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Limits on the use of Nuclear Explosives for Asteroid Deflection

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Limits on the use of nuclear explosives for asteroid deflection

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Abstract:

Recent studies by the US National Research Council identified nuclear explosives as the only current technology able to deflect large asteroids (> than 500 meters) or to mitigate impacts of smaller bodies when the warning time is short. Previous work has shown that either a standoff burst or a very low yield surface burst is easily capable of deflecting large (1 km) asteroids without fragmentation. Alternatively large near surface or just sub-surface bursts can fragment smaller bodies (300 m) with speeds such that large fractions (>99.99%) miss the earth entirely. Even for very short times (< month) more than 995% can be deflected. However, deflecting small bodies without fragmentation becomes challenging when the required kinetic energy increment is a substantial fraction of the bodies potential. The ability of any impulsive method to deflect small bodies, without substantial low speed debris, is a challenge examined in this paper.

Introduction

While payload delivered to deep space continues to be a limitation, nuclear explosives will remain an option for asteroid deflection. At present, nuclear munitions are the only available technology capable of deflecting large bodies. Knowledge of the performance and output of nuclear explosives is assured from an extensive test history, and the deposition of that energy into any material is a well-characterized problem. Any uncertainty in the results of nuclear mitigation resides in our ignorance of the range of structures and material properties that characterize the Near Earth Object (NEO) population. Relatively little quantitative assessment of nuclear deflection has been done, and we agree with the letter released by the Office of Science and Technology Policy (OSTP) telling the US Congressional Committee on Science and Technology that "significantly more analysis and simulation are needed".

With decades of warning, the speed perturbation required to eliminate an impact is millimeters to a centimeter per second, though a bit more may be desired for a comfortable miss. For large bodies (500 m to 1000 m diameters), the necessary speed change is much less than the 25 to 50 cm/s escape velocity, and it was reasonable to assume that the impulse to provide such small velocity perturbations would not lead to fragmentation or excessive ablation (Ahrens and Harris, 1992; Solem, 2000). These expectations were met in detailed hydrodynamic simulations presented at earlier Planetary Defense Conferences (Dearborn 2006 and 2009), and these earlier results standoff and very low yield surface bursts will be briefly reviewed in the next section.

This situation changes when the approach time is short, particularly when the body is small. With only a few years to impact, the speed change required to deflect a 100 m body approaches the escape velocity, and fragmentation is difficult to avoid. In such a case, a surface burst is capable of dispersing a body with sufficient speed that the majority of the material misses the earth (Wie and Dearborn 2010 AAS 10-137, Kaplinger, Wie, and Dearborn, 1010 AAS 10-225), greatly reducing the damage potential.

With the clear understanding that nuclear explosives have a place in the mitigation technologies, questions must be asked about the limits of that place. As the outputs of nuclear explosives are well known, the challenge in predicting an asteroid's response lies in the uncertainty of its structures. NEOs are diverse objects with sizes from meters to kilometers, and rotation rates from trivial to near break-up. Densities are highly variable, and shapes complex. There remains much work to determine the best way to use nuclear explosives for large bodies where other technologies are insufficiently robust. Here we will present new work aimed at the question of how they can be used to deflect smaller bodies. As the NEO surveys penetrate to substantial completeness at smaller sizes, it becomes probable that we will have decades of warning for the small to moderate sized bodies that could cause local or regional catastrophe.

Earlier work (Decades to impact):

A series of deflection calculations were done examining nuclear energy deposition from a standoff burst on an inhomogeneous (core and mantle), spherical structure with bulk density 1.99 g/cc. The energy was deposited into thin and tapering set of surface zones (approx 10 zones deep), across 41^o of a hemisphere (half-angle), consistent a source about 165 meters above the surface of a 1 km sphere.

It was assumed that the nuclear explosive was selected for optimized neutron output (high fusion to fission yield), as the cross-section of energetic neutrons is dominated by scattering, and so nearly independent of composition for materials between carbon and iron. This results in a penetration depth of 17 g/cm^2, heating substantially more mass than the same flux of x-rays, and providing a larger impulse for the same energy. Detailed Monte Carlo simulations of energetic neutrons incident on granite (Bedrossian, 2004) found that >70% of the incident energy was deposited (efficient deposition). Similar simulations on a 1 Km body with different composition found energy absorption efficiencies as high as 75%. Ten kilotons deposition then converts about 4000 tons of surface material into plasma expanding at over at 2 km/s (Dearborn 2004).

