



**ANALYSIS OF NEUTRON EFFECTS FOR
ASTEROID DISRUPTION**

THESIS

Aaron J. Ferguson, Major, USA
AFIT-ENP-MS-16-M-068

**DEPARTMENT OF THE AIR FORCE
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Wright-Patterson Air Force Base, Ohio

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Degree of Master of Science

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Major, USA

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ANALYSIS OF NEUTRON EFFECTS FOR ASTEROID DISRUPTION

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Abstract

The use of nuclear weapons is one possible method for disrupting or deflecting an asteroid on a trajectory to impact the earth. A largely unexplored component of weapon yield in a disruption scenario is the impact of the neutron output. The results of MCNP-6 simulations are presented demonstrating the effect that incident neutron energy has on the total energy deposited in an asteroid, including that the efficiency of energy deposition in a material is inversely proportional to the incident neutron energy due to negative Q-value reactions. The effects of material composition on the total energy deposited as well as the spatial distribution are also explored. The neutron energy deposition profiles are further assessed using the hydrodynamics code Spheral, to evaluate the effect of varying energy deposition profiles on disruption effectiveness. In most materials, an increase in neutron energy results in an increase in per-neutron energy deposition. In meteoric iron, however, an increase in incident neutron energy above 12 MeV results in lower per-neutron energy deposition due to a sharp rise in the occurrence of the (n,2n) reaction in some of the isotopic constituents. This suggests that isotopic composition, and not just elemental composition, could influence the energy deposition due to the neutron yield of a nuclear weapon. Neutron yield coupling efficiency and disruption efficiency for 14.1 MeV neutrons is significantly lower than for 2.45 MeV neutrons or a thermonuclear neutron spectrum.

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To Lindsay

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Aaron J. Ferguson

Table of Contents

	Page
Abstract	iv
Acknowledgements	vi
List of Figures	x
List of Tables	xvii
I. Introduction	1
1.1 Motivation	1
1.1.1 Asteroid Threat	1
1.1.2 Mitigation Strategies	4
1.2 Background	6
1.3 Problem	7
1.4 Hypothesis	7
1.5 Assumptions and Limitations	8
1.6 Approach	8
II. Theory	10
2.1 Neutron Energy	10
2.2 Neutron Interactions	10
2.2.1 Scattering	11
2.2.2 Capture	13
2.3 Reaction Cross Section	17
III. Methodology	21
3.1 MCNP-6	21
3.1.1 Model	21
3.1.2 Procedures	30
3.2 Spherical	33
3.2.1 Model	34
3.2.2 Simulation inputs	36
IV. Results and Analysis	41
4.1 MCNP	41
4.1.1 Data Acquisition	41
4.1.2 Energy Coupling	41
4.1.3 Neutron Capture and Secondary Particle Creation	48
4.1.4 Geometric Losses from Curvature	53

	Page
4.1.5 Geometric Loss due to Location of the Neutron Source	56
4.1.6 Timing	59
4.1.7 Energy Contours	62
4.2 Spheral	65
4.2.1 Disruption Assessment	65
4.2.2 Alternate Disruption Assessment Methodology	72
V. Conclusion	77
5.1 Summary	77
5.2 Future Work	78
Appendix A. Asteroid Characterization	79
A.1 Definitions	79
A.2 Characterization	79
A.2.1 Size	79
A.2.2 Density	80
A.2.3 Mass Approximation	81
A.2.4 Composition	81
A.2.5 Energy released in fireball	81
A.2.6 Impact Interval	82
Appendix B. Example MCNP Decks	83
Appendix C. Material specific neutron yield coupling efficiency and secondary particle creation	86
C.1 Ice	87
C.2 Wet Tuff	89
C.3 Quartz	91
C.4 Granite	93
C.5 Allende Meteorite	96
C.6 Olivine (Mg)	99
C.7 Olivine (Fe)	101
C.8 Meteoric Iron	103
Appendix D. Center Line Energy Deposition	106
Appendix E. MCNP 2D Energy Deposition Profiles	109
E.1 Ice	110
E.2 Quartz	113
E.3 Allende Meteorite	116
E.4 Meteoric Iron	119

