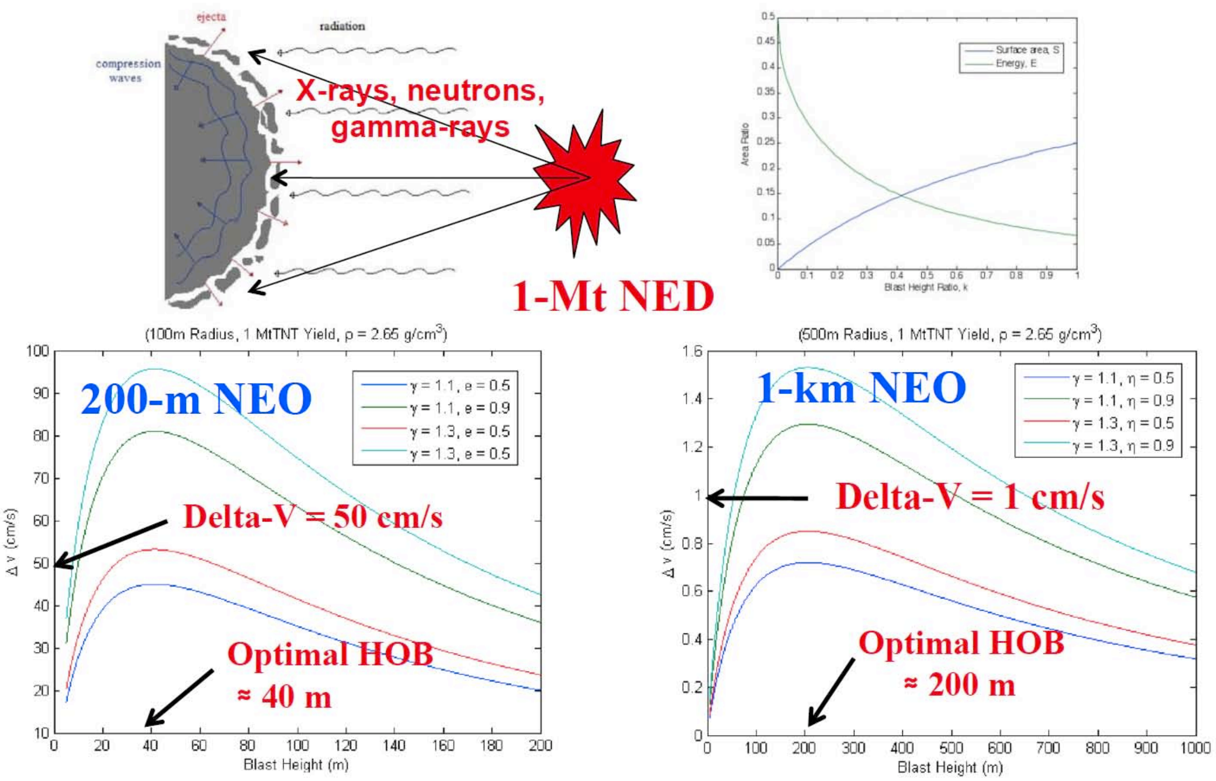


Figure 2: A summary of the ideal deflection ΔV performance characteristics of a standoff nuclear explosion [3].

have very low porosity that may absorb excess energy without the hydrodynamic rebound that can amplify the original impulse.

Because nuclear energy densities are nearly a million times higher than those possible with chemical bonds, it is the most mass-efficient means for storing energy with today's technology. Consequently, even in the standoff mode, a nuclear explosion is much more effective than all other non-nuclear alternatives, especially for larger NEOs with a short mission lead time. A summary of the deflection ΔV performance characteristics of a nuclear standoff explosion is provided in Fig. 2 [3]. It is very important to note that any NEO deflection/disruption effort must produce an actual orbital change much larger than predicted orbital perturbation uncertainties from all sources. Also, any NEO deflection/disruption approach must be robust against the unknown material properties of a target NEO.