Simulations were run with either no strength or linear strength (compressive strength proportional to the pressure up to the crush pressure, no tensile strength) models, but for deflection models, strength is unimportant to the results why is this? The calculations were generally taken to 40 seconds after deposition, at which point over about 97.5% of the body remained bound (Fig 1) with speeds ranging from 2.2 to 2.4 cm/s. On many orbits, a speed change done near perihelion, 30 years prior to impact required only 5 mm/s for a comfortable miss.

These simulations did not incorporate a crush curve to treat the energy loss to strong shocks from micro-porosity. This process is potentially significant in early-time, strong shock regions where shock strengths may approach a megabar. Crushing minimizes any hydrodynamic rebound, and in the extreme limits the momentum pulse to that material that is vaporized. A series of models run only through this early phase provided pulses speed changes of 0.5 - 1 cm/s, with <<1% of the material ablated.

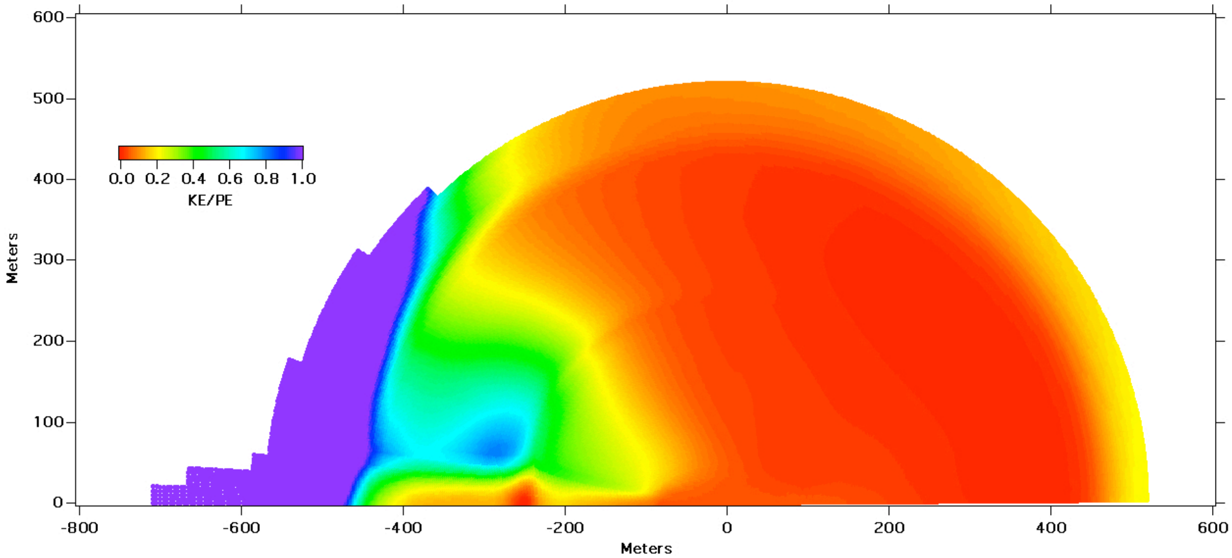


Figure 1: the material speed is shown 40 seconds after the hemisphere Only the expanded purple region has sufficient energy to escape from the asteroid.

In the 2006 Near-Earth Object Survey and Deflection Study by NASA, a new approach for perturbing the orbit of a threatening asteroid was proposed. The idea was to detonate a very low yield nuclear explosive (or explosives) on the surface. These simulations used the same 1 km structures, and the energy sourced into a 5 Meter cube at the surface. The 1 Kt source easily vaporizes all of the material in the source region, while the 100-ton source is about as low as is appropriate for this volume. The models were run more that 20 seconds after the burst, in excess of 70 shock crossing times. As expected, a crater was formed, but away from the crater, there was relatively little motion

A 1 Kt burst was found to be a bit too large. It posed no danger of fragmenting a 1 km body, but the speed change (2.8 cm/s) and mass ejected (7.5% of the asteroid mass) was far more than required. A half-kiloton model gave a speed change of 0.92 cm/s while ejecting 1.9% of the mass, and the 100-ton simulation changed the speed 2.3 mm/s and ejected only less than 0.4% of the mass (fig 2). Most of this the ejected material has speeds in excess of 10 m/s, and will pass nowhere near the earth.

