ASTEROID DEFLECTION: SENSITIVITY TO MATERIAL PROPERTIES. M. T. Burkey,[1] M. Bruck Syal,[1] R. A. Managan,[1] Owen, J. M.,[1] and D. S. P Dearborn,[1] [1]Lawrence Livermore National Laboratory, P.O. Box 808, Livermore, CA, 94550, USA.

Introduction: While the orbit of 99942 Apophis is well-defined and gives no indication for concern about an Earth impact in the near future, its 2029 close passage offers an extraordinary opportunity to learn more about potential near-Earth asteroid threats. In particular, there is much to be gained by sending a reconnaissance mission to Apophis, as the material properties of near-Earth asteroids remain poorly constrained. If a deflection mission is needed in the future, accurate numerical simulation of asteroid response depends partly upon our understanding of near-Earth asteroid material properties.

The 2010 National Research Council report to the United States Congress found that with enough notice, a kinetic impactor would be the first choice of defense against an Apophis-like catastrophe [1]. On a timescale of a decade or more, an impactor can be effective in some scenarios. However, in the event of a surprise shift in trajectory such as passage through a gravitational "keyhole," or if another Apophis-like asteroid were to present itself with little time before impact, nuclear mitigation would be the next best deflection option before resorting to emergency response. Recent research has shown that 101955 Bennu, which has a 1/2700 chance of impacting Earth in the late 2100's, would require six successful deflections by the maximum transportable payload by NASA's SLS rocket, even with 25 years of warning time [2]. In contrast, one nuclear deflection with extant technology is sufficient (and would not require the SLS) [3].

As a result, there has been significant work within the planetary defense community to model both kinetic and nuclear deflection of asteroids using multi-physics codes, including ongoing interagency collaboration to quantify uncertainties associated with using these approaches to deflect an asteroid. Outside uncertainties associated with modeling these exotic worlds completely and correctly, including the general lack of knowledge about a targeted asteroid's structure and geo-technical properties, would be a large limiting factor in determining the range of outcomes for the asteroid's response. The close approach of Apophis to Earth in April 2029 would be an ideal opportunity to put constraints on the most relevant uncertainties for the small but rapidly growing body of knowledge gathered from probes directly visiting asteroids that could one day be applied to a new near-Earth asteroid (NEA) threat.

Kinetic Deflection Uncertainties: Previous work has looked extensively at how near-Earth asteroid material properties can affect kinetic impact deflection outcomes [4]. Strength, porosity, shape, rotation, and equations of state can each affect the impact ejecta properties and extent of damage in the asteroid. Both of these outcomes are important for predicting the total delivered impulse (spacecraft momentum plus ejecta momentum) and the risk of weak disruption in a vigorous push scenario (where the needed change in speed approaches the asteroid's escape speed).

More recent work has added in the details of rubble pile structure effects, wherein the porosity of an asteroid can be accounted for in a stochastically-varying distribution of boulder shapes and sizes, with matrix material filling in the gaps (Fig. 1). Stress wave interactions with these more realistic structures are substantially different than for a homogenous asteroid model. This has repercussions for both kinetic and nuclear deflection of asteroids. Another aspect of advancing simulation capabilities is fine resolution of the spacecraft shape itself, while including the entire asteroid in the calculation (Fig. 1). Much of this work is motivated by the upcoming DART mission [5].

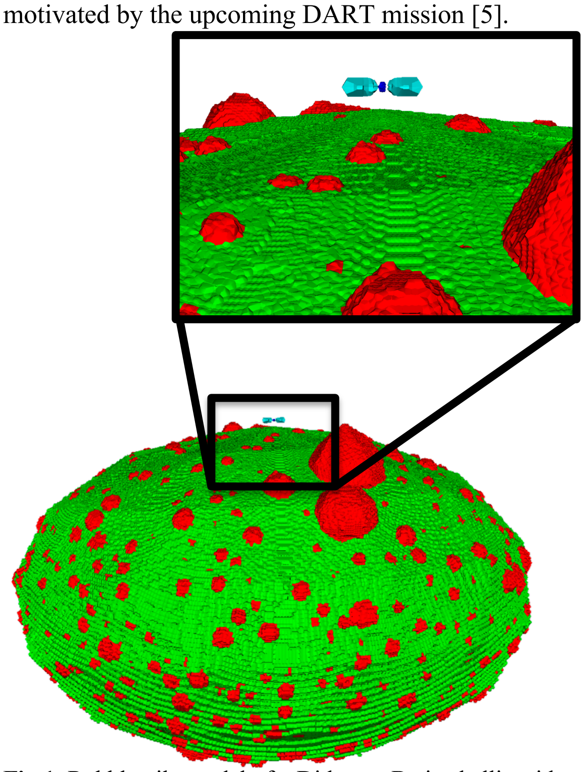

Fig 1. Rubble pile model of a Didymos B-sized ellipsoid and DART-scale impactor. Boulder material (red) is modeled with distinct properties from the matrix material (green).