Another nuclear technique involving the subsurface use of nuclear explosives is in fact more efficient than the standoff explosion. The nuclear subsurface method, even with shallow burial to a depth of 3-5 m, delivers large energy so that there is a likelihood of totally disrupting the NEO. A common concern for such a powerful nuclear option is the risk that the deflection mission could result in fragmentation of the NEO, which could substantially increase the damage upon its Earth impact. In fact, if the NEO breaks into a small number of large fragments but with very small dispersion speeds, the multiple impacts on Earth might cause far more damage than a single, larger impact.

However, despite the uncertainties inherent to the nuclear disruption approach, disruption can become an effective strategy if most fragments disperse at speeds in excess of the escape velocity of an asteroid so that a very small fraction of fragments impacts the Earth. When the warning time is very short, disruption is the only feasible strategy, especially if all other deflection approaches were to fail.

HYPERVELOCITY NUCLEAR INTERCEPTOR (HNI) CONCEPT OVERVIEW

In the mid 1990s, researchers at the Russian Federal Nuclear Center examined a conceptual configuration design of a rigidly connected, two-segment nuclear penetrator system as illustrated in Fig. 3 [4]. Because this configuration, even with a fore segment equipped with shaped charge, still limited the impact velocity to less than 1.5 km/s, researchers at the Central Institute of Physics and Technology in Moscow, Russia also conducted a preliminary simulation study of a concept for high-speed penetrating subsurface nuclear explosion [5]. The concept employed a fore body followed by an

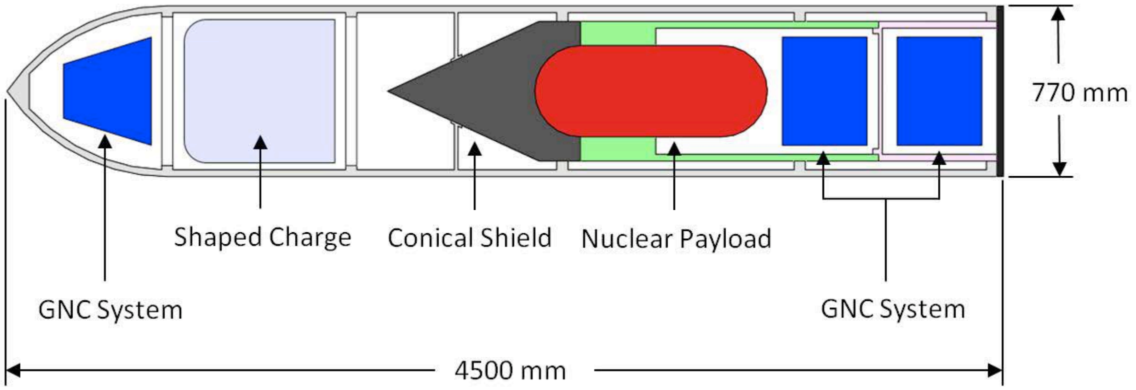


Figure 3: Conceptual illustration of a two-segment nuclear penetrator system proposed by Russian scientists in 1997, which still limited the impact velocity to less than 1.5 km/s [4].

