

4 IAA Planetary Defense Conference – PDC 2013  
13-17 April 2015, Frascati, Roma, Italy

IAA-PDC-15-03-14  
LOS ALAMOS RAGE SIMULATIONS OF THE HAIV MISSION CONCEPT

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**Keywords:** *asteroid deflection techniques, radiation-hydrocode simulations, HAIV/NIAC, nuclear subsurface burst*

**Extended Abstract—**

There are a significant number of asteroids and comets that have their orbits bring them in close proximity to the Earth. These objects are called Near Earth Objects (NEOs). Those NEOs that are large enough (say greater than ~20 m) and are projected to have a potential for a substantial damage to the Earth's environment are called Potentially Hazardous Objects (PHOs). The mitigation of PHOs can be accomplished by a variety of methods including kinetic impactors, gravity tractors and several nuclear explosion options. Depending on the available time prior to Earth impact, non-nuclear options can be very effective at altering a PHO's orbit. For short warning time cases, a report by the United States National Research Council (NRC) suggests the use of a nuclear explosive device [1]. As outlined by Wie in [2], there are two main nuclear options that are generally considered for deflection or disruption of a PHO: 1) use a stand-off nuclear burst to irradiate the PHO and deflect the object; or 2) use a partially buried nuclear explosive to effect a total disruption of the PHO. Wie designed the Hypervelocity Asteroid Intercept Vehicle (HAIV) [2] to have a subsurface nuclear burst to potentially enhance significantly the energy coupled to the PHO. The concept for the HAIV is to have a spacecraft with two parts: a leader kinetic impactor, which creates a crater in the target PHO and 2) a follower portion that carries a shielded Nuclear Explosive Device (NED) into the crater creating a subsurface nuclear explosion. Subsurface explosions can be many times more effective in coupling energy to the PHO than contact or stand-off bursts. The goal of this mission would be to totally disrupt the PHO such that the mass fraction that would actually hit the Earth is minimized.

However, in order to implement a nuclear option, the entire community must be confident that the mission will be effective, since the incorrect use of could lead to undesirable fragmentation of the PHO resulting in still substantial hazard to the Earth. One of the NASA Innovative Advanced Concepts (NIAC) program's efforts is to develop the HAIV concept. This mission concept was presented by Barbee et. al. at several meetings, including the last PDC-2013 [3].

In this paper, we look more closely at the physics of the HAIV concept and perform radiation-hydrodynamic simulations of both the crater formation and the subsequent nuclear explosion. We use the adaptive mesh radiation-hydrocode RAGE [4] to simulate the crater formation by the kinetic impactor as well as the explosion and energy coupling from the follower NED timed to detonate at ~ 1 ms. Here, we show preliminary rad-hydro simulations of this concept and discuss potential methods to improve the mission.

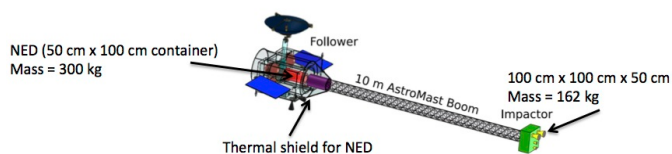


Figure 1. The HAIV mission as shown in [3]

The RAGE code has been well validated for a wide variety of applications [5]. The geometry of the spacecraft with the extended AstroMast Boom is shown in Figure 1. Based on [3], we use a 162 kg kinetic impactor followed by a 300 kt NED that is 10 meters behind the impactor. Both are moving at a velocity of 11.5 km/s to a spherical 100 meter diameter target of

density 2.0 g/cc.

We start with some basic physics of a NED explosion and the coupling of the NED energy output to a target rock material (density = 2.0 g/cc). Any NED has a very high energy density due to the high source energy compared to the mass. Typical temperatures during the NED explosion are about 10-20 million °K. Typical pressures during the explosion are  $\sim 10^8$  MPa. Under these conditions, significantly more than 50% of the NED

pushes the over-burden out, again representing a radiative loss of energy for the coupling.

