PROGRESS ON PLANETARY DEFENSE AT LOS ALAMOS NATIONAL LABORATORY. M. L. Harwell[1], C. S. Plesko[1,2], S. A. Becker[1], C. M. Biwer[1], M. B. Boslough[1], L. Margolin[1], A. L. Truitt[1] [1]Los Alamos National Laboratory, [2]Corresponding Author: plesko@lanl.gov.

Introduction: Los Alamos National Laboratory (LANL) has been tasked by the National Nuclear Security Agency (NNSA) to study the mitigation of the impact hazard of asteroids and comets on the Earth as part of an inter-agency agreement (IAA) with National Aeronautics and Space Administration (NASA). We are modeling deflection or disruption of hazardous objects by kinetic impactor (KI) and nuclear explosive device (NED). KIs transfer momentum directly through impact and target-dependent momentum enhancement of ejecta. NEDs impart momentum to the target by vaporizing target material and lofting it, and in some cases entrained solid material, away from the body.

The goal of the interagency collaboration is to foster a joint capability between NASA and NNSA to model the effects of an impact on Earth, to model the mitigation of a potentially hazardous object (PHO), and to develop designs for reconnaissance and mitigation missions in fulfillment of goals 2 and 3 of the National Action Plan [1]. To date, we have completed a code-to-code comparison [2], two case studies [3,4], and one mitigation mission design study [4]. We are currently working on a third case study and will participate in a mission design study for a reconnaissance mission during the last week of August 2019.

Methods: We use the RAGE [5,6], Flag [7] and Pagosa [8] hydrocodes with various strength and porosity models to simulate the effect of different impactors on target asteroids of varying shape and composition. We also model x-ray energy deposition from a nuclear stand-off burst using the RAGE and Flag hydocodes' gray diffusion radiation transport model in combination with the SESAME equation of state and opacity tables to simulate the flow of wave-like light in a problem [9]. Gray diffusion is similar to a black body model except the bodies absorb and radiate with an inefficiency, $\sigma < 1$.

Our figure of merit for KIs is β, the ratio of the momentum of the remaining target after all ejecta with $v > v_{esc}$ has left the system. We calculate β using -1x the momentum of all ejecta where $v_y > v_{esc}$, since our models are frequently symmetric across the y-axis. Our models to date do not include gravity, so our βs may be over-estimates because there is no gravitational force opposing the surface reflection of the impact shock that spalls material outside the crater. Our figure of merit for NEDs is the change in velocity of the target object.

Recent Results: We have worked on two sets of KI scenarios during 2019. In support of the IAA's second case study, we modeled KI mitigation attempts against a target similar to the DART mission team's pre-launch design reference asteroid model for Didymos B [10] using larger, higher-velocity impactors intended to deflect it (Tab. 1).

Model	Impactor Mass [kg]	Impactor Velocity [km/s]	Impact Angle [°]
1	10350.4	19.75	0
2	10350.4	19.75	90
3	7897.0	8.1	0
4	7897.0	8.1	90

Table 1. Case Study 2 KI impact parameters.

We find that our 2D axi-symmetric Flag models predict that the chosen KI scenarios, which assumed β~1, pose a risk of disruption to the target (Tab. 2) because a significant amount of spalled material is predicted to be thrown off the object from outside the crater (Fig. 1), suggesting β >>1, and changes in velocity larger than the escape velocity of the target object, which would risk disruption.

Model	m_i [kg]	v_i [km/s]	θ_i [°]	m_{ej} [kg]	β	Δv [cm/s]
1	10350.4	19.75	0	$> 6.7 \times 10^7$	> 7	> 30
2	10350.4	19.75	90	$> 1.2 \times 10^9$	> 17	> 100
3	7897.0	8.1	0	8.2×10^8	21	36
4	7897.0	8.1	90	1.3×10^8	20	38

Table 2. Case Study 2 model results.

These results are expected to be an upper bound on spall and β for the modeled scenario, but they do indicate a need for further study.

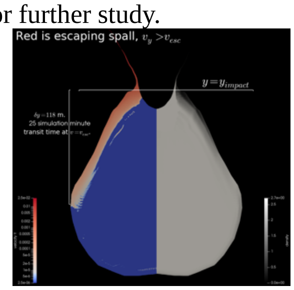

Figure 1. KI impact along the long axis of a Didymos B-like target showing a substantial amount of surface spall at $v_y > v_{esc}$.

In support of the IAA's third case study, we are studying KI and NED attempts against an irregularly shaped object. We are using the shape model for comet 67P [11], but scaled down to ~200 m diameter, and assuming a dry SiO_2 composition with a bulk density of

0.5 g/cc. The initial conditions for the KI scenarios are shown in Tab. 3.