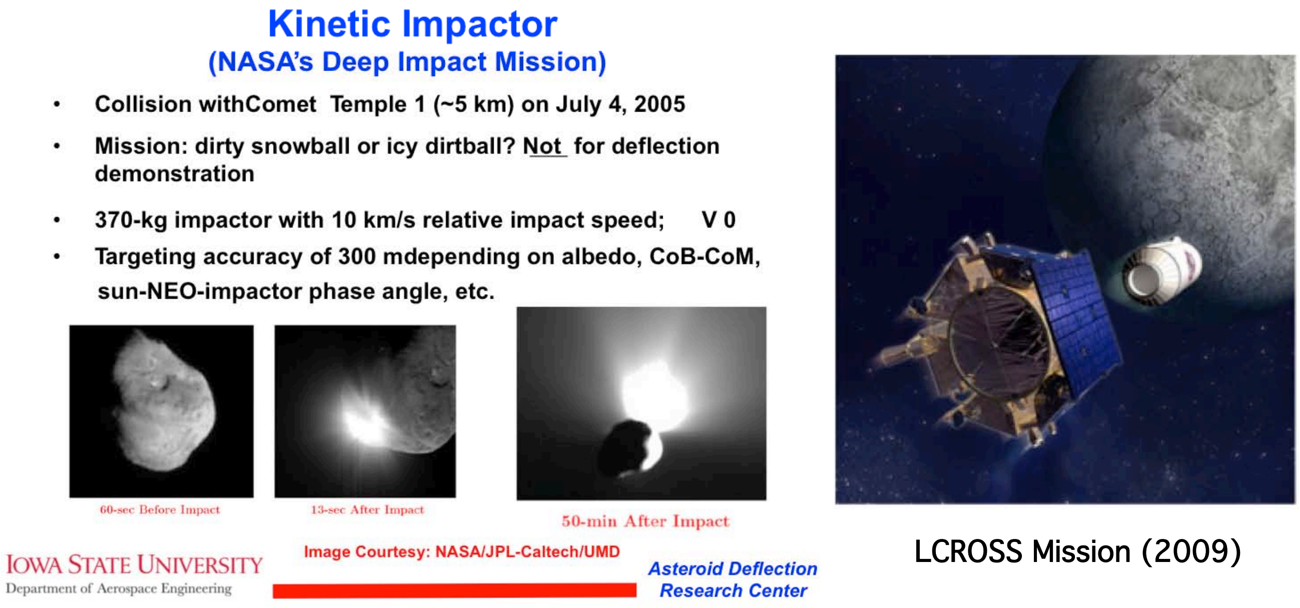
aft body (carrying nuclear explosives), allowing an impact velocity of 30 km/s. The fore body impacts the asteroid surface first, creating a large crater, followed by the aft body, which penetrates to a depth of three meters. However, a further simulation of nuclear subsurface explosion and a detailed system-level design were not discussed in [5]. It is now time to further examine this concept to develop a technically feasible option for mitigating the impact threats of NEOs with a short warning time.

NASA's most recent impactor endeavor was the Lunar Crater Observation and Sensing Satellite (LCROSS) mission designed to investigate the possibility of water on the moon [6]. LCROSS was launched in June 2009, in conjunction with the Lunar Reconnaissance Orbiter (LRO), as part of the Lunar Precursor Robotic Program. For this mission, LCROSS did not carry a sophisticated impactor spacecraft; rather it used an SUV-sized Centaur booster rocket from the Atlas V launch vehicle, as illustrated in Fig. 4. The Centaur booster rocket was successfully fired at the Cabeus crater at the lunar South Pole, with an estimated velocity of 2.78 km/s. The impact was expected to form a crater 20 m in diameter and 4 m deep and excavate more than 350 metric tons of lunar regolith with a plume as high as 10 km from the surface. Four minutes after the Centaur impact, the LCROSS spacecraft followed the impactor through the dust plume to determine the composition of the ejected material and relay the information back to Earth.

A preliminary conceptual design of an interplanetary ballistic missile (IPBM) system carrying a nuclear interceptor has been conducted at the ADRC [7, 8]. The proposed IPBM system consists of a launch vehicle (LV) and an integrated space vehicle (ISV), as illustrated in Fig. 5. The ISV consists of an orbital transfer vehicle (OTV) and a terminal maneuvering vehicle (TMV) carrying nuclear payloads. A Delta IV Heavy launch vehicle can be chosen as a baseline LV of a primary IPBM system for delivering a 1500-kg ($\approx$ 2-Mt yield) nuclear explosive for a rendezvous/intercept mission with a target NEO. A secondary IPBM system using a Delta II class launch vehicle (or a Taurus II) with a smaller ISV carrying a 500-kg (500-kt yield) nuclear explosive is also described in [7]. An OTV can be used as the fore body KEI spacecraft when a TMV is the aft body spacecraft carrying nuclear explosives.