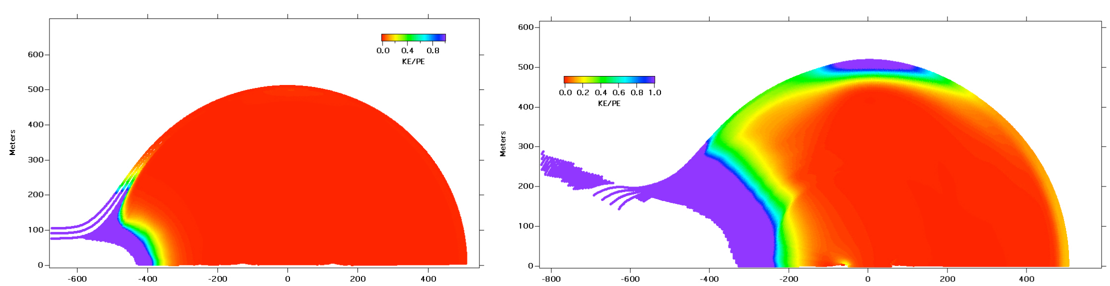


Figure 2: The potential energy is color coded for models with a 100-ton surface burst (left) and a 1 Kt (right). The purple material is ejected, though most of the ejecta is outside the printed frames.

Both the standoff and the surface burst can leave ≈98% of the body bound assuming only its own weak gravity. The amount of the ejecta will depend on the porosity of the regolith. A dissipative, low-density regolith will reduce the ejecta, but also reduce the speed change. While the surface burst approach will clearly work for very low yields, the standoff approach has the advantage in that there is no need to maneuver for a low approach. On the other hand, the yield requirements for the surface burst suggest that a proximity burst with a fuse capable of responding at orbital approach speeds is a possibility.

Years to impact:
When the time to impact is short (less than a decade), the necessary speed change becomes a significant fraction of the escape speed, even for large bodies, and fragmentation may be difficult to avoid. When fragmentation occurs near the earth, allowing a substantial fraction of the material to impact, this can worsen the event. However, if the time to impact and the dispersal speeds are sufficient to cause most of the material to miss the Earth, fragmentation can achieve substantial mitigation, and smaller bodies may be fragmented into pieces unable to penetrate the atmosphere.

Fragmentation was examined for both a 1 km body (about a billion tons) and a 270 m body (a bit over 20 million tons). As before the structures had a high density core (density 2.63 g/cc), and a lower density (1.91g/cc) mantle using an EOS developed to represent tuff, a soft, porous rock that formed by the compaction of volcanic ash. The bulk density of the structures was 1.99 g/cc, close to that measured for asteroid Itokawa (r=1.95 g/cc (Abe et al. 2006).

The energy deposited corresponded to 900 Kt into the larger structure and 300 Kt into the smaller body simulating surface explosions. The source regions were a cylindrical, and the dimensions in the smaller body were about 1 meter in diameter and 5 meters long. There the source volume was about 4.5 cubic meters containing a bit over 8 tons of material. In the larger body, the source region had a volume near 10 cubic meters.

Two-dimensional hydrodynamic modeling of the subsequent explosion led to expanding clouds of debris. The structures were modeled with different strength approximations, including no material strength, a linear strength model (strength proportional to pressure, limited by a crush strength) often used for shock propagation in rubble, and a model that includes full strength in the core. The yield strength in the core is set to 14.6 MPa, with a shear modulus of 35 MPa. This is somewhat weaker than measured for most granite, and is near the low-end for limestone.

The energy source region expands creating a shock that propagates through the body resulting in fragmentation and dispersal. While the materials representations used have been tested in a terrestrial environment, there are low-density objects, like Mathilde (Chapman et al., 1999), 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 work is needed to understand the limits of very lhigh porosity.

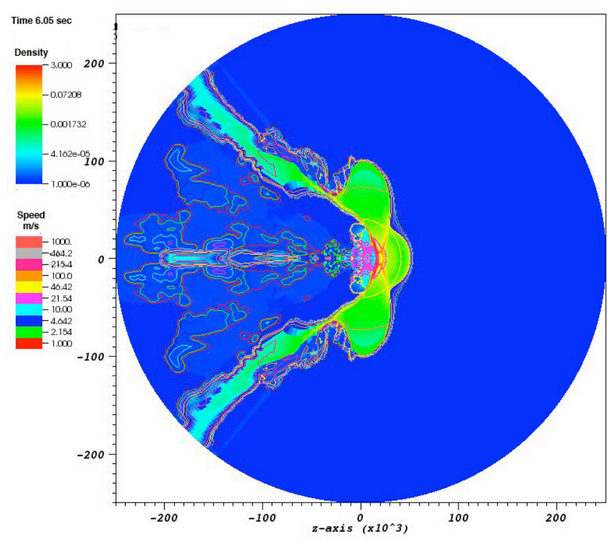


Figure 3: Density and speed structure of the 270 meter body 6 seconds after the 300 kt burst.

