3	.30 cal	45.0	Deflected	
KEV1	1	.30 cal	77.6	Yes	
KEV2	2	.30 cal	50.2	Deflected	Deflected up above witness plate
KEV3	19	.30 cal	53.5	Yes	
KEV4	20	.30 cal	50.6	Deflected	Deflected right of witness plate
NI1	27	.30 cal	60.2	Yes	Deflected up above witness plate
NI2	26	.30 cal	63.2	Deflected	Deflected down into test stand
NI3	6	.30 cal	81.6	Deflected	Deflected down into test stand
TS1	18	.30 cal	60.4	Yes	
TS2	16	.30 cal	60.5	No	Projectile stuck in target
TS3	17	.30 cal	85.5	No	Projectile stuck in target
TS4	15	.30 cal	80.4	No	Projectile stuck in target

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Verification Testing

Panel	Round Used	Penetration (Yes/No)	Comments
CER3+	.30 cal	No	
TS5.5	.50 cal	No	Oblong entrance hole, first of two shots on same target
TS5.5	.50 cal	No	Second of two shots on same target
CER4	.50 cal	No	Bulged backface of pannel, oblong entrance hole
CER7	.50 cal	No	First of two shots on same target
CER7	.50 cal	No	Oblong entrance hole, second of two shots on same target
TS5.5	.50 cal	No	First of three shots on same target
TS5.5	.50 cal	No	Oblong entrance hole, second of three shots on same target
TS5.5	.50 cal	No	Third of three shots on same target
TS5	.50 cal	No	Silght bulge on back face o panel
CER5+C	.50 cal	Yes	
CER5+A	.50 cal	No	

- **Twenty-two (22) panels scaled up to 12” x 12” and provided for verification testing**
  - Only eight (8) panels tested due to time constraints
- **Final testing performed at Aerojet’s Camden facility**
  - Test range shortened to maximize impact velocity
  - Impact angle remained 90 degrees
  - As-manufactured ammunition provided from same lot as previous testing
- **CER7 and TS5.5 considered best performers**

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CER7 Verification Testing

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CER7	Aluminum
	AlO Tiles
	Kevlar
	Pumice
	Kevlar
	AlO Tiles
	Kevlar
	Pumice
	Kevlar
	Aluminum

- **CER7–based on CER4 design but using less expensive alumina ceramic tiles**

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TS5.5 Verification Testing

Raytheon

TS5.5	Aluminum
	Tool Steel
	Kevlar
	Pumice
	Tool Steel
	Pumice
	Kevlar
	Aluminum

- **TS5.5–built to split difference in tool steel thickness between the TS5 and TS6 panels**

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Future Plans/Conclusion

- **Optimize CER7 and TS5.5 Panel Designs**
  - Characterize impact-resistant material (tool steel/ceramic)
  - Characterize shock absorption materials (pumice)
  - Optimize/reduce panel weight–21-32%
  - Reduce panel depth–26-57%
  - Validation of optimized panel designs
- **Layered pumice panels provide a viable solution to protecting weapon systems from the .50-cal projectile during transportation cycles**

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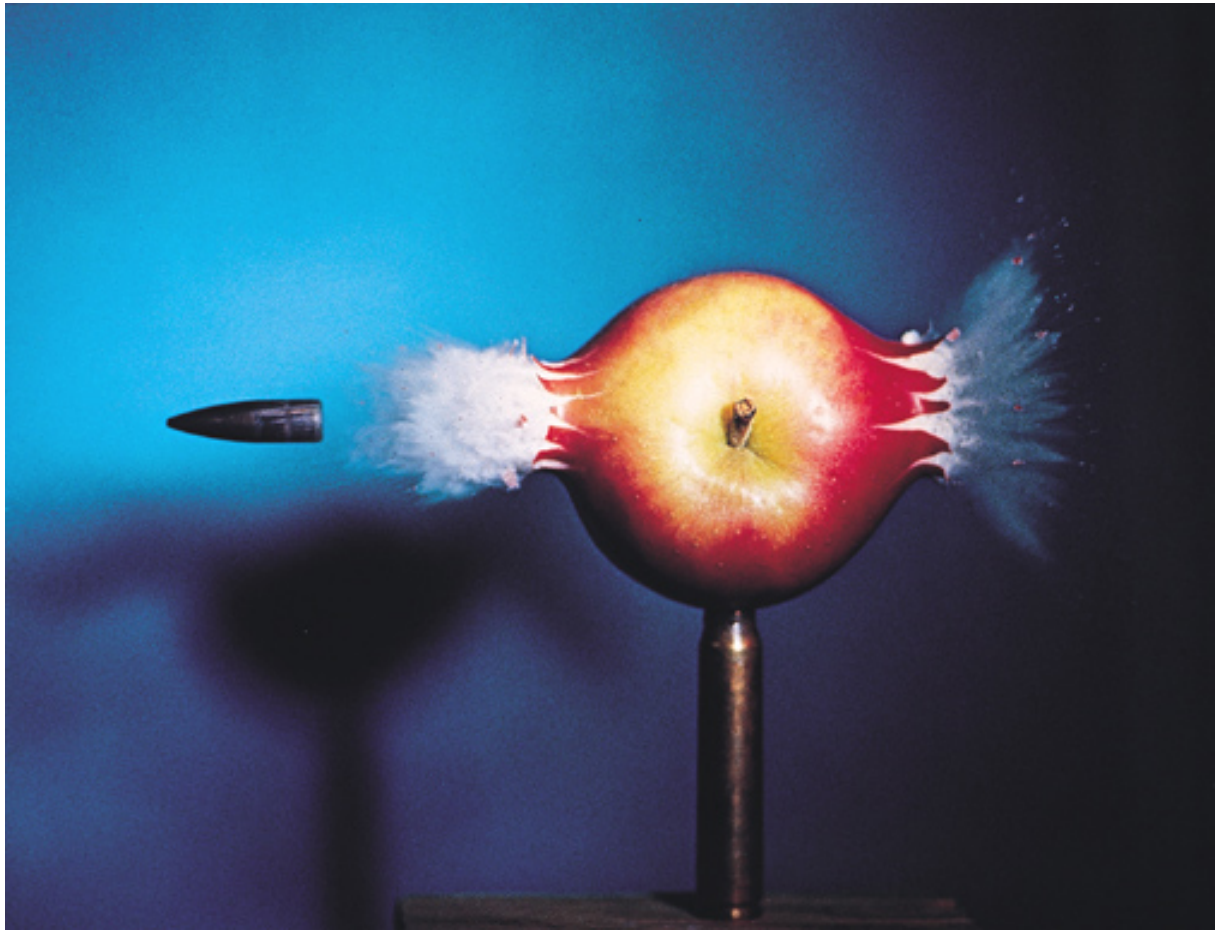
Backup Slides



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Typical Panel Failure

- **Target AL2**
  - .50-cal projectile
  - 8000 frames/second
  - Target bulk density: 70.18 lb/ft^3

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More TS6 Pictures

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•First steel plate shattered and blew out front of target after round ricocheted off second steel plate

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Witness Plates

- Witness plate simulates the shipping container wall
- If rounds penetrated the witness plate, panels are considered a failure

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