INL/CRADA-07-17

CRADA FINAL REPORT

Advanced Modeling and Simulation of Ballistic Event

Idaho National Laboratory

and

Alcoa, Inc.

Completed: November 24, 2009

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Project Report

Alcoa CRADA

November 24, 2009

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1. Abstract

In an attempt to explore the existence of a "shattering transition" and accompanying dip in the penetration-velocity curves, ballistic testing was conducted to create a series of high-velocity impacts of copper rods into a copper block. The program explored different launching methods and sabot designs. Testing included 23 shots, four of which resulted in usable test data. Future work is recommended to build on the developments of this small program.

2. Objectives

The purpose of this CRADA was to investigate the "dip" in the penetration-velocity curves that were previously observed and published by A.A. Abrikosov in 1957. A "shattering transition" was observed through experimental testing and explained with non-steady-state material equations of state. To explore the validity and accuracy of this historical study, projectile penetration testing was to be conducted at INL.

3. Project Specifics

CRADA No. 08-CR-17 between Alcoa and INL: Modification No. 1 (signed 12/4/08) extended the period of performance to November 27, 2009. The project budget was $30,000.

4. Progress

Upon initial ballistic testing, it was revealed that ballistic launching of a small copper rod was not reliable. Consequently, a study was necessary to first develop a reliable and repeatable means of launching small copper rods at velocities fast enough to probe the penetration-velocity "dip." In order to conserve the expensive copper rods, identically shaped steel rods were fabricated and used throughout this initial development.

All ballistic testing was conducted with a 14.5mm rifled-bore breach-loaded rail-mounted canon. Velocity measurements were made by a light-screen setup made by Oehler Research consisting of 3 LED-light screens (Model 57) spaced at 15 inch increments for a total span of 2 feet 6 inches. The three light screens were connected to a chronograph box (Model 87) which used a laptop's interface to provide a readout of each shot velocity. The center light screen was located 10 feet downrange from the end of the muzzle. 10 more feed downrange of the center light screen was the target. Pre-shot alignment measurements were taken to ensure that the target face was normal to the flight path. Targets were positioned on a test sled but not specifically attached. The target was allowed to slide backwards under the influence of the ballistic impact and only slight translation was observed because the relative inertia of the target was so much greater than the incoming projectile. Test-method development was conducted over an 11-month span that included varying temperatures, but final testing was conducted on a single day to prevent the bias of weather-related variables such as material properties.

Multiple sabots were developed to hold the copper rod while in the gun barrel. The first was a four-petal separating sabot. It featured a concave nose to drive separation under the influence of aerodynamic forces. Through testing, however, it was observed that the separating sabot petals would often "kick" the tail of the copper rod in flight, thus inducing yaw to the flight of the copper rod. This sabot was incapable of reliably launching a small rod such so that it would impact a target oriented normal to the target surface.

The second series of sabots was designed to initially stabilize the flight of the rod and separate in a less abrupt manner. The sabots were shaped like a bullet with a conical nose, and the copper rod sat in a hollow cylindrical core at the center of the sabot. In case the sabot failed to separate from the rod, the sabot was designed to have minimal impact on the target surface – the sabot was made of nylon, a soft polymer. This series of sabots was modified in a variety of ways in an effort to cause optimal in-flight separation. The sabot was partially and wholly split into two halves, the sabot was vented to enhance aerodynamic drag, the hollow core was bored to a variety of different sizes to achieve different tightnesses of fit on the contained rod.

Testing revealed that the split and vented modifications were unsuccessful at separating from the rod without disrupting the steady flight of the rod. The most successful means of ensuring a normal impact of the rod with the target surface was to allow the sabot to remain attached to the rod throughout the duration of the flight. In some fortunate instances, the sabot would slide off the back of the rod mid-flight – this was the best possible separation scenario, but did not occur reliably, more often the sabot stayed on the rod all the way to impact. Upon impact with "practice" targets made of steel, the nylon sabot caused no cratering on the impact surface. However, during actual testing, the soft copper surface was significantly affected by the impact of the soft nylon sabot. This does not disqualify the use of a non-separating nylon sabot as long as the method is consistent throughout testing. If the sabot is made of a consistent material, its effect on the target impact zone will not bias the rod penetration depth.