The models were evolved until the bodies had substantially expanded, and the velocity gradients indicated homologous expansion. After about 20 seconds, the kilometer sized bodies showed material with expansion speeds up to 50 m/s. The mass averaged speeds ranged from 12 to 14 m/s depending on the model. The smaller body (fig 3, 4) was run with a linear strength model, and after 6 seconds, it achieved homologous expansion with a mass averaged fragment speed near 50 m/s and a peak near 30 m/s.

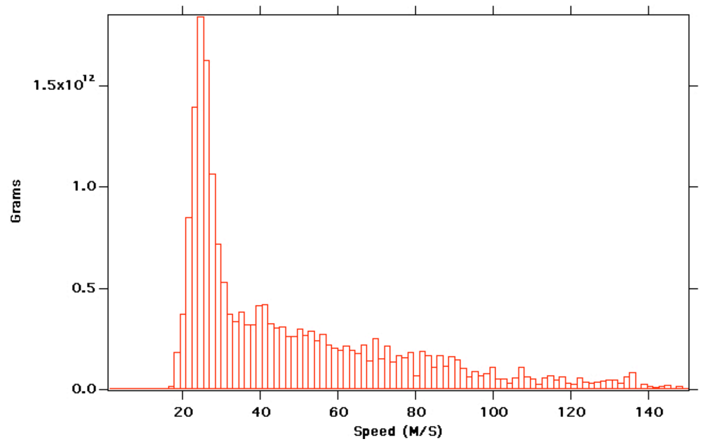


Figure 4: Speed distribution of fragments 6 seconds after the burst.

The following shows the fragment mass distribution for the Apophis sized model. Here, the number of fragments was proportional to the mass to the power -1.85, and no effort was made to fit the distribution to a theoretical model.

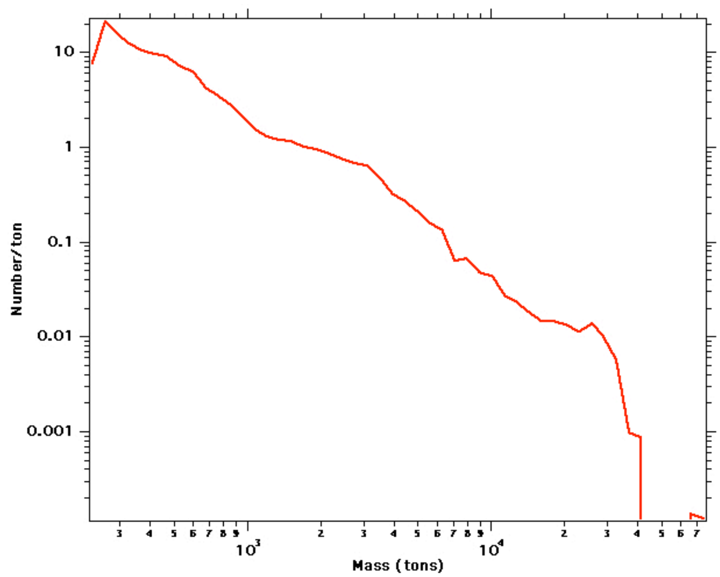


Figure 5: Mass distribution of fragments from 270 meter body.

These 3D fragment distributions were then be placed on an impacting trajectory at different times to impact. On this orbit intercepting an Apophis sized body only 15 to 20 days before impact resulted tremendous mitigation. For such short times, the direction of push matters, and by 20 days less than 1% of the material impacted even when pushing in the poorest direction. Even a kilometer sized object can be dispersed with a megaton class explosive detonated on the surface. The lower dispersal speeds require earlier fragmentation, but with a year to impact, the cumulative material from the >100 impacting fragments of order a Tunguska. None of this material would penetrate the atmosphere.