	Page
Appendix F. Height of Burst Variation	122
Appendix G. MCNP Physics Model Discrepancies	127
Bibliography	132
Vita	134

List of Figures

Figure		Page
1.1	Projected fatalities relative to the diameter of the impactor. Energy scale assumes a density of 2 and a velocity of 17 km/s.	3
1.2	Estimated and discovered NEO cumulative populations. Diameter scale assumes an albedo of 0.14. Energy scale assumes a density of 2 and a velocity of 17 km/s.	5
2.1	Hierarchy of neutron interactions.	11
2.2	Nuclear reaction.	14
2.3	Neutron cross sections in ^{28}Si for reactions occurring at energies below 2 MeV.	18
2.4	Neutron cross sections in ^{28}Si for reactions occurring at energies below 15 MeV.	18
2.5	Neutron cross sections in ^{16}O for reactions occurring at energies below 2 MeV.	19
2.6	Neutron cross sections in ^{16}O for reactions occurring at energies below 15 MeV.	19
3.1	Cross section view of the MCNP asteroid model in the YZ plane.	22
3.2	Cross section view of MCNP tally cell fine grid.	27
3.3	Top down view of the MCNP tally cells.	28
3.4	Cross section view of the MCNP tally cells.	29
3.5	Generic thermonuclear weapon neutron energy spectrum.	30
3.6	Asteroid model in Spheral, side view.	35
3.7	Asteroid model in Spheral, side cross section zoomed in.	37
3.8	Asteroid model in Spheral, top view, zoomed in.	38
4.1	Total energy deposited per source neutron for a surface source.	42

Figure		Page
4.2	Iron Secondary Particles.	43
4.3	Energy lost to escape for a surface source.	44
4.4	Available neutron energy coupling efficiency for a surface source.	46
4.5	Neutron yield coupling efficiency for a surface source.	46
4.6	Neutron yield coupling efficiency for a surface source.	47
4.7	Neutron yield coupling efficiency for subsurface source.	48
4.8	Neutron yield coupling efficiency for a subsurface source.	49
4.9	Neutron yield coupling efficiency ratio for a subsurface versus a surface source.	50
4.10	Probability of capture for neutrons.	51
4.11	Neutron capture and secondary particle creation in quartz.	52
4.12	Illustration of geometric loss.	53
4.13	Relative curvature for specified radii.	54
4.14	Fraction of source neutrons captured in quartz.	55
4.15	Neutron yield coupling efficiency in quartz.	55
4.16	Available neutron energy coupling efficiency in quartz.	56
4.17	Fraction of source neutrons captured in quartz.	57
4.18	Neutron yield coupling efficiency in quartz.	57
4.19	Neutron mean free path.	58
4.20	Neutron yield coupling efficiency in quartz.	59
4.21	Fraction of neutrons captured in quartz.	60
4.22	Mean lifetime for captured neutrons.	61
4.23	Mean lifetime for captured neutrons in quartz.	62

Figure		Page
4.24	Energy deposition contour centerline profile.	63
4.25	Energy deposition contour centerline profile.	64
4.26	Node location before and after disruption for an energy profile from thermonuclear neutrons in quartz.	67
4.27	Material parameters following disruption.	68
4.28	Least squares fit by material for fraction ejected.	69
4.29	Least squares fit by neutron energy for fraction ejected with energy deposition simulated using both cross section data and physics models.	71
4.30	Least squares fit by neutron energy for fraction ejected for materials with energy deposition simulated using cross section data.	71
4.31	Earth's intersection with the spherical shell representing the possible location of particle i at time $t < R_{earth}/v_i$	73
4.32	Earth's intersection with the spherical shell representing the possible location of particle i at time $t > R_{earth}/v_i$	74
4.33	Spherical Cap	75
B.1	MCNP Deck for total energy deposited in quartz for 2.45 MeV neutrons and a HoB of 400 cm.	83
B.2	MCNP Deck for total energy deposited in granite for 0-0.1 MeV spectrum of neutrons and a HoB of 0.01 cm.	84
B.3	MCNP Deck for total energy deposited in meteoric iron for a thermonuclear neutron spectrum and a HoB of 0.01 cm.	85
C.1	Available neutron energy and energy deposited per neutron for ice.	87
C.2	Neutron yield coupling efficiency for ice.	88
C.3	Secondary particle creation and neutron capture probability for ice.	88