Final ballistic testing was conducted on November 19, 2009, using nylon bullet-shaped sabots carrying copper rods (2mm diameter, 2cm length). The sabot core was bored to a diameter to hold the copper rods strong enough that the rod would not slide out under the influence of gravity alone, but would also be easily removable by pinching the end of the rod with fingernails and pulling it out of the sabot. 10 shots were conducted, launching the copper rods at a variety of velocities toward a solid block of copper. Many of the shots flew off-line and resulted in a non-usable impact, however 4 different flights and impacts were satisfactory. They are highlighted in Table 1 below. Following ballistic testing, the budget for this project had been exhausted.

5. Discussion

Precise measurement of the penetration depth should still be conducted. In addition, more shots should be conducted at higher velocities and a separate test series should examine the impact of copper rods into an aluminum block to develop a similar velocity-penetration depth curve. Most of the original budget was spent developing a reliable testing method and future testing can be conducted with less preliminary development.

The primary source of difficulty in the development of a feasible testing method was the instable flight of the small rod. The small mass of the rod makes it especially susceptible to the influence of aerodynamic forces.

6. Conclusions and Recommendations

This phase of funding was used to develop a reliable method of rod launching and the optimal method was used to generate four ideal impacts. To build on this success and complete the project objectives, additional funding is necessary. Future work should first include a precise measurement of the four impact depths by electrical discharge machining (EDM) sectioning the copper blocks through the cross-section of each impact zone. Afterwards, additional testing should be conducted to gather more data points – specifically data points at higher velocities.

Future ballistic testing could employ a variety of different launching methodologies. For example, testing could involve larger cylinders that might enable the use of alternative sabot technologies that reliably separate from the rod without disturbing the flight of the rod. In fact, other research projects at INL have been developing reliable rod sabots for larger diameter rods. Additionally, a smooth-bore, small-diameter ($d_{bore} \approx d_{rod} = 2mm$) gas gun could be used to accelerate a bare copper rod toward the target with no sabot. Alternative velocity measurement methods could be employed and the flight distance reduced – from 20 feet as in the testing described above to less than 3 feet. These changes will help prevent destabilization of the rod caused by sabot separation and exposure to aerodynamic forces involved in extended flight.

7. Appendix

TWO TYPES OF SABOTS THAT WERE USED.

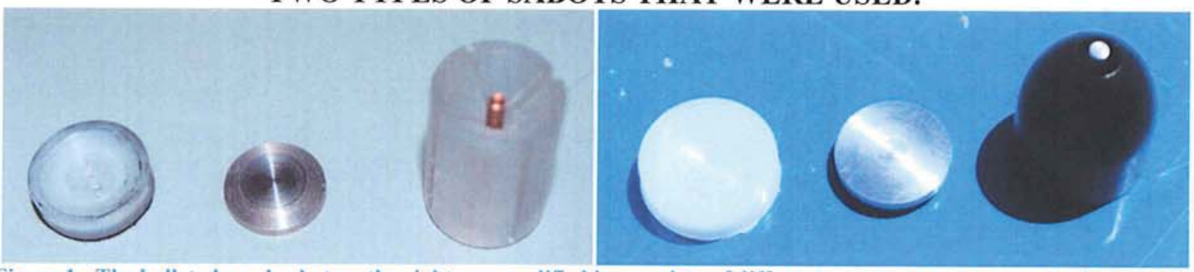


Figure 1 - The bullet-shaped sabot on the right was modified in a variety of different ways to create a vented sabot, a split sabot, and a solid sabot with a variety of different mouth openings and tightnesses of fit against the rod.