We use the RAGE code at Los Alamos to study the HAIV concept. The RAGE code can simulate the integrated mission with a single axi-symmetric run. We have obtained the engineering drawings for the spacecraft from Barbee [5]. This geometry of the extended two-part spacecraft is imported into the RAGE set-up geometry and situated at the surface of a 100 meter diameter spherical asteroid. The asteroid in these simulations has a density of 2 g/cc with a tabular alluvium sesame equation-of-state (EOS). A weak Steinberg-Guinan strength is applied to the asteroid material. The energy source into the NED container is 300 kt and the entire spacecraft (impactor and follower) are given an initial velocity of -11.5 km/s. Other codes with coupled radiation-hydrodynamics capability could also be used for this study.

Preliminary RAGE simulations show that the kinetic impactor will carve out a surface crater on the object and the subsequent NED explosion at the bottom of the crater transfers energy to the target. Figure 2 shows the initial RAGE 2D setup geometry for this study. Figure 3 shows the AMR RAGE mesh created for this geometry.

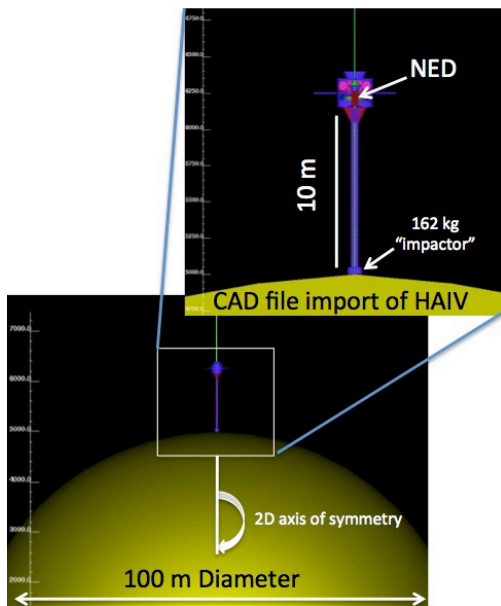


Figure 2. The initial geometry of the RAGE HAIV 2D simulation.

yield is emitted in the form of soft x-rays, with most of the remaining yield in the form of kinetic energy (KE).

For stand-off, contact and even shallow buried NED explosions the use of a radiation-hydrodynamics code is required to properly account for the large amount of soft-x-rays from the NED and their effect on the asteroid surface. The mean-free-path of typical asteroid materials is measured in millimeters, depending weakly on the actual materials and composition. A large amount of radiant energy is absorbed in this very thin layer causing it to also heat up to high temperatures. This hot surface then re-radiates a significant amount of energy back away from asteroid (a loss of energy). Complicating the physics of such a contact burst is the radiation absorbed by the surface layer then ablates away enhancing the momentum coupling to the asteroid. In order to obtain the energy and momentum coupled to the target asteroid properly for a contact burst, the difference between the radiation energy absorbed by the target surface and that re-radiated must be carefully simulated. For shallow buried bursts the NED radiation output vaporizes the surrounding material and creates a hot bubble with significant pressure. This bubble then expands and

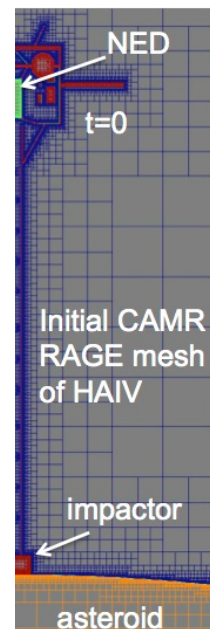


Figure 3. The initial AMR RAGE mesh.

At 11.5 km/s it takes  $\sim 1$  ms for the follower to get to the bottom of the pre-transient crater created by the leading 162 kg impactor. This pre-transient crater is calculated to be very shallow, about 1-2 meters deep. The RAGE mesh colored by density during the initial phases of the NED explosion is shown in Figure 4.