The terminal-phase guidance and control of a two-body HNI system, consisting of two separated, but formation flying, spacecraft presents a technically challenging problem, involving high impact velocities, up to 30 km/s, and small, faint targets [9]. A successful rendezvous mission, for flyby or proximity operations, can approach a target asteroid from any angle. However, precision interceptor missions may require impact-angle control for impact at a specified angle. Communications with Earth may not be feasible during the terminal phase, so the control scheme must rely on onboard measurements and computations. The combination of a high velocity and a small target means that an effective guidance system will require only optical measurements. Recent work shows that the trajectories of fragments from a nuclear explosion, and the eventual impact locations on the Earth, of the dispersed fragments depend significantly on the impact angle of the interceptor. Attaining the desired impact angle while still successfully achieving impact is crucial for a successful nuclear deflection/disruption attempt.

The current study effort at the ADRC will provide requirements and limitations on the intercept mission, including on maneuvering fuel requirements, interceptor design, relative impact velocity, and GN&C sensors. Every potentially hazardous NEO will have different orbital characteristics and composition. This research will identify which factors affect angle-constrained terminal-phase guidance, and what strategies to employ for a variety of scenarios. Most current space missions do not require a specific encounter angle to be commanded in the terminal phase. Instead, the encounter angle is

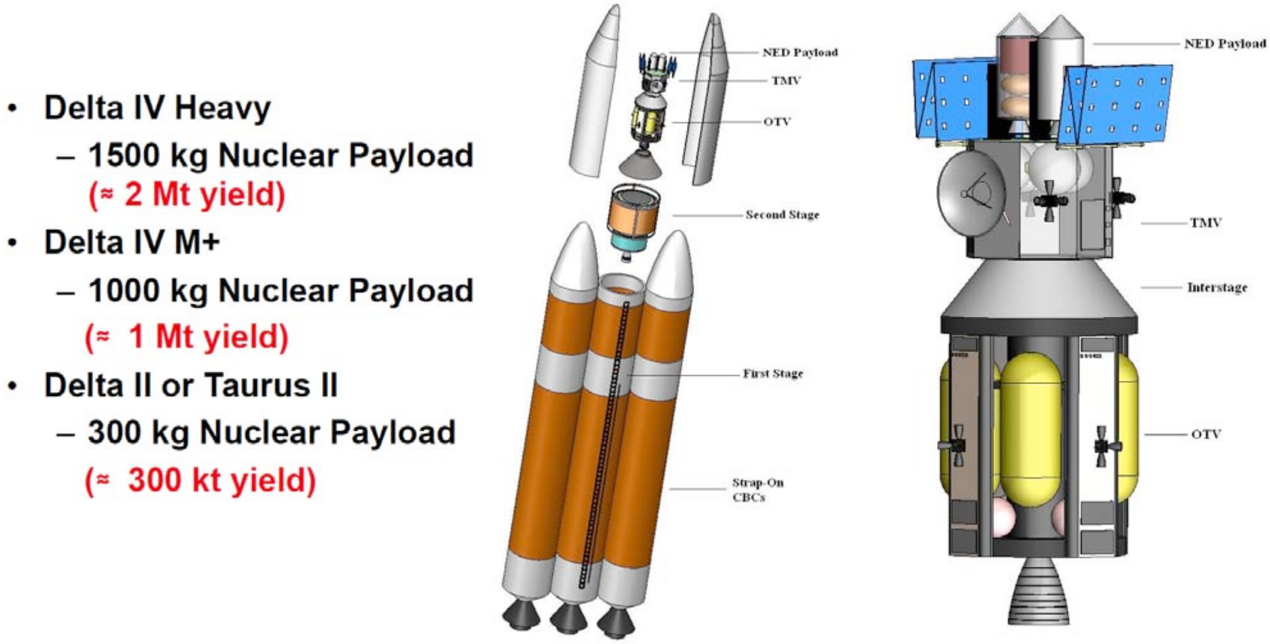


Kinetic Impactor

(NASA's Deep Impact Mission)

- Collision withComet Temple 1 (~5 km) on July 4, 2005
- Mission: dirty snowball or icy dirtball? Not for deflection demonstration
- 370-kg impactor with 10 km/s relative impact speed; V 0
- Targeting accuracy of 300 mdepending on albedo, CoB-CoM, sun-NEO-impactor phase angle, etc.