PHOTOS OF COPPER TARGET

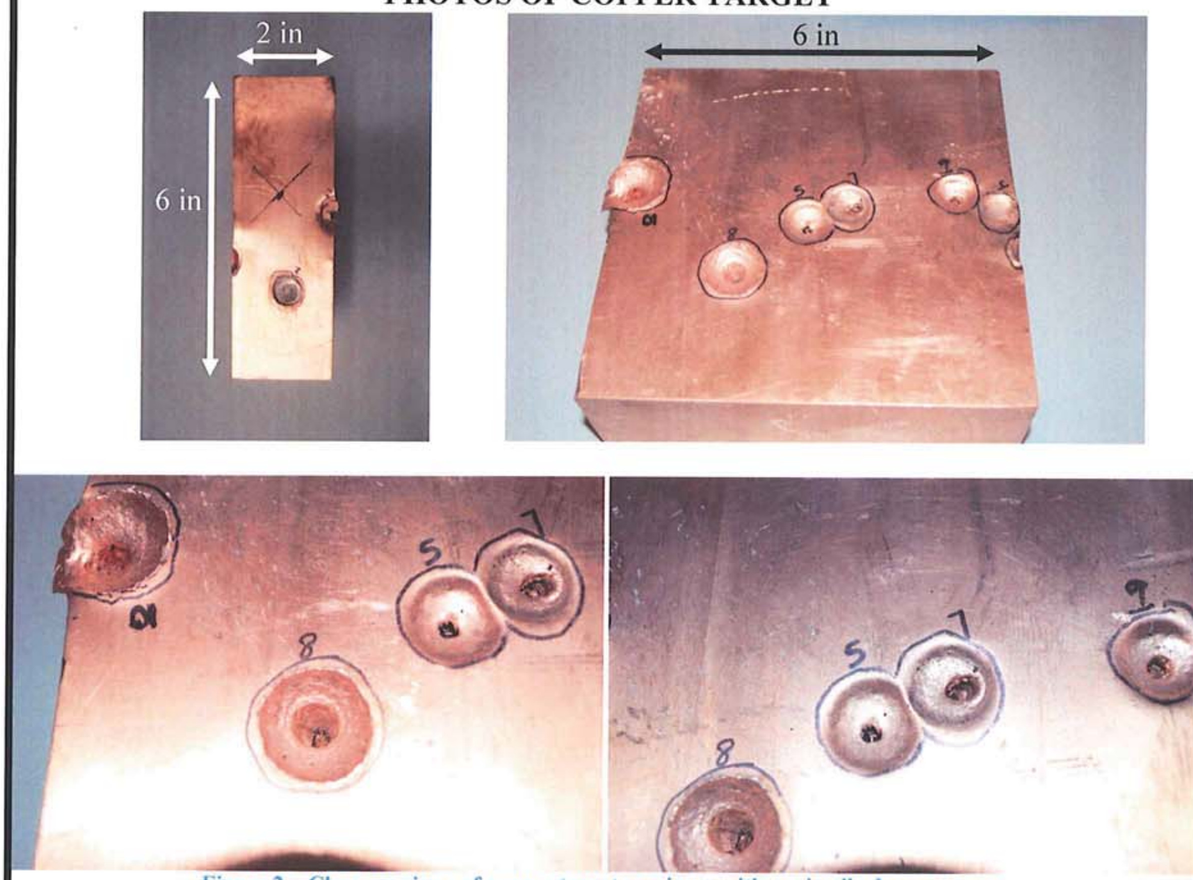
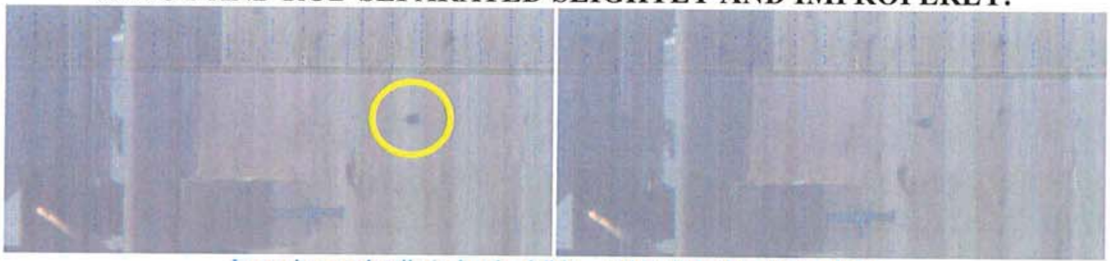
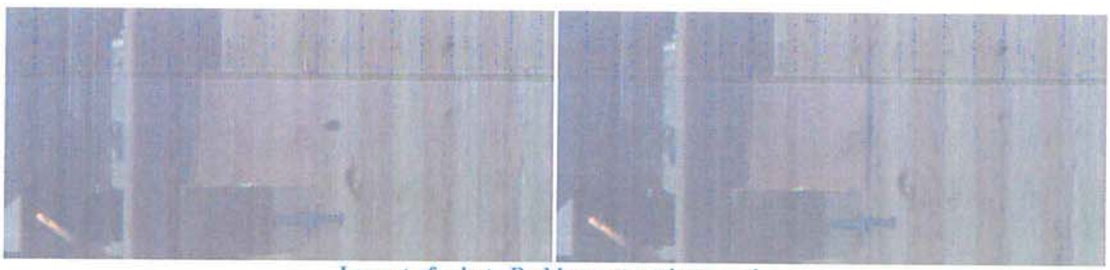


