Energy Deposition of Radiation from a Nuclear Explosive on an Asteroid

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Abstract— **Nuclear weapons can be used to break up or deflect asteroids heading towards the Earth. In this process, a nuclear weapon is detonated at a distance from the asteroid's surface, and the emitted radiation is used to impact energy to the asteroid. If enough energy is imparted, asteroid material will "blow-off" resulting in a change of trajectory. This project analyzed the energy deposition of various types of radiation given off by a nuclear detonation and found that energy deposition is highly dependent on source particle type, source particle energy, isotopic composition of the targer, and source distance from the target.**

I. INTRODUCTION

Large cosmic objects such as asteroids pose a catastrophic threat to the earth should their orbits intersect [9]. Many potential solutions for planetary defense against such objects have been discussed, including the use of a nuclear weapon to fragment the asteroid or remove enough of its mass to change its trajectory [5]. This could be done by detonating a weapon of a particular yield a certain distance from the surface of the asteroid. One of the main issues with this approach is the lack of information relating the yield of a nuclear device to its ability to fragment an asteroid. One metric which can be used to gain a qualitative understanding of the effects of a nuclear detonation on an asteroid is the energy deposited by the radiation from the detonation. This measurement can be used to determine neutron yield coupling efficiency [1], which can calculate the amount of mass blown off by a nuclear explosion to analyze change in trajectory. This project examined changes in energy deposition and energy depth profile by varying parameters in a simulated detonation on an asteroid using MCNP6.

II. PROBLEM DESCRIPTION

There are many factors to consider when building an MCNP model to simulate energy deposition on an asteroid. Asteroid size and composition, radiation particle type and energy, and detonation distance all have effects on the energy impacted onto the asteroid. Specifics of the MCNP model of the asteroid were drawn from work done by Major Aaron Ferguson (USA) for his Master's thesis [1]. The asteroid was modeled as a sphere of radius 25 m; a probable size for a cosmic object which could impact the earth [7]. Two different asteroid compositions were analyzed; the Allende meteorite [2] and ice. Each asteroid was subjected to neutron radiation at thermal, 500 keV, 1 MeV, 14.1 MeV and ^{235}U Watt Spectrum energies, as well as hard x-rays at 1, 5, 10 and 20 keV. The distance between asteroid surface and radiation source was varied at 1 m, 10 cm, and 1 cm to examine possible changes to energy deposition depth profile. Total energy deposition in the asteroid was calculated along with the energy deposited as a function of distance into the asteroid. Varying this wide range of parameters and analyzing their effects on the two aforementioned energy measurements produced data to better understand effectiveness of a nuclear explosive device in planetary defense.

TABLE I
ASTEROID COMPOSITION DATA

Composition	Density g/cm^3	Mass (g)
Allende	2.997	1.96330E+11
Ice	0.917	6.00175E+10

III. DESCRIPTION OF WORK

First, a generic input file for the asteroid was constructed in MCNP to quickly vary the parameters being examined and give a total energy deposition tally. A second file was created with concentric spherical cells to examine energy deposition as a function of radial distance. Next, MATLAB scripts were written to process the MCNP tally data and graphically interpret the energy deposition tally data.

A. MCNP Model

The 25 m sphere geometry was defined in the input file, and a cell corresponding to the sphere volume was assigned to the Allende meteorite or ice composition [2] [3]. The radiation source was defined as a point source directly above the surface of the asteroid. Each time the file was run, the ERG, PAR, or POS parameters in the Source Definition (SDEF) card were changed to tally energy deposition for the different particle energies, detonation distances, and particle types discussed in Section II. A +F6 tally was used to tally energy deposited per gram of asteroid from all particles in the system [3], requiring the MODE card to be activated for neutrons, photons, protons, deuterons, tritons, and alphas. Physics models were used when cross-sectional data for heating values and $\frac{dE}{dx}$ were not available for certain particle interactions or energy ranges. Figure 1 shows the ipplotter visualization of the MCNP geometry.

To calculate energy deposited as a function of radial distance into the asteroid, a second input file geometry was created with a number of concentric spheres of varying radii contained within the main 25 m sphere. The +F6 tally was taken in every cell containing the space between these shells

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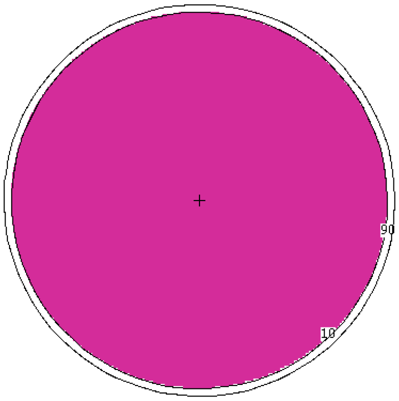

Fig. 1. MCNP6 model of asteroid in ipplotter

in order to examine how energy deposition varied with depth. The distance between each shell and number of cells added was modified in the input file based on the type of radiation and composition of the meteorite. Figure 2 shows a close up of the geometry of the input file used for neutron irradiation of the Allende meteorite composition.