Figure 4: Illustrations of NASA's Deep Impact mission in 2005 and the LCROSS mission launching the Centaur booster rocket as a kinetic-energy impactor toward the moon in 2009 [6].



- Delta IV Heavy
  - 1500 kg Nuclear Payload (≈ 2 Mt yield)
- Delta IV M+
  - 1000 kg Nuclear Payload (≈ 1 Mt yield)
- Delta II or Taurus II
  - 300 kg Nuclear Payload (≈ 300 kt yield)

Figure 5: Illustration of a proposed IPBM system architecture [7].

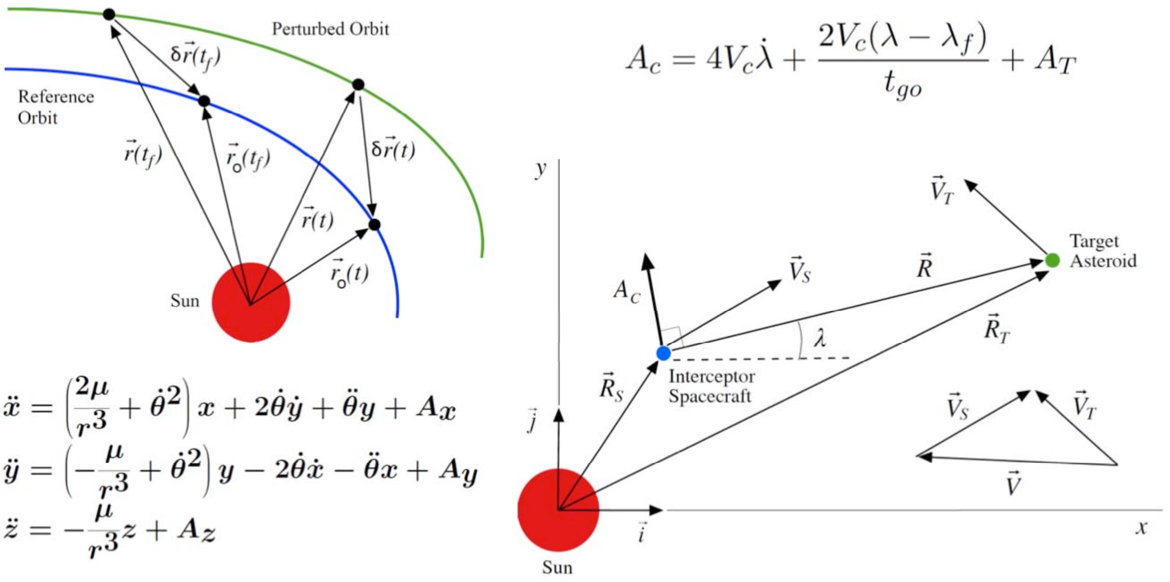


Figure 6: Illustration of the terminal-phase guidance and control problem [9].

chosen as a consequence of the orbit the spacecraft follows from the Earth. Maneuvering thrusters are not typically used to significantly change the trajectory of the spacecraft near encounter with an object, but rather to make small adjustments to make the actual trajectory match the nominal mission trajectory. The current study will evaluate the feasibility of implementing practical control laws on interceptor spacecraft for real missions, namely high-speed intercept missions with angle-of-impact constraints enforced in the terminal phase with precision targeting requirements. The fundamental nature of terminal guidance and control problem is illustrated in Fig. 6. Some preliminary results of developing terminal guidance and control algorithms for asteroid intercept missions can be found in [9].

It is important to note that the Deep Impact mission has validated the kinetic-impact technology for a relatively large, 5-km target body at an impact speed of 10 km/s in reasonably good lighting condition. Precision targeting of a smaller (e.g., $<$ 500 m), irregularly shaped target asteroid with an impact speed of 30 km/s in worst-case circumstances needs to be flight tested/validated/demonstrated in the near future.