Figure		Page
C.4	Available neutron energy and energy deposited per neutron for wet tuff.	89
C.5	Neutron yield coupling efficiency for wet tuff.	90
C.6	Secondary particle creation and neutron capture probability for wet tuff.	90
C.7	Available neutron energy and energy deposited per neutron for quartz.	91
C.8	Neutron yield coupling efficiency for quartz.	92
C.9	Secondary particle creation and neutron capture probability for quartz.	92
C.10	Available neutron energy and energy deposited per neutron for granite.	93
C.11	Neutron yield coupling efficiency for granite.	94
C.12	Secondary particle creation and neutron capture probability for granite.	94
C.13	Available neutron energy and energy deposited per neutron for Allende Meteorite.	96
C.14	Neutron yield coupling efficiency for Allende Meteorite.	97
C.15	Secondary particle creation and neutron capture probability for Allende Meteorite.	97
C.16	Available neutron energy and energy deposited per neutron for olivine (Mg).	99
C.17	Neutron yield coupling efficiency for olivine (Mg).	100
C.18	Secondary particle creation and neutron capture probability for olivine (Mg).	100
C.19	Available neutron energy and energy deposited per neutron for olivine (Fe).	101
C.20	Neutron yield coupling efficiency for olivine (Fe).	102

Figure		Page
C.21	Secondary particle creation and neutron capture probability for olivine (Fe).	102
C.22	Available neutron energy and energy deposited per neutron for meteoric iron.	103
C.23	Neutron yield coupling efficiency for meteoric iron.	104
C.24	Secondary particle creation and neutron capture probability for meteoric iron.	104
D.1	Energy deposition contour centerline profile.	107
D.2	Energy deposition contour centerline profile.	108
E.1	Near surface energy contour in ice for a 2.45 MeV neutron source.	110
E.2	Full energy contour in ice for a 2.45 MeV neutron source.	110
E.3	Near surface energy contour in ice for a 14.1 MeV neutron source.	111
E.4	Full energy contour in ice for a 14.1 MeV source.	111
E.5	Near surface energy contour in ice for a thermonuclear neutron spectrum.	112
E.6	Full energy contour in ice for a thermonuclear neutron spectrum.	112
E.7	Near surface energy contour in quartz for a 2.45 MeV neutron source.	113
E.8	Full energy contour in quartz for a 2.45 MeV neutron source.	113
E.9	Near surface energy contour in quartz for a 14.1 MeV neutron source.	114
E.10	Full energy contour in quartz for a 14.1 MeV source.	114
E.11	Near surface energy contour in quartz for a thermonuclear neutron spectrum.	115

Figure		Page
E.12	Full energy contour in quartz for a thermonuclear neutron spectrum.	115
E.13	Near surface energy contour in Allende Meteorite for a 2.45 MeV neutron source.	116
E.14	Full energy contour in Allende Meteorite for a 2.45 MeV neutron source.	116
E.15	Near surface energy contour in Allende Meteorite for a 14.1 MeV neutron source.	117
E.16	Full energy contour in Allende Meteorite for a 14.1 MeV source.	117
E.17	Near surface energy contour in Allende Meteorite for a thermonuclear neutron spectrum.	118
E.18	Full energy contour in Allende Meteorite for a thermonuclear neutron spectrum.	118
E.19	Near surface energy contour in meteoric iron for a 2.45 MeV neutron source.	119
E.20	Full energy contour in meteoric iron for a 2.45 MeV neutron source.	119
E.21	Near surface energy contour in meteoric iron for a 14.1 MeV neutron source.	120
E.22	Full energy contour in meteoric iron for a 14.1 MeV source.	120
E.23	Near surface energy contour in meteoric iron for a thermonuclear neutron spectrum.	121
E.24	Full energy contour in meteoric iron for a thermonuclear neutron spectrum.	121
F.1	Energy deposition profiles in quartz for a neutron source located 0.01 cm above the asteroid surface.	122
F.2	Energy deposition profiles in quartz for a neutron source located 12.5 cm above the asteroid surface.	123