Model	m_i [kg]	v_i [km/s]	θ_i [°]	m_{ej} [kg]	β	Δv [cm/s]
2a	1156.0	8.218	0	$> 2.6 \times 10^{10}$	> 11	> 1.7
2b	1156.0	8.218	90	$> 1.3 \times 10^{8}$	> 8	> 1.34

Table 3. Initial 3D KI model results.

Our calculations are ongoing, in a 3D cartesian geometry, and suggest some concerns about extra-crater material ejected from the surface at $v > v_{esc}$ contributing more momentum than expected to β. The extreme (80%) porosity of this case limits the effect, which is not as strong as is seen in Case Study 2 (25% porosity).

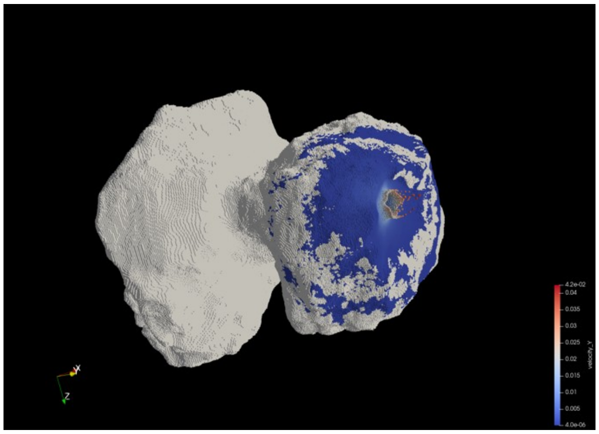

Figure 2. 3D Flag model of a KI attempt on a bi-lobate, highly-porous, 200-m target, colored by velocity.

We begin calculations for deflection with a NED stand-off burst by estimating the desired Δv and the energy required to disrupt and disperse the target (Q^*_D). Requiring $\Delta v < v_{esc}$, the maximum kinetic energy that can be imparted to the target is 1.1×10^4 J, or 3×10^{-9} kt. Estimating $Q^*_D \sim 0.05$ J/kg or $Q^*_D \sim 100$ J/kg per [12], with the specific internal energy of silicate vapor at T~ 0.5 eV ~ 6.5 MJ per [9], no more than 0.001% of the target can be vaporized to stay below that limit.
If a 2.5 cm layer of the broad side of the target (about 3×10^5 kg) were heated to T ~ 0.5 eV, that would impart 1.8×10^6 MJ, or about 1×10^{-4} kt. Alternately, at 6.5 MJ/kg, it would take about 1 MT of energy soured evenly into the target to vaporize it. A margin corresponding to a multiple of 1/f, where f is the fraction of the energy that passes through the solid angle subtended by the target at the desired height of burst, divided over multiple launches, may be feasible [4].

Future Work: We will participate in a mission design lab (MDL) exercise at NASA Goddard during the last week of August 2019, where we will assist in the development of a reconnaissance mission concept driven by the target properties that are most important for predicting the outcome of a mitigation attempt, specifically, the object's composition, mass, shape, and approximate bulk density and strength. We are supporting the DART mission as part of the mission investigation team's impact working group. Future studies will also include mitigation of notional targets that include a significant proportion of volatiles, and studies of the effects of airbursts on Earth's atmosphere.

References: [1] "National Near Earth Object Preparedness Strategy and Action Plan", https://www.whitehouse.gov/wp-content/uploads/2018/06/National-Near-Earth-Object-Preparedness-Strategy-and-Action-Plan-23-pages-1MB.pdf, accessed June 24, 2019. [2] Weaver, R. P. et al., LA-UR-16-20205. [3] Syal, M. B. et al., Acta. A. in press. [4] Barbee, B., et al., Acta A. 143, pp. 37-61 (2018). [5] Gittings M. L. et al., Comp. Sci. Disc 1, 2008. [6] Plesko, C. S. Thesis, UCSC, 2009. [7] Burton, D. E. Advances in the Free-Lagrange Method Including Contributions on Adaptive Gridding and the Smooth Particle Hydrodynamics Method pp. 7-19. [8] Weseloh, W., LA-CP-12-00586. [9] Lyon, S. P., Johnson, LA-UR-92-3407, 1992. [10] Hergenrother C. W., et al. *Icarus 226:663–670, 2014.* [11] Preusker, F., et al. A&A v. 607 L1, 2017. [12] Dobrovolskis, A. R., and D.G. Korycansky. Icarus, 303:234-250 (2018).

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