An asteroid approximately the size of the asteroid Apophis is considered as a reference target asteroid in the current study. The model asteroid has a total mass of 2.058E13 kg with a diameter of 270 meters. An ideal nuclear subsurface explosion of this model was developed by Dr. David Dearborn at Lawrence Livermore National Laboratory. This ideal model assumed a subsurface explosion in a cylindrical region below the surface of the body by sourcing in energy corresponding to 300 kt [10-12]. It assumed a two-component (inhomogeneous) spherical structure with a high density (2.63 g/cm^3) core consistent with granite and a lower density (1.91 g/cm^3) mantle. The bulk density of the structures was 1.99 g/cm^3, close to that measured for asteroid Itokawa (density = 1.95 g/cm^3). The energy source region expands, creating a shock that propagates through the body resulting in fragmentation and dispersal. The structure of the asteroid was modeled with a linear strength model and a core yield strength of 14.6 MPa. The mass-averaged speed of the fragments after 6 seconds was near 50 m/s with peak near 30 m/s [10-12]. A three-dimensional fragment distribution was constructed from the hydrodynamics model by rotating the position, speed, and mass of each zone to a randomly assigned azimuth about the axis of symmetry. While the material representations used have been tested in a terrestrial environment, there are low-density objects, like Mathilde, where crater evidence suggests a very porous regolith with efficient shock dissipation. Shock propagation may be less efficient in such porous material, generally reducing the net impulse from a given amount of energy coupled into the surface. More research in this area is needed to understand the limits of very low porosity.

The preliminary results for the Ap300 model with 15 days before impact [11-16] indicate that only 3% of the initial mass resulted in impacting the Earth even for such a very short time after interception. The impact mass can be further reduced to 0.2% if the interception direction is aligned along the inward or outward direction of the orbit, i.e., perpendicular to NEO's orbital flight direction. Such a sideways push is known to be an optimal when a target NEO is in the last terminal orbit before the impact. Furthermore, in a real situation, we will probably employ a larger nuclear explosive device (e.g., 1-2 Mt instead of 300 kt) against a 300-m class target asteroid.

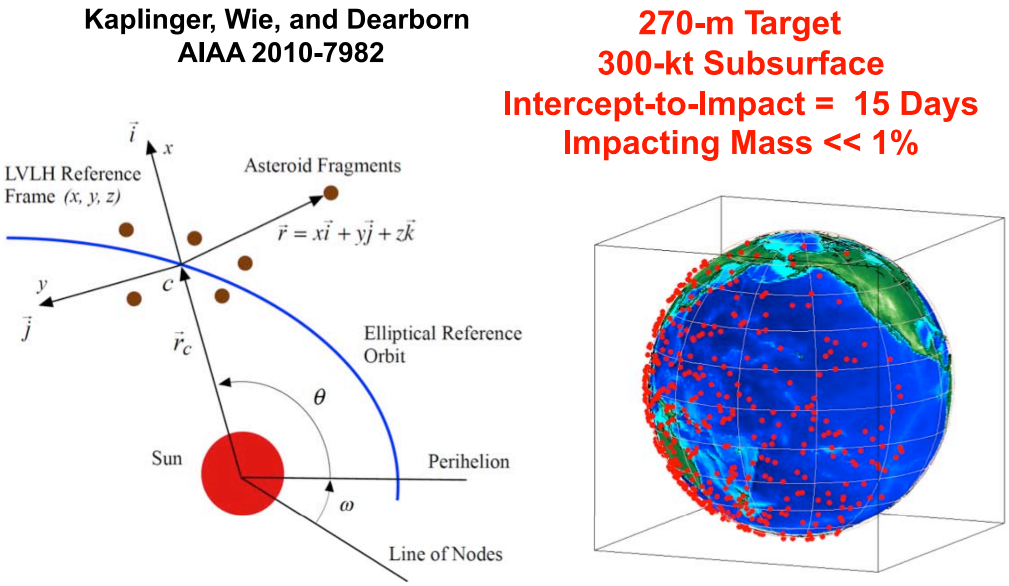


Figure 7: Preliminary results for high-fidelity modeling and simulation of orbital dispersion of asteroids disrupted by nuclear explosives [14].