Figure		Page
F.3	Energy deposition profiles in quartz for a neutron source located 25 cm above the asteroid surface.	123
F.4	Energy deposition profiles in quartz for a neutron source located 50 cm above the asteroid surface.	124
F.5	Energy deposition profiles in quartz for a neutron source located 100 cm above the asteroid surface.	124
F.6	Energy deposition profiles in quartz for a neutron source located 200 cm above the asteroid surface.	125
F.7	Energy deposition profiles in quartz for a neutron source located 400 cm above the asteroid surface.	125
F.8	Energy deposition profiles in quartz for a neutron source located 800 cm above the asteroid surface.	126
G.1	Material cards containing unspecified isotopic compositions.	127
G.2	Material cards with all isotopic compositions specified.	128
G.3	Comparison of fraction of source neutrons captured using physics models and cross section tables for a surface burst.	128
G.4	Comparison of energy deposited per neutron using physics models and cross section tables for a surface burst.	129
G.5	Comparison of neutron yield coupling efficiency using physics models and cross section tables for a surface burst.	129
G.6	Comparison of average neutron capture time using physics models and cross section tables for a surface burst.	130
G.7	Comparison of mean free path using physics models and cross section tables for a subsurface burst where no neutrons escape.	131

List of Tables

Table		Page
2.1	Neutron scattering properties of nuclei.	12
2.2	Neutron reaction Q values (MeV).	15
2.3	Neutron reaction threshold energy (MeV).	16
3.1	Materials with mass fraction of constituents. Allende Meteorite composition from [1].	24
4.1	Reaction Q values (+) or threshold energies (-) in meteoric iron.	43
4.2	Q values (+) or threshold energies (-) for neutron reactions in quartz (MeV).	52
4.3	Theoretical and actual energy deposited in the Spherical model (kt).	69
4.4	Fitting parameter for materials.	70
4.5	Fitting parameter for neutron energy.	72
C.1	Reaction Q values (+) or threshold energies (-) for ice.	89
C.2	Reaction Q values (+) or threshold energies (-) for wet tuff.	91
C.3	Q values (+) or threshold energies (-) for neutron reactions in quartz (MeV).	93
C.4	Reaction Q values (+) or threshold energies (-) for granite.	95
C.5	Reaction Q values (+) or threshold energies (-) for Allende Meteorite.	98
C.6	Reaction Q values (+) or threshold energies (-) for olivine (Mg).	101
C.7	Reaction Q values (+) or threshold energies (-) for olivine (Fe).	103

Table		Page
C.8	Reaction Q values (+) or threshold energies (-) for meteoric iron.	105

I. Introduction

1.1 Motivation

1.1.1 Asteroid Threat

Cosmic objects such as asteroids pose a potentially catastrophic threat to earth in the event that their two orbits intersect. The largest recent such event was on 15 February 2013, when a 17-20 meter asteroid impacted without warning near Chelyabinsk, Russia. The total energy released when the asteroid exploded in the upper atmosphere was approximately 440 kt. Even though the energy released was almost 30 times the yield of the bomb dropped on Hiroshima, there were no fatalities reported [2]. Prior to that, the largest known recent impact was on 30 June 1908 near the Stony Tunguska River in Siberia. When the 120 ft space rock detonated in the upper atmosphere, the blast released approximately 2.5 Mt of energy. Again, no fatalities were reported, but eight hundred square miles of trees were ripped out of the ground or knocked over by the blast [3]. If a similar impact were to occur over a populated region such as New York City, hundreds of thousands of deaths could be expected in addition to numerous injuries and severe damage to the city [4].