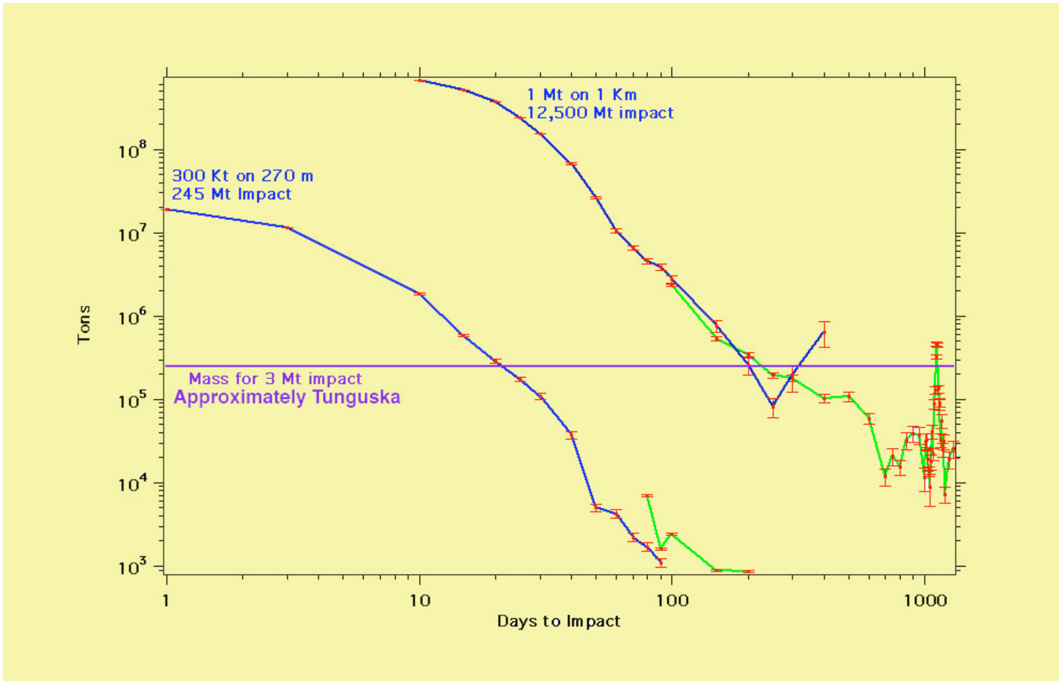


Figure 6: Fraction of the mass that remains a threat to the earth versus time to impact. When the original fragment distribution (blue) was too sparse, the fragments were subdivided to a larger number for a better statistical result (green).

The Code used:
While we have codes capable of three-dimensional (3D) radiation/hydrodynamics calculations in a massively parallel environment, we chose to start with a two-dimensional (2D) code. This allows, better resolution and more simulations to test sensitivity to material properties. CALE is a 2D Arbitrary Lagrangian Eulerian hydrodynamics computer program written in C, to give both portability and high flexibility in defining complex data structures. CALE has been ported to many machines and is currently developed on DEC Alphas, Linux platforms, Windows, and Macintosh OSX. The physics algorithms and approximations incorporate a wide variety of ideas and techniques developed by many different people at LLNL over the last 30 years. CALE generally follows the basic structure of the astrophysics ALE hydro code written by R. Barton under the guidance and oversight of J. LeBlanc and J. Wilson (Barton:1984). The Lagrange phase of CALE generally follows the work of M. Wilkins' HEMP code (Wilkins:1964). The 2D artificial viscosity comes from the work of W. Schulz, R. Christensen, and R. Tipton. The anti-hour glassing filter comes from the work of L. Margolin on the CONCHAS-SPRAY code of LANL (Cloutman:1982). The ALE grid motion algorithms stem from the basic work on equipotential grids done by A. Winslow and P. Crowley (Winslow:1963) and elaborations by R. Barton, J. LeBlanc and R. Tipton. The original advection scheme of R. Barton, J. LeBlanc and J. Wilson has been modified to include the basic monotonicity ideas of B. Van Leer with further elaborations by R. Christensen. The `volume fraction' method for Eulerian interface tracking was developed by J. LeBlanc and J. Wilson and extensively modified by R. Tipton. The discontinuous velocity slide line treatment was developed by R. Barton. The energy diffusion and magnetic diffusion algorithms draws on the work of A. Winslow as elaborated by R. Tipton (1987).