For a larger 1-km NEO, two basic models (M97 and M20e) were also described in [12]. Both models sourced 900 kt into a cubic surface region of the same 1 km diameter object, with an initial mass of 1.047×10^9 tons. The difference is that M97 was a finely zoned model. Approximately 20 seconds after the energy deposition, M97 had 31,984 zones of asteroid material for 9.6732×10^8 tons, 92.8% of the initial mass. The missing 7.2% was ejected from the mesh at high speed prior to the end of the hydrodynamics simulation.

Expanding upon these nuclear fragmentation models (Ap300, M97, and M20e) of Dr. David Dearborn, we are currently developing high-fidelity nuclear fragmentation models including the effect of hypervelocity impact crater condition uncertainties, caused by the fore body KEI spacecraft, on the dispersal velocity distribution and the size of each fragment, to develop optimal intercept/impact strategies for robust nuclear fragmentation and dispersion [17]. The fore body impacts the asteroid surface first, creating a large crater, followed by the aft body carrying nuclear explosives, which penetrates to a depth of several meters. We will refine the "static" nuclear blast models used in [10-16] to assess the overall mission robustness in employing such impulsive, high-energy nuclear subsurface explosions in the face of various physical modeling uncertainties, especially, caused by the initial kinetic-energy impact crater conditions created by the fore body KEI spacecraft. *Modeling and simulation of this type of complex multi-phase physics problem has never been discussed in the open literature. The objective of the current study is to validate the overall effectiveness and robustness of the proposed two-body HNI system.*

Some preliminary results of hypervelocity impact modeling and simulation using a GPU (Graphics Processing Unit) accelerated hydrodynamics code, which is being developed at the ADRC, are shown in Fig. 8 [17]. Further refined results will then be used for the design consideration of thermal shields of the follower spacecraft.

PARAMETRIC CHARACTERIZATION OF MODELING UNCERTAINTIES

Space missions to deflect or disrupt a hazardous NEO will require accurate prediction of its orbital trajectory, both before and after a deflection/disruption event. Understanding the inherent sensitivity of mission success to *the uncertainties in the orbital elements and material properties of a target NEO* will lead to a more robust mission design, in addition to identifying required precision for observation, tracking, and characterization of a target NEO. The unique technical challenges posed by NEO deflection/disruption dictate the level of precision needed in the physical modeling of hazardous NEOs and the identification of relevant parameters through computational/analytical/experimental studies, remote observation, and/or characterization missions. Consequently, the uncertainty modeling and its parametric characterization are of current interest to the planetary defense community. The current study at the ADRC also focuses on the parametric characterization of various physical modeling uncertainties, especially for nuclear deflection/disruption missions.

