EXPERIMENTAL STUDIES INTO THE SURVIVAL AND STATE OF THE PROJECTILE. R. T. Daly[1] and P. H. Schultz[1], [1]Department of Geological Sciences, Brown University, 324 Brook Street, Box 1846, Providence, RI, 02912; (ronald_daly@brown.edu).

Introduction: Over the past few decades, our insight into impact cratering processes and products has increased dramatically. However, our understanding of what happens to the projectile during impact remains incomplete. Impactor contamination continues to be suggested as a possible explanation for exciting new observations, such as dark crater materials on Vesta [1,2]. As a result, questions about how much of the projectile survives impact and is retained by the target, along with questions about the physical state and particle sizes of surviving projectile material, must be resolved.

We report results from experiments at the NASA Ames Vertical Gun Range (AVGR) that determine the fraction of solid projectile material retained on the floor, sub-floor, and near-rim portions of the crater and characterize the physical state of surviving projectile material. Here we focus on projectile material that survives (solid state or quenched melts).

Prior Work: Previous experiments and numerical models have shed some light on what happens to the projectile during impact. Experiments reveal that the projectile decapitates during oblique impact, with the upper part of the projectile decoupling from the lower part and impacting downrange of the main crater [3,4,5], especially at large scales [4,6].

Numerical models (at higher speeds than laboratory experiments can attain) have studied the thermodynamic state of the projectile [7,8] and tried to determine how much of it is retained by the target [7–11]. But, uncertainties in how tracers are advected through hydrocode models lead to uncertainties about the results of these studies [9]. In addition, the models in [8–11] assume that the target retains all material moving with $v < v_{esc}$. While this is a useful criterion, it would be more useful to understand how the retained projectile is distributed in and around the crater and across the target. Bland et al. [7] report some models that examine this question, but more work is needed for different target types and conditions.

Methods: Experiments at the AVGR enabled studying the survival of aluminum and basalt projectiles impacting porous silicate and porous ice targets. Impact speeds ranged from 4 to 6 km s^{-1} with impact angles between 15° and 90° with respect to horizontal using aluminum, Pyrex, and basalt projectiles (0.635 cm to 1.27 cm in diameter).

Another series of experiments assessed Pyrex and basalt projectiles fired into copper blocks using similar velocities at 30° from horizontal. Most experiments used ¼" diameter projectiles. However, a lower-velocity experiment used a ½" diameter basalt sphere. This larger projectile enables easy recovery and characterization of the surviving projectile material.

Impact speeds used in these experiments capture the majority of impact speeds expected at Vesta, and in the asteroid belt generally [12]. Indeed, the mean impact speed at Vesta is 4.75 km s^{-1} [12]. As a result, these experiments are directly relevant to Vesta and to the origin of crater-related dark materials.

The AVGR impact chamber was cleaned prior to and in between experiments to minimize contamination. After each experiment, projectile fragments were collected on the crater floor, near the rim, and in the region beyond the target bucket. For impacts into snow or ice, the snow or ice was melted and the melt water filtered or evaporated in order to isolate the surviving projectile fragments. We hand-sorted collected material grain-by-grain, under a microscope, to remove stray debris. For experiments into porous silicate targets, surviving projectile material was hand-picked from the target and then sorted to remove contamination. Other experiments used a small tray of target material and captured projectile remnants in catchers below. This strategy retains the initial shock conditions but reduces the amount of material that must be sorted through. Finally, selected experiments captured projectile remnants in aerogel downrange.

The present study focuses on the projectile retained in the crater floor, sub-floor, and near-rim and its results. This strategy is highly relevant to the small, localized regions of dark material associated with some impact craters on Vesta, but less so to the global dispersion of dark material that Reddy et al. [2] suggest may be due to the Veneneia impactor. The localized focus of this study complements the more global focus of some of the prior numerical models (e.g., [5;7–8]).

Fractions of the projectile ejected at high speeds typically cannot be recovered. Nevertheless, aerogel permits the capture of some projectile fragments during oblique impacts. Large or multiple fragments may shatter the aerogel. Placing the aerogel behind a small opening mitigates this issue.