One component of assessing the risk posed by asteroids is understanding the frequency with which these events can be expected. The average interval between asteroid impacts is inversely related to their size. The smallest particles, some no larger than a grain of sand, can be seen as meteors, or “shooting stars” at a rate of two to three per hour in the night sky, while the largest asteroids with a diameter of 10 km

or greater, are predicted to strike only once every 10^8 years [5][4]. The right hand axis and supplemental bottom axis of Figure 1.2 shows the relationship between the size of a Near Earth Object (NEO-see Appendix A) and the average interval between impacts for the assumed population based on the results of optical surveys.

The second component for assessing the risk due to asteroids is the severity of the event. One measure of severity is the expected number of fatalities caused by an impact. This metric is used in Figure 1.1 which shows fatalities vis-à-vis the size of the impactor. The sharp spike in total fatalities for NEOs larger than 1 km in diameter is due to the global effects resulting in potentially an extinction level event. Despite the potential for world-wide catastrophe, the risk posed by asteroid impacts is estimated to be an average of 91 deaths per year. This number is incredibly skewed, however, since it trivializes the potential threat due to the incredibly infrequent rate of catastrophic events occurring [4]. In fact, there has been only been one person recorded to have been struck by a meteorite [6], and there are no authenticated record of a human death caused by a meteorite [7].

While the impact intervals of NEOs in general represent a probabilistic risk, each specific asteroid behaves in a completely deterministic manner. Because of that, for asteroids which have been identified and whose orbits are known, the potential for earth intersect, and the time at which that might happen can be known to the accuracy of our measurements and uncertainty in orbital calculations for an n-body problem. Furthermore, as the population of identified NEOs increases, the population of unknown NEOs decreases, and with it the probabilistic risk associated with the impact of an unidentified NEO. In order to quantify the risk presented by the unidentified NEOs, an estimate of the total population must be made. An estimate proposed by Stokes et al. (2003) and NASA PA&E (2006) representing a conservative upper bound for the number, N , of NEOs with diameter greater than D , in