Figure 2 – Close-up views of copper target specimen with projectile damage zones

SERIES OF HIGH SPEED PHOTOS SHOWING AN EDGE IMPACT IN WHICH THE SABOT AND ROD SEPARATED SLIGHTLY AND IMPROPERLY.

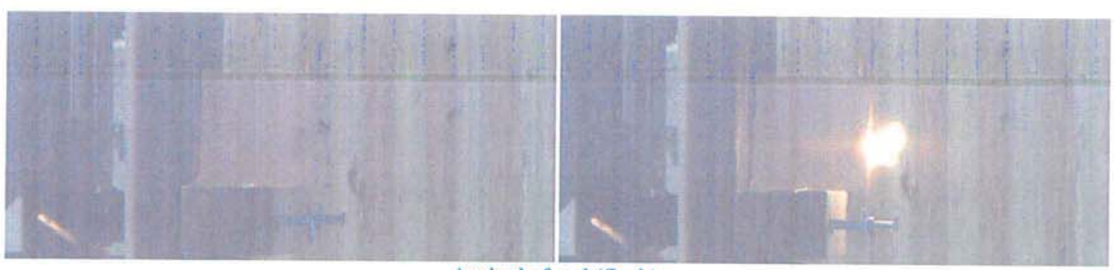


Incoming projectile (sabot is visible – rod is slightly behind sabot)

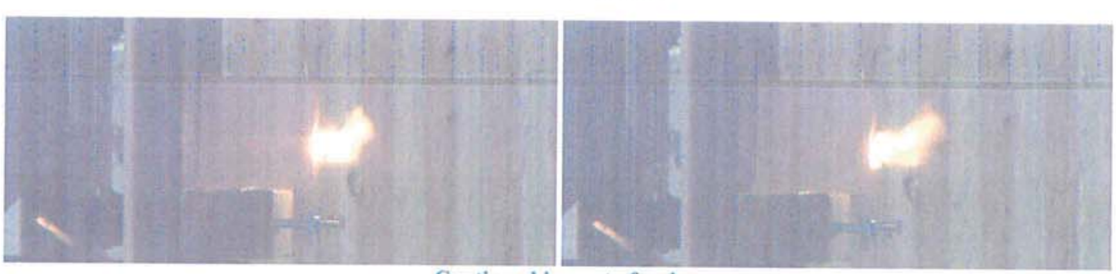


Impact of sabot. Rod has not yet impacted.