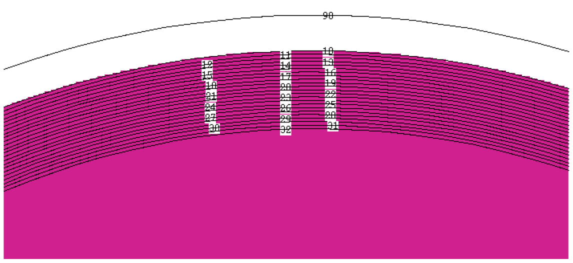

Fig. 2. MCNP6 model of asteroid in ipplotter

B. MATLAB Data Processing

Each MCNP output file gave a tally of collisional heating (H) (MeV/g) per incident radiation particle in each cell volume tallied. The output files also provided the calculated mass of each cell. This data was put into a text file and imported into a MATLAB script which can be referenced in the linked github folder. The script took all the data for each composition, source particle type/energy and detonation distance, calculated the energy deposited, and displayed these results graphically. This was done for both the total energy deposition and the radial energy depth profile data.

$$E_{dep} = H * m \tag{1}$$

IV. RESULTS

A. Total Energy Deposition

Equation 1 gives the total energy deposited in the asteroid per source particle in MeV. Four plots were produced from the MATLAB script, showing energy deposited from neutrons and protons on both compositions. Each plot also shows the effects of incident radiation energy and detonation distance.

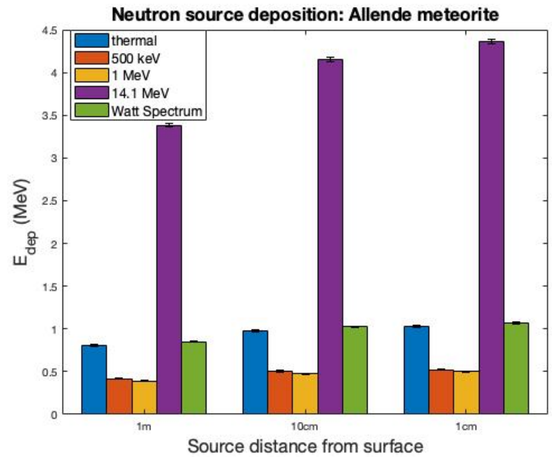

Fig. 3. Energy Deposition on Allende meteorite from neutron source

Figure 3 shows energy deposition from a neutron source at three different distances and 5 different energies on the Allende meteorite composition asteroid. Energy deposited per source particle increased as source distance to the surface decreased. Decreasing the distance for neutrons to travel to the asteroid decreased the probability of a neutron traveling through empty space and exiting the system. One interesting feature of this plot is that energy deposition from neutrons at thermal energies was greater than that from both 0.5 and 1 MeV neutrons. Apart from ^{16}O, the main constituents of this asteroid's composition are ^{24}Mg, ^{28}Si and ^{56}Fe. These isotopes have high neutron scattering and absorption cross sections at thermal energies [6]; thermal neutrons have a higher probability of interacting and depositing energy in the asteroid. If E_{dep} is normalized to the yield of the weapon, thermal neutrons have a very significant contribution to energy deposition in a meteoric composition. Therefore, thermal neutrons would do more damage in an metallic asteroid than neutrons in the epithermal range.

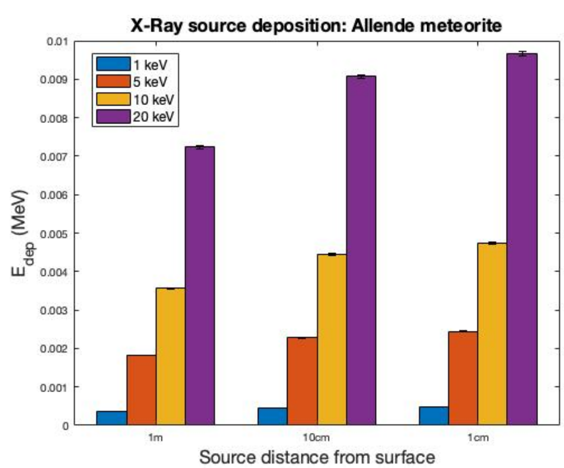

Fig. 4. Energy Deposition on Allende meteorite from x-ray source

Figure 4 shows energy deposition from an x-ray source on the Allende meteorite composition asteroid. As incident photon energy increased, so did energy deposited per photon, as expected. Energy deposition also increased as detonation distance was decreased.