The thermal diffusion package is capable of modeling both thermal heat conduction and radiation diffusion in the same problem at the same time. The package uses a two-temperature model with a matter temperature and radiation temperature. The electrons and ions are assumed to have a Maxwellian distribution and to be in thermodynamic equilibrium with each other. The radiation field is assumed to be a Planckian distribution with a temperature that may differ from the matter temperature. When thermal conduction is considered in the absence of radiation diffusion, the radiation temperature is numerically “clamped” to the matter temperature and the model effectively becomes a one temperature model.

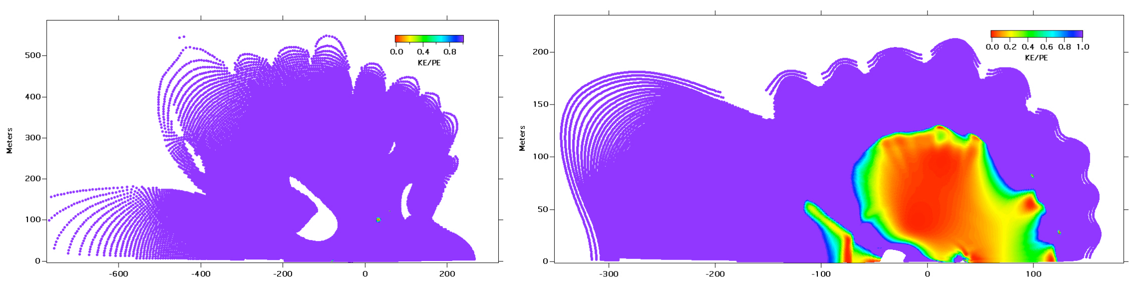
With these assumptions, the amount of radiant energy that is spatially transported from zone to zone is controlled by the

Rosseland mean opacity. The rate at which energy is exchanged between the matter energy field and the radiation energy field is controlled by the Planck mean opacity. In the case of thermal conduction, a conductive opacity is used to produce the correct spatial transport of the thermal energy and a Planck opacity of near infinity is used to clamp the radiation temperature to the matter temperature.

Standoff deflection of an Apophis sized body:
As discussed in the introduction, large bodies (500-1000 m) with escape speeds of 25 to 50 cm/s can be given an impulse sufficient to induce a miss (≈ 1 cm/s) with essentially no danger of fragmentation. As the size declines this is becomes more difficult. At a size of 100 meters, the escape speed is near 5 cm/s, and inducing a 1 cm/s speed change will almost certainly result in extensive debris ejection or fragmentation. Fortunately, bodies of this size may be addressed by impactors, and they can be successfully deflected by a series of smaller speed changes. Even here there is a concern that the cumulative ejecta may become a large fraction of the body's mass. As was shown (Wie and Dearborn 2010 AAS 10-137, Kaplinger, Wie, and Dearborn, 1010 AAS 10-225), robustly fragmenting a body creates a debris field so extended that the remaining threat to the earth is minimal. This is not true if the body is barely disrupted such that a concentrated debris field is still on a collision path. On such small bodies, if impactors failed or if the time is short, deflection via the nuclear option would be very difficult, and robust fragmentation by nearby high yield burst should be considered.

The Apophis sized body is near the boundary at which impactor deflection missions become heroic and nuclear deflection might be considered. We have done a series of calculations in which a standoff source of high-energy neutrons heat the surface of a 270 m homogeneous sphere. Models were done with a density associated with non-porous Linchburg Limestone, as well as a crush curve and density of a 16% porous Ste Genevieve Limestone. The masses of the higher density models were 27.8 million tons, while the porous models were 23.4 million tons.

In the first pair of simulations modeled approximately 70 kt of neutron output originating 60 meters from the surface of the body. This deposits about 17 kt of energy in the surface, more than was used to deflect 1 km bodies in previous work. The figure below shows the ratio of the kinetic to potential energy approximately 6 seconds after the burst. The non-porous body has Ke/Pe>1 and is completely fragmented. In the porous body, more than 65% of the material is nominally bound, and is expected to coalesce. The momentum in this bound material provides a speed change of several centimeters per second. Propagating the bound piece, and individual fragments of these models along an orbit (a ≈ 2 AU, e≈0.5), show that the porosity actually provided a superior result in shorter time.