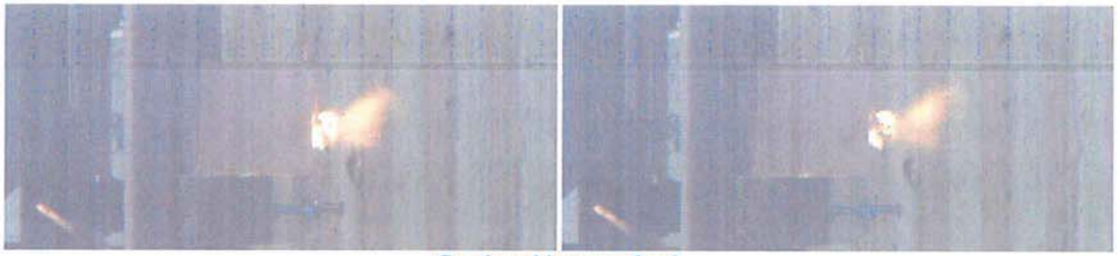
Continued impact of sabot



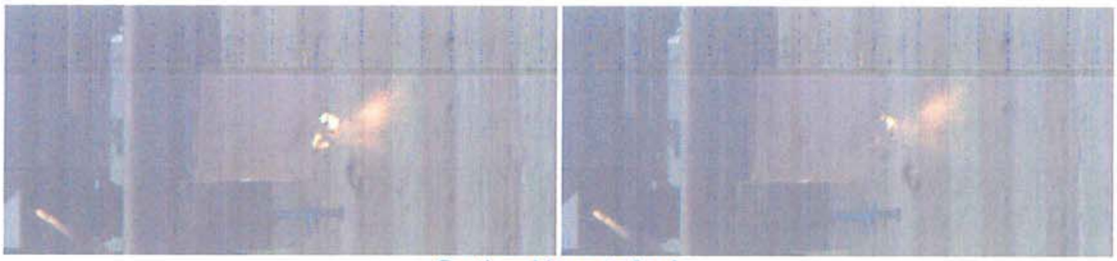
Arrival of rod (flash)