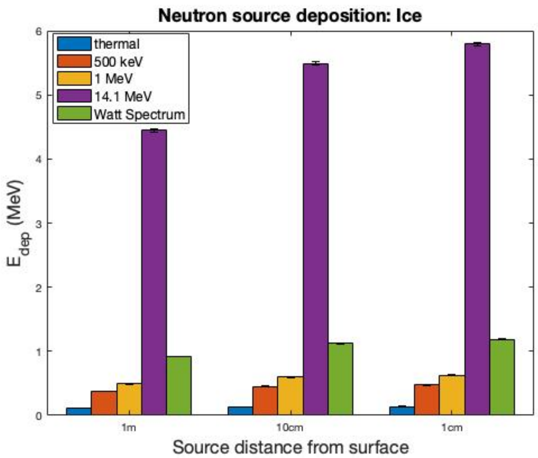

Fig. 5. Energy Deposition on ice meteorite from neutron source

Figures 5 and 6 show energy deposition from neutron and x-ray sources on an asteroid composed of ice. The neutron and x-ray energy deposition increased as source energy increase; the behavior from thermal neutrons for the Allende composition was not seen here. Both simulations showed the expected increased in energy deposition with decreasing detonation distance. However, thermal neutrons did not interact with the ice like they did with Allende, and did not deposit as much energy in this composition.

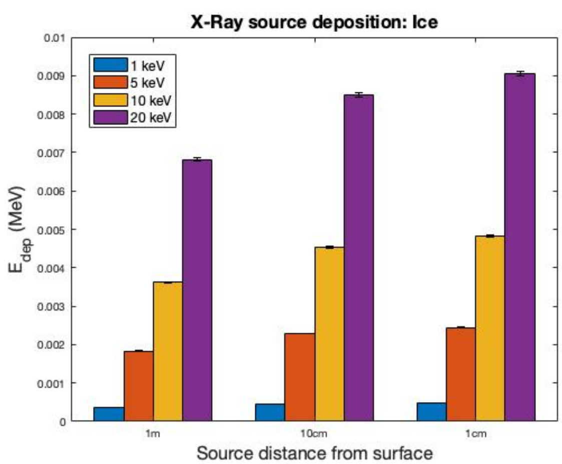

Fig. 6. Energy Deposition on ice meteorite from x-ray source

B. Depth Profile

Figure 7 shows the energy deposition depth profile for a neutron source of various energies 1 cm from the surface. Thermal neutrons penetrated no more than 1 m into the surface, while higher energies penetrated up to 2.1 meters. The bulk of the energy was deposited within the first meter.

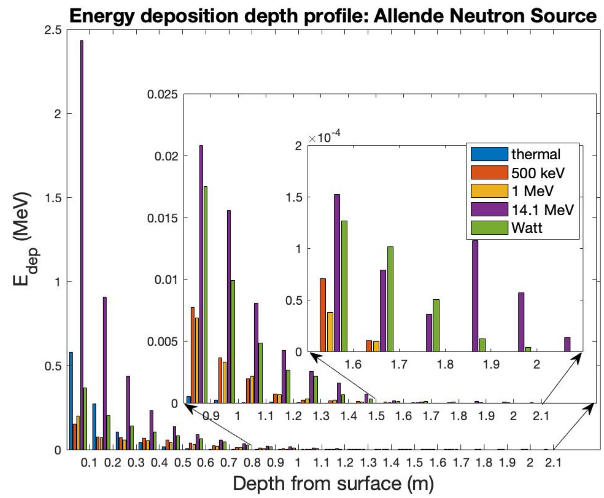

Fig. 7. Depth Profile for neutron source on Allende meteorite

Compared to the neutron source, x-rays were not very penetrative in the Allende composition asteroid.

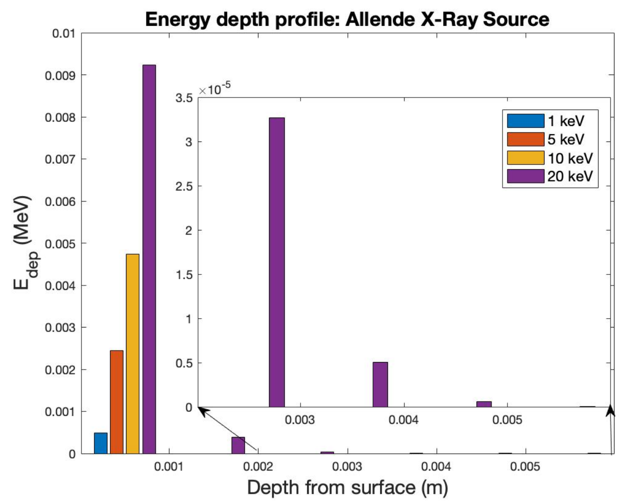

Fig. 8. Depth Profile for x-ray source on Allende meteorite

As seen in Figure 8, only 20 keV x-rays were able to penetrate further than 1 mm into the surface. The higher density of the meteorite composition and the lower energy of the photons prevented them from penetrating much further than the asteroid's surface.