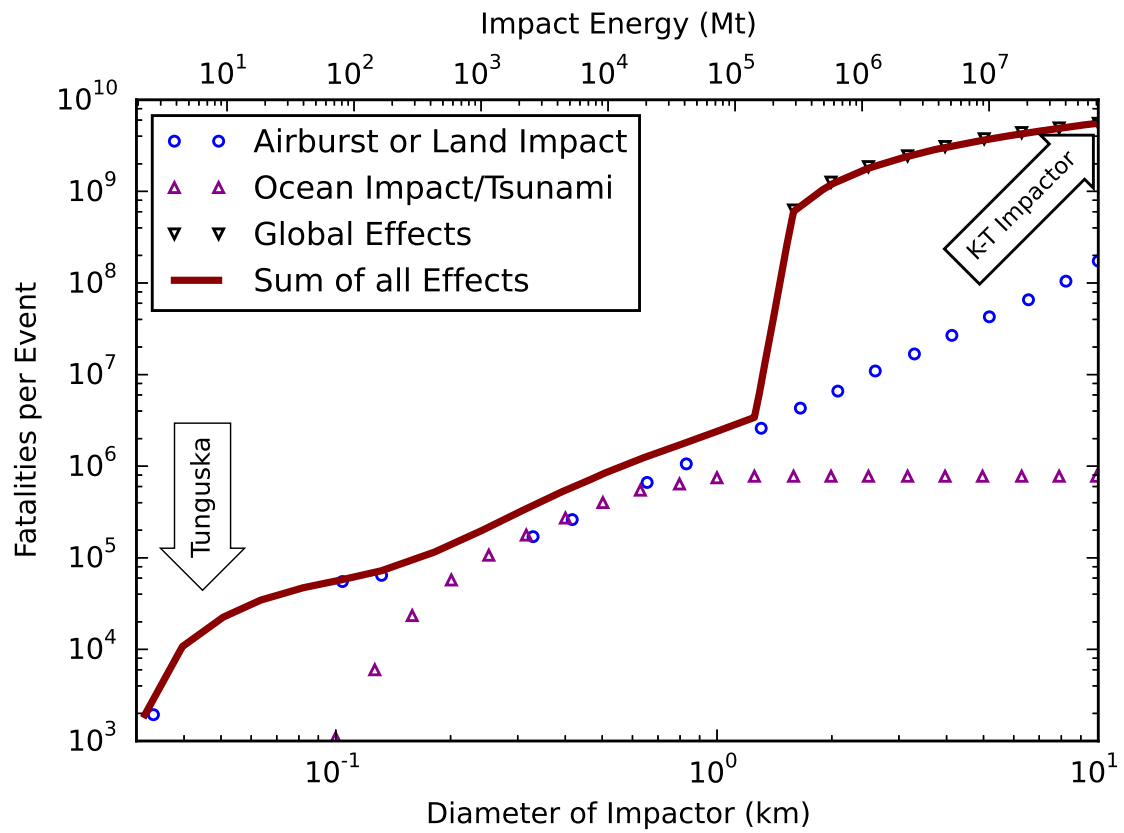


Figure 1.1. Projected fatalities relative to the diameter of the impactor. Energy scale assumes a density of 2 and a velocity of 17 km/s. Reproduced from [4].

kilometers, is given by

$$N = 942D^{-2.354}. \quad (1)$$

A comparison of the population estimate and the number discovered compared to the size is shown in Figure 1.2. The size scale is in terms of absolute magnitude (defined in Appendix A). A significant feature of this graph is the disparity that begins to emerge between population estimate and the number discovered for NEOs smaller than 1 km in diameter. The implication is that a 1 km object would be the largest object to strike with little or no warning, since over 90% of the predicted NEOs larger than 1 km are already being tracked (880 NEOs larger than 1km are being tracked as of 10 February 2016) [8].

1.1.2 Mitigation Strategies

For an asteroid that strikes with only one to two years of warning, civil defense may be the only feasible mitigation strategy. Techniques employed could include evacuations, stockpiling supplies, and coordinating relief efforts among others. This also includes any response to an asteroid that strikes without any warning.

On the opposite end of the time spectrum are “slow-push” or “slow-pull” methods, which could require decades to be effective, and are only useful for objects up to around 100 meters or so. The most efficient direction to apply force is along the direction of travel, either speeding up or slowing down the asteroid. Applying force perpendicular to the direction of travel is much less effective in altering the orbit.

A second technique to alter the trajectory is kinetic impactors. This technique involves sending spacecraft with massive payload(s) to intercept the asteroid, and then have the payloads impact the asteroid. The massive payload(s) impacting at a high velocity would then alter the trajectory.