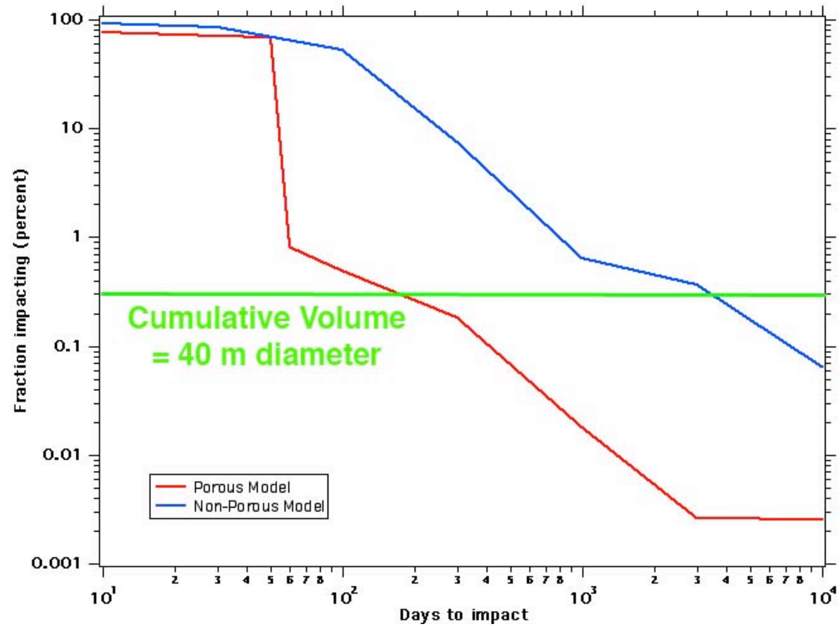
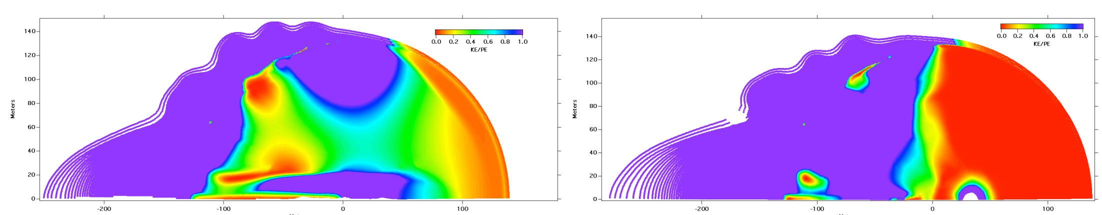


Figure 7: The non-porous and porous models 6 seconds after burst. The Purple material is unbound. The lower plot shows the fraction that remains a threat versus time to impact.

The fragmented (non-porous) model was weakly dispersed, and even after 100days, most of the material still impacts the earth. The speed increment of the bound portion of the porous model, resulted in a miss by this material after only 60 days. With earlier dispersal, the debris field of the ejected material dilutes expands at about the same rate as the non-porous model, but as the mass fraction of the debris is smaller, the cumulative impacting material is below that of Tunguska after only 200 days.

This pair of simulations shows that the yield was too high for this height of burst (HOB) on a 270-meter body, and demonstrates that we can recover the weakly fragmented case that should be avoided. It also provides an interesting result that in an energy rich environment, porosity can actually help. In the absence of a characterization mission, and with the need for a strong push, assuming non-porous is the conservative choice.

This next pair of models reduced the source yield to 7 kt at 60 m HOB, such that 1.7 kt was absorbed. The peak flux on the body was equivalent to the 70 kt source at 190 meters, but by maintaining the burst height, the energy heated the same azimuthal region as the previous calculation. The amount of material that was still nominally bound was between 60 and 65% in both the porous and non-porous models. The coalesced pieces of the non-porous model had higher speed, and missed after only 20 days of flight, but even the large piece of the porous model missed by 60 days. Here the time for the cumulative volume of the threatening fragments to drop below Tunguska is about 300 days.