Continued impact of rod

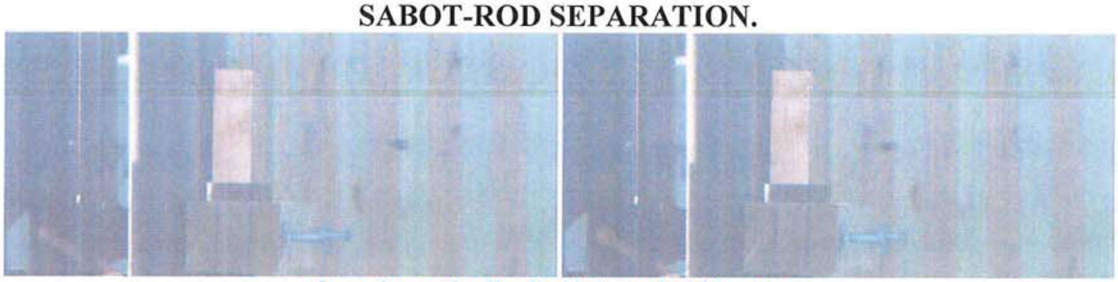


Continued impact of rod

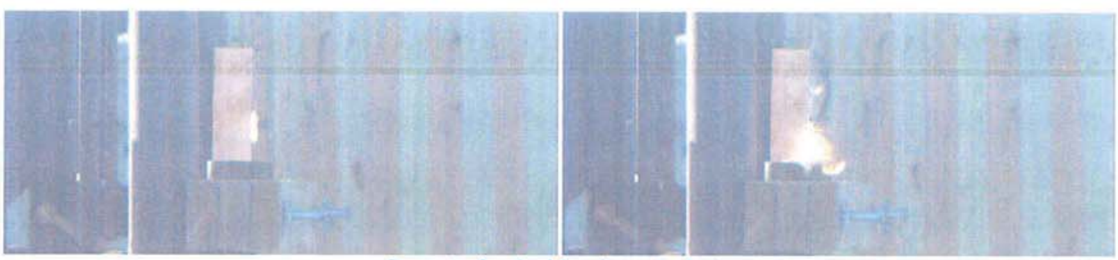


Continued impact of rod

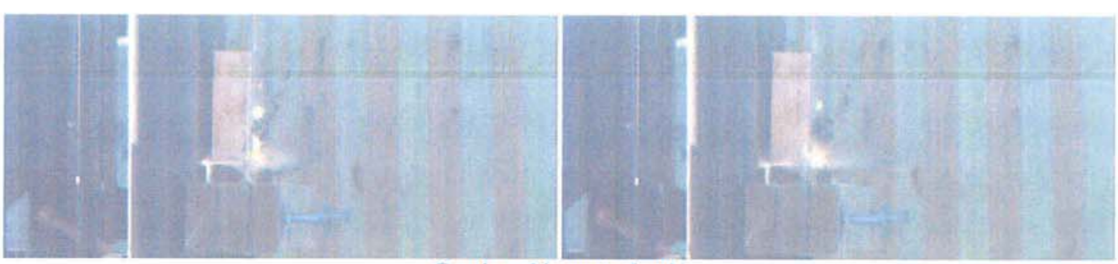
SERIES OF HIGH SPEED PHOTOS SHOWING A PROPER IMPACT WITH NO SABOT-ROD SEPARATION.



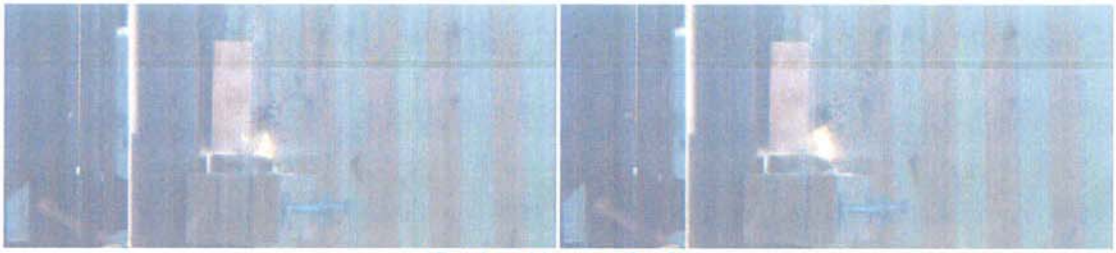
Incoming projectile. Rod is housed within sabot.

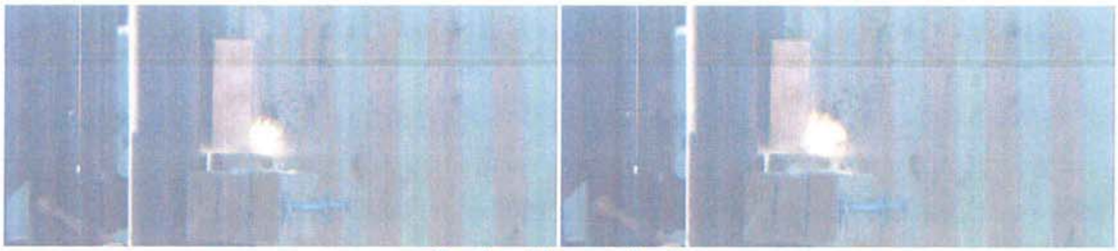


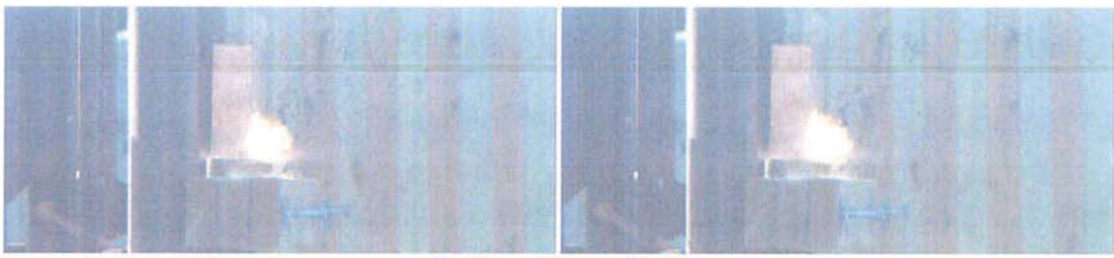
Impact of rod with sabot attached.