The same tests were run for the ice asteroid. Neutrons were able to penetrate up to 3.75 m deep, due to the lower density and lack of metal elements. Most of the energy was deposited by neutrons in the first meter, as seen in Figure 9. The neutron depth profile in ice showed similar behavior to the depth profile for the Allende composition seen in Figure 7, with E_{dep} falling off exponentially.

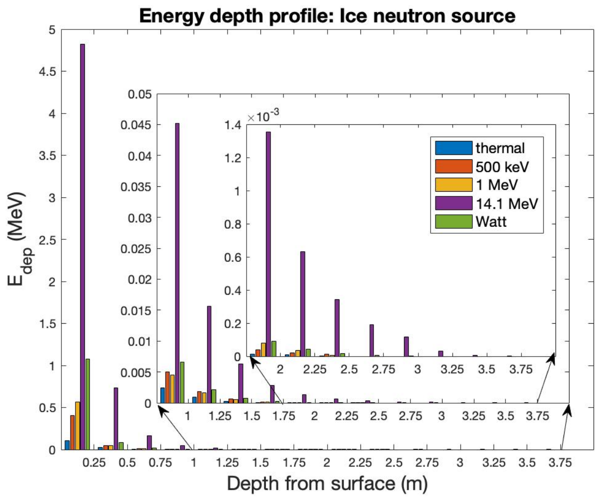

Fig. 9. Depth Profile for neutron source on ice meteorite

The x-ray source depth profile for ice was similar to that of the Allende meteorite. Only 20 keV x-rays penetrated deeper than 5 cm, as seen in Figure 10.

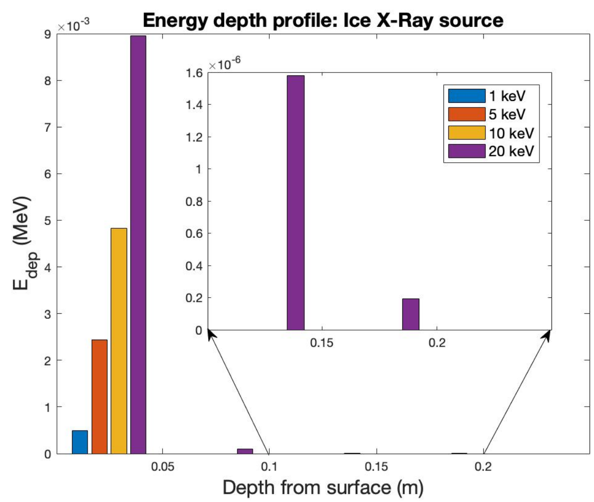

Fig. 10. Depth Profile for x-ray source on ice meteorite

V. CONCLUSIONS

A nuclear weapon's ability to disrupt the trajectory of an asteroid is directly related to the radiation energy it can impact on the target. Energy deposition is highly dependent on the energy and type of the source particle. For example, 14.1 MeV neutrons can deposit more than 4 MeV per nucleon into an asteroid, while slower neutrons deposit less than 1 MeV. X-rays can deposit most of their energy into the surface of a cosmic object, but are not very penetrative and won't do much damage past the surface. Neutrons can penetrate more than a few meters into an asteroid depending on its composition, increasing likelihood of "blow-off" for the purpose of shifting an asteroid's trajectory. The higher the energy of radiation given off by a nuclear detonation, the more energy it will be able to deposit on the surface of an asteroid, and the more damage it can do for the purpose of planetary defense. Additionally, minimizing distance between detonation and the surface of the asteroid maximizes energy deposited. Lastly, the composition of the target will affect energy deposition due to variations in reaction cross sections for different isotopes, indicating that the effectiveness of a nuclear weapon in this situation is also dependent on the isotopic composition of the asteroid. Thermal neutrons deposit more energy than epithermal neutrons in a mass containing metal ions, due to the cross section values for scattering and absorption. This indicates that in metallic asteroids, thermal neutrons deposit a significant amount of energy as these particles make up more of the total weapon yield. This trend can be seen if E_{dep} is normalized to weapon yield for each particle.

Future work which can be done to enhance this project could include creating a detailed mesh in the asteroid surface to get a more in-depth tally of depth profile, not only radially but across the surface of the asteroid as well. Additional radiation sources can be tested, including a detailed thermonuclear spectrum containing all the types of particles emitted from a detonation along a spectrum of energies. This energy deposition data can be used to calculate neutron yield coupling efficiency to determine the overall effectiveness of a nuclear weapon for planetary defense.

APPENDIX

All MCNP input files, output files, and MATLAB code associated with this project can be found in 2d Lt Ashwin Rao's NENG 685 Project Github repository.

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