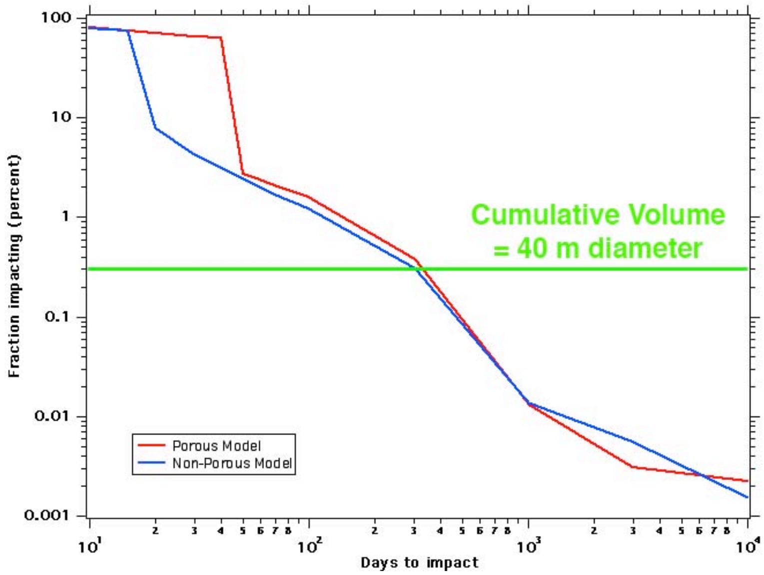
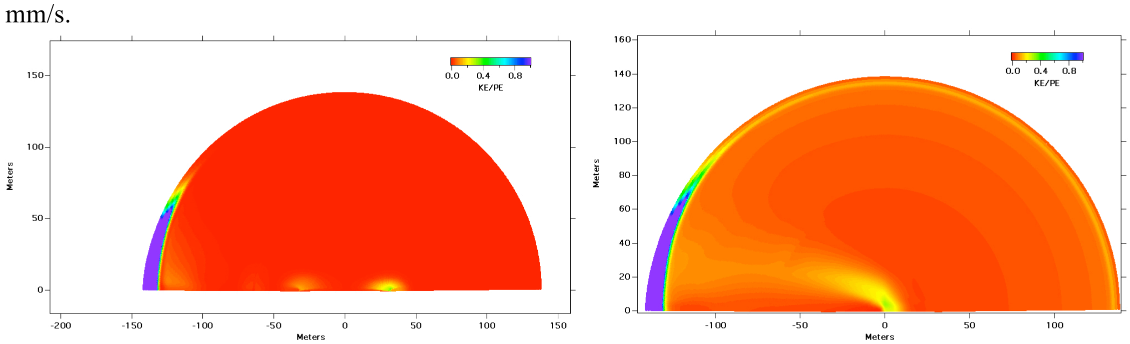


Figure 8: Again the non-porous and porous models and the fraction that remains a threat versus time to impact.

For a simple deflection, the yield chosen here was still too high (or the HOB too low). Most of the mass remains bound, and the mitigation is substantial if done a year out. Stepping down again in yield, models were run for 0.7 Kt at 60 m HOB (or approximately 70 kt at 600 meters). The absorbed energy is decreased to 0.17 kt. At the time of the conference, these models had run for less than 2 seconds. While this is many sound crossing times and sufficient to that most of the material will remain bound (>99.7% of the bodies), the speed change of the bound portion was only 0.5 to 0.7 mm/s. With more expansion of the vaporized material this will increase, and we expect a speed change of 1 to a few mm/s.



Conclusions:
Nuclear explosives are a well-characterized technology, and for the most catastrophic threats (> 500 m) are the only present technology capable of deflecting disaster. Even for smaller bodies, if alternate methods fail, or if the time is too short, the nuclear option provides considerable mitigation when used only a few years prior to impact. The payload mass necessary to deliver sufficient energy is well within current space capabilities and many popular objections to their use are myths based in ignorance.

We have now extended earlier simulations of nuclear deflection to examine the challenge of a smaller body, and potentially shorter times (years). We have also included micro-porosity to begin to see when it is a sensitive uncertainty. We found that a modest yield standoff burst can fragment a non-porous rubble structure, but that 16% porosity resulted in a substantially bound body. This showed the non-porous case was the worst for fragmentation, but also suggests that robustly fragmenting smaller bodies can be done by high yield standoff bursts reducing the mass requirements fro a rendezvous mission. This is something that we will study in more detail in the future.

Of interest, we found that even when substantial material is ejected, so long as the bound material has a substantial speed change, the mitigation against an Apophis sized object is substantial when done a year before impact, and that very low yields, or large heights of burst can deflect bodies of this size when there are decades to impact.

Despite NEO structural uncertainties, detailed simulations show that nuclear explosives will provide considerable protection. While their use to perturb a body some decades out remains the more desirable option, fragmenting the body remains a viable back-up option with only a few years of lead-time. The ability to react to small bodies discovered some months prior to impact is limited by delivery, not availability of a nuclear package. In particular, the bus or seeker section that carries an impactor or explosive package from the lift vehicle to the asteroid is a non-standard component that would have to be designed.

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