The importance of including the radiation energy and transport in these near surface bursts is shown in Figure

5, which shows the RAGE mesh colored by radiation temperature. For this integrated simulation, the pre-transient crater formed by the low density 162 kg impactor looks very close to a contact burst since the crater is wide open and allows a significant amount of radiation to escape. The effective energy coupled to the target asteroid for this shallow open crater is essentially the same as that calculated for a contact burst of the same energy.

A buried burst RAGE simulation is shown in Figure 6

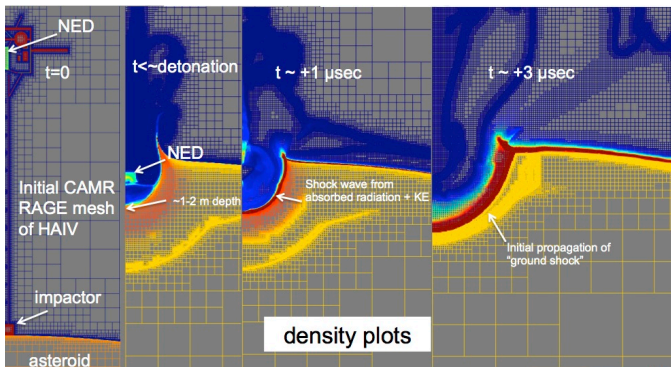


Figure 4. The RAGE mesh colored by density during the initial phases of the NED explosion.

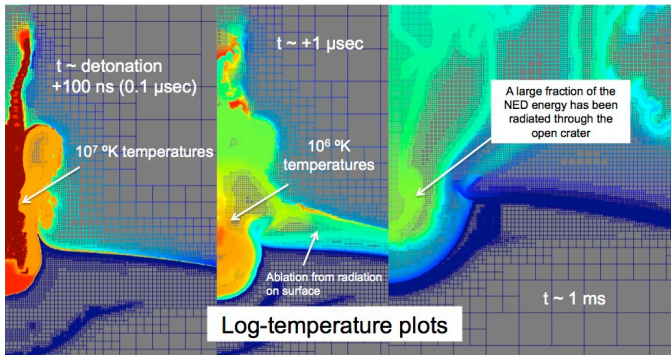


Figure 5. The RAGE mesh colored by radiation temperature during the initial phases of the NED explosion.

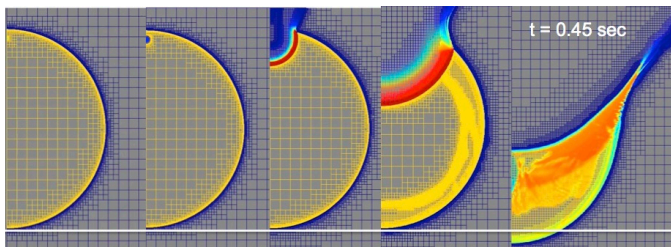


Figure 6. The RAGE mesh colored by density for a 5 m (contained) buried burst.

as a series of images over time to 0.45 sec. The effective energy coupled from this 5 meter buried burst

(300 kt) is about 4 times more than the contact burst. It was expected that for a Earth based subsurface explosion of 300 kt at 5 meters depth that the coupled energy should be more like 20 times that from a contact burst. This difference between sub-surface Earth energy-coupling and that to a 100 m asteroid is being investigated.

In order to improve the efficiency of this HAIV concept, the leader should be re-designed to be a penetrator to maximize the depth of the pre-transient crater formation. For example, if the leader were made out of a much denser material than the target, say steel, and more properly shaped for penetration ( $H/W > 6$ ) then there is potential to increase the 1ms crater depth to 5-10 meters or more. At these depths the radiative losses from the NED explosion would be minimized and the coupling efficiency would be much greater than a contact burst.

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