After collection, the surviving projectile material from each experiment was weighed. In addition, optical and electron microscopy helped characterize the physical state of the projectile fragments.

Results: Impacts into icy, volatile-rich targets and porous silicate targets lead to surviving projectile material with different morphologies. An aluminum projectile into pumice leads to intimate mixtures of melted projectile material and compressed vesicular pumice (Figure 1). Most of the mass of the surviving projectile material, along with the largest projectile-pumice aggregates, is located in the crater floor.

An aluminum projectile into a snow target, however, leads to several distinct fragments that appear to be pure aluminum, along with small (microns) frothy gray fragments of aluminum oxide. The distinctive survival of the large aluminum fragments is attributed to the rapid quenching by the icy target, with most of the projectile's mass concentrated in a few relatively large, irregularly-shaped pieces (Figure 1).

Many of the larger aluminum fragments from impacts into snow are curved, with a shiny, concave face and a duller, convex side (Figure 2). In two experiments, breccias of sand grains bound together by melted aluminum formed. Ongoing studies using optical and electron microscopy will establish the nature of these complex aggregates, as well as the physical state of the recovered projectile fragments.

Conclusions: We have studied the amount of projectile that survives impact during experiments at the NASA Ames Vertical Gun Range. We have also examined the physical state of surviving projectile fragments. Experiments include aluminum and basalt projectiles impacting into porous silicate and porous icy targets at speeds ranging from 4 to 6 km s^{-1}. Preliminary results indicate successful recovery of projectile fragments from the crater floor, sub-floor, and near-rim, with the morphology of surviving projectile material highly dependent on the volatile content of the target. This work sheds new light on the fate of the projectile during impact and will provide additional constraints on the formation of dark material on Vesta dark material and affords insights into the role of quenching during impact on icy surfaces, e.g., Mars polar terrains and possibly Ceres.

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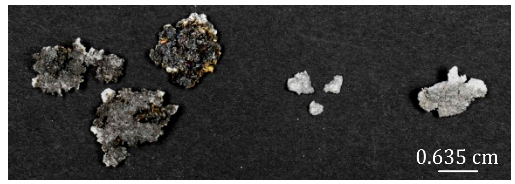

Figure 1. Projectile material from the impact of a 6.35 mm diameter aluminum projectile into pumice at 5.58 km/s (at left), a 6.35 mm diameter aluminum projectile into snow at 5.34 km s^{-1} (at center), and a 6.35 mm basalt projectile into pumice at 4.47 km/s (at right). The scale bar indicates the original projectile diameter.

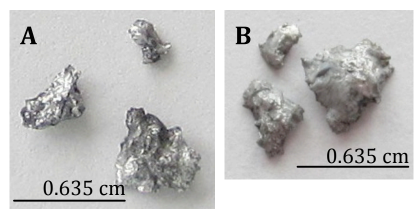

Figure 2. The three largest recovered fragments from a 6.35 mm diameter aluminum projectile impacting snow at 5.34 km/s (60°). The images show two sides of the same fragments. The scale bar shows the original projectile diameter. Note the different lusters of the fragment faces in A and B. In addition, the surfaces in A are roughly concave, while the surfaces shown in B are approximately convex. The surface of largest fragment in B shows evidence of flow-textures.

Table 1. Projectile Survival During Impact of ¼" Diameter Aluminum Projectiles

Target	Speed (km/s)	Angle (°)	Recovered Projectile Material (g)	% of Original Projectile Mass	Undivided Sample (g)[b]
Snow	5.10	30	0.0713	18.9%	1.0803
Snow	5.34	60	0.1007	26.8%	0.0396
Pumice	5.58	90	2.0959	557%[a]	N/A

[a]Totals >100% indicate that the collected material is a mixture of melted projectile and pumice.

[b]The finest fraction of the samples is too fine-grained to separate Al fragments from other debris without losing projectile material. As a result, these fractions are unsorted, but they are largely composed of frothy-looking dark material, which may be aluminum oxide.