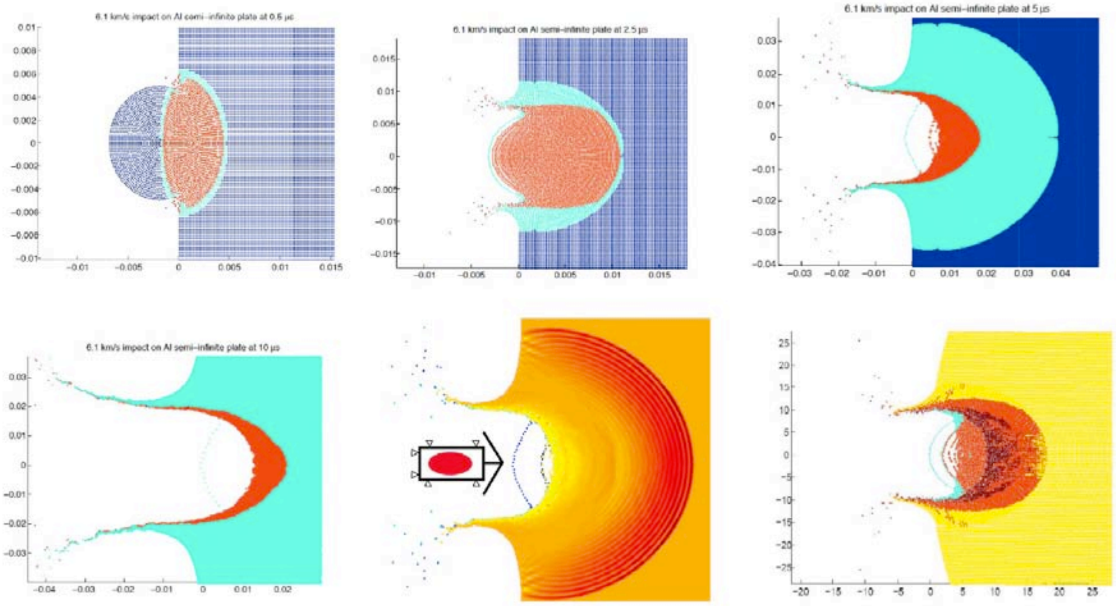


Figure 8: Preliminary illustrative results for the hypervelocity penetrated subsurface nuclear explosion option [17].

NASA's NEO Observations Program office has been funding NEO characterization studies by Dr. Keith Holsapple at the University of Washington and Dr. Daniel Scheeres at the University of Colorado at Boulder since 2010. Their studies are concerned with the fundamental physical understanding and modeling of various physical parameters that influence the effectiveness of high-energy impulsive approaches. The effectiveness of impulsive approaches using kinetic impacts or nuclear explosives is strongly dependent on the mechanical strength and porosity of near-surface regions of the asteroid. In particular, Dr. Holsapple's research focuses on a complementary experimental, theoretical and code studies of the effects on an asteroid of the energy deposition of impacts or explosives. Dr. Scheeres' research is concerned with the response of an aggregate, accounting for the complex dynamics of a rubble pile when energy has been added to the system as part of an impulsive mitigation event.

Because the required degree of physical modeling accuracy strongly depends on the specific mitigation mission types, the current study emphasizes the parametric characterization of physical modeling uncertainties and their resulting orbital perturbation effects on the outcome of various nuclear deflection/disruption options, such as high- or low-altitude standoff, surface contact burst, and penetrated subsurface nuclear explosions. The effectiveness and robustness of each option in the presence of significant physical modeling uncertainties needs to be further examined.

Space missions requiring nuclear deflection/disruption of NEOs are in general concerned with: i) robust predictability of the sufficient miss distance for a successfully deflected NEO; ii) robust predictability of the fragments impacting on the surface of the Earth (for a worst-case situation with a very short warning time); iii) a reliable assessment of reduced impact damages due to a last minute disruption mission; and iv) an accurate modeling of $\Delta\vec{V}$ (magnitude and direction of velocity change) within desired error bounds. Uncertainties in mass, density, porosity, material strength, and other physical parameters can substantially influence the outcome of any nuclear deflection/disruption attempt. Therefore, a detailed study is needed to characterize these uncertain parameters, especially for robust nuclear deflection/disruption mission design.

Also, we need to characterize, computationally and/or analytically, the modeling uncertainties and the resulting orbit perturbation effects in terms of effective $\Delta\vec{V}$ uncertainties and/or uncertain perturbations in orbital elements (Δa, Δe, Δi, $\Delta\Omega$, $\Delta\omega$, ΔM_0) as well as dispersion velocities of fragments. In particular, the uncertainty associated with initial dispersal velocity and mass distribution of fragments needs to be rigorously modeled and characterized for robust disruption mission design. Self gravity of fragments also needs to be included in the high-fidelity dispersion modeling and simulation.

Finally, we need to increase communication and interaction among NEO deflection research engineers and NEO characterization research scientists through building a consensus on the necessary reliable models in the face of significant physical modeling uncertainties as well as the practical mission constraints.

CONCLUSION

A concept of using a fore body (a leader spacecraft) to provide proper kinetic-energy impact crater conditions for an aft body (a follower spacecraft) carrying nuclear explosives has been proposed in this paper as a technically feasible option for the most probable impact threats of NEOs with a short warning time (e.g., much less than 10 years). The current as well as planned studies at the ADRC would enable an important step forward for this area of emerging international interest, by finding the most cost effective, reliable, versatile, and technically feasible solution to the NEO impact threat mitigation problem, which is now one of NASA's Space Technology Grand Challenges.

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