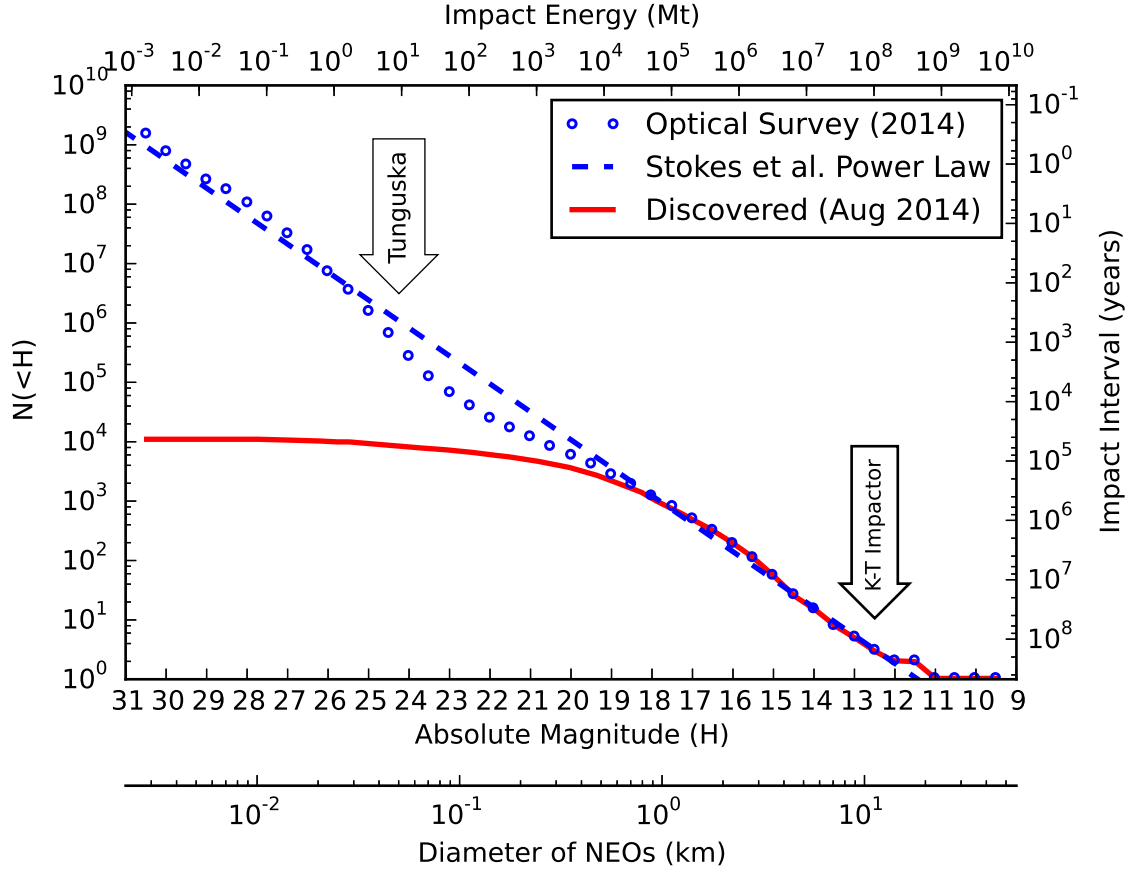


Figure 1.2. Estimated and discovered NEO cumulative populations. Diameter scale assumes an albedo of 0.14. Energy scale assumes a density of 2 g/cm^3 and a velocity of 17 km/s . Reproduced from [9].

The final mitigation strategy is a nuclear explosion, which can be used to either deflect the asteroid by altering its trajectory like with the kinetic impactor, or disrupt it by fracturing it and dispersing the resulting fragments to the greatest extent possible [4].

1.2 Background

The use of kinetic impactors and nuclear explosives for asteroid deflection has been extensively studied [10]. The escape velocity for an object is the speed another, generally much smaller, object would require to escape the gravitational field of the larger body. When the speed change for a successful deflection is small compared to the escape velocity, as is the case for large bodies (500-1000 m in diameter) with decades of warning, a nuclear explosion can be successfully employed with minimal fragmentation. However, for smaller objects and/or shorter approach times, the required speed change approaches the escape velocity. Under these conditions, an attempt to deflect using a nuclear explosion may result in significant fragmentation of the object, leading to some fraction striking earth [11]. An alternative mitigation strategy, disruption, then becomes the preferred technique. The goal of disruption is to fragment the asteroid to the greatest extent possible, and disperse the fragments with the greatest possible speed relative to the un-disrupted center of mass frame of reference. The fragmentation minimizes the size of each piece, leading to a greater probability that each fragment will burn up in the upper atmosphere with minimal effect to earth, while the dispersal potentially reduces the total mass striking the earth.

Disruption using a nuclear explosion is a much less developed area of study with current efforts focusing on the x-ray component of the nuclear output (J. Wasem, personal communication, July 20, 2015).

1.3 Problem

For conventional military explosive demolition calculations, in the absence of specific information about the target composition, target strength, or explosive type, the rule of thumb is “P’ is for plenty”. Likewise, for asteroid disruption with a nuclear explosive, the same rule applies. Absent any knowledge about