Continued impact of rod.


Continued impact of rod.


Continued impact of rod.


Continued impact of rod.

LIST OF ALL SHOTS

Shot Date	Primer (grains)	Powder (grains)	Sabot (see drawings below)	Projectile	Target	Velocity (feet/sec)	Result
1/14/09	57 gr Factory	400 gr BMG-50	4-petal	Cu rod	n/a	293.5	Good separation – straight flight
1/14/09	60 gr Factory	600 gr BMG-50	4-petal	Cu rod	n/a	?	Good separation – rod skew
1/14/09	60 gr Factory	600 gr BMG-50	4-petal	Cu rod	n/a	1840	Good separation – rod skew
1/14/09	60 gr Factory	600 gr BMG-50	4-petal	Cu rod	n/a	4146	
3/24/09	59 gr Factory	900 gr Reloader-22	4-petal	Cu Rod	n/a	?	
3/24/09	59 gr Factory	700 gr Reloader-22	4-petal	Cu Rod	n/a	?	
3/24/09	59 gr Factory	550 gr Reloader-22	4-petal	Cu Rod	n/a	?	Good separation – rod tumbling
5/21/09	59 gr Factory	600 gr IMR 4350	Bullet-shaped (tight)	Steel Rod	n/a	4292	No separation
5/21/09	59 gr Factory	500 gr IMR4350	Bullet-shaped (tight)	Steel Rod	HH Steel (0.25")	4299	No separation
7/20/09	59 gr Factory	601 gr IMR 4895	Bullet-shaped (5/64" hole)	Steel Rod	HH steel (0.25")	4596	No separation
7/20/09	59 gr Factory	600.7 gr IMR 4895	Bullet-shaped (5/64" hole)	Steel Rod	HH steel (0.25")	4930	Slight separation – rod slightly skew
7/20/09	59 gr Factory	500 gr IMR 4895	Bullet-shaped (2-part split)	Steel Rod	HH steel (0.25")	4215	Sabot split – rod tumbled
7/20/09	59 gr Factory	500.1 gr IMR 4895	Bullet-shaped (4-vent)	Steel Rod	HH steel (0.25")	4701	Separation – rod tumbling
11/19/09	59 gr Factory	250 gr IMR 4350	Bullet-shaped (5/64" hole)	Cu rod	Wood	2815	Penetration
11/19/09	59 gr Factory	250 gr IMR 4350	Bullet-shaped (5/64" hole)	Cu rod	Cu block	2212	Slight separation - Right edge impact
11/19/09	59 gr Factory	250 gr IMR 4350	Bullet-shaped (5/64" hole)	Cu rod	Cu block	2994	Left edge impact
11/19/09	59 gr Factory	250 gr IMR 4350	Bullet-shaped (5/64" hole)	Cu rod	Cu block	3307	Missed
11/19/09	59 gr Factory	250 gr IMR 4350	Bullet-shaped (5/64" hole)	Cu rod	Cu block	3111	HIT
11/19/09	59 gr Factory	350 gr IMR 4350	Bullet-shaped (5/64" hole)	Cu rod	Cu block	1293	Missed (hit light screen shield)
11/19/09	59 gr Factory	350 gr IMR 4350	Bullet-shaped (5/64" hole)	Cu rod	Cu block	3365	HIT
11/19/09	59 gr Factory	450 gr IMR 4350	Bullet-shaped (5/64" hole)	Cu rod	Cu block	3849	HIT
11/19/09	59 gr Factory	550 gr IMR 4350	Bullet-shaped (5/64" hole)	Cu rod	Cu block	3121	HIT
11/19/09	59 gr Factory	650 gr IMR 4350	Bullet-shaped (5/64" hole)	Cu rod	Cu block	4219	Edge impact

Table 1 – List of all shots including powder, sabot, projectile, and target details.

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