Nuclear Deflection Uncertainties: Nuclear mitigation can be divided into two different methods, where the mode of choice depends on the details of the orbit, warning time, and size of the asteroid.

Nuclear Deflection. The first method, nuclear deflection, involves detonating a nuclear device at a distance with the intent of releasing enough photons and neutrons to melt and vaporize some surface material, which will ablate away and deliver opposing momentum to the still-intact asteroid. An example simulation of a nuclear deflection for a Bennu-shaped asteroid can be seen in Fig. 2.

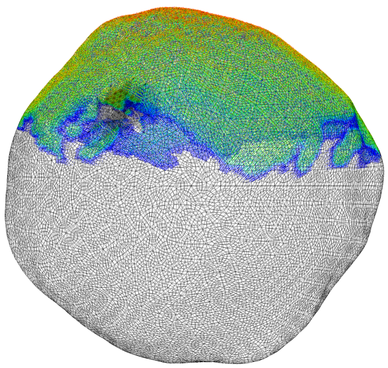

Fig 2. Nuclear deflection using x-rays deposited on a half-scale Bennu shape model (250-m diameter). Red indicates velocities of 10 km/s and blue indicates 10 cm/s. Here, only the near-surface region is modeled, to focus on quantifying blow-off momentum from vaporized and melted material.

When using this method, the surface properties of the asteroid are of particular interest. Understanding the energy deposition behavior for the materials present in the asteroid's surface is paramount to making a correct deflection velocity (Δv) estimate. Prior work has included some initial scans over material choices to calculate sensitivities, finding variations in the resulting Δv of up to a factor of three [3,6]. None of those explorations included the detailed mineralogies of asteroidal materials (or approximate surrogates); studies are currently underway to determine what the effects of adding iron, or using more realistic asteroid compositions might yield. Preliminary studies (see Fig. 3) indicate that the presence or lack of iron could have a nontrivial impact on Δv estimates.

Nuclear Disruption. For short warning time scenarios, when deflection can't work, a nuclear disruption can be carried out (Fig. 4). This involves coupling as much energy as possible to the asteroid, so that the shock wave pulverizes the asteroid into a well-dispersed fragment distribution. The fragment distribution is then tracked using an n-body integrator, to confirm that these smaller pieces will miss the Earth by a wide margin.

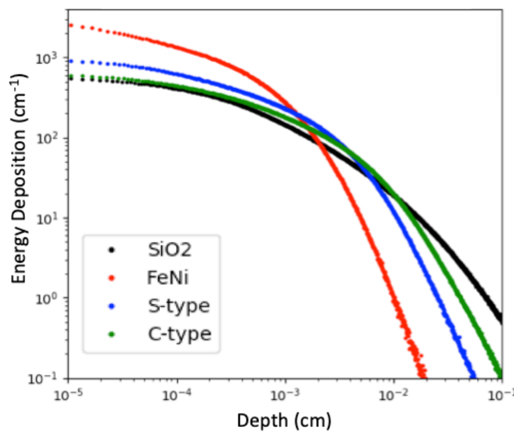

Fig 3. Normalized x-ray energy depositions for various asteroid compositions.

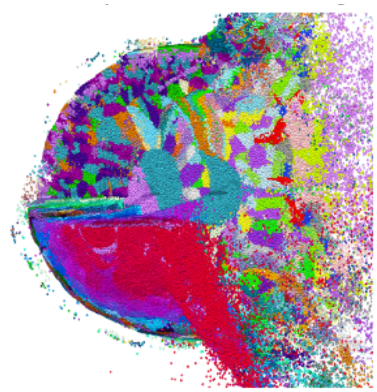

Fig 4. Disruption calculation for a 50-m Fe-Ni asteroid, using 1 Mt proximity burst. Each color represents a fragment after the shock wave shatters the asteroid.

Applications for Apophis: We will present the current understanding of how asteroid material properties affect both kinetic and nuclear deflection and disruption outcomes. This will include new energy deposition and reradiation calculation efforts. These results will be relevant for Apophis mission design and instrumentation choices which seek to inform planetary defense.

References: [1] National Research Council Reports to Congress, Defending Planet Earth: Near-Earth Object Surveys and Hazard Mitigation Strategies. (2010). [2] Barbee B. W. et al. (2018) *Acta Astronautica, 143,* 37–61. [3] Dearborn D. S. P. et al. (2020) *Acta Astronautica, 166,* 290–305. [4] Bruck Syal M., Owen, J. M., and Miller, P. L. (2016) *Icarus, 269*, 50-61. [5] Stickle, A. M. et al. (2017) *Proc. Eng., 204*, 116-123. [6] Howley K. M., Managan R. A., and Wasem J. (2014), *Acta Astronautica*, *103,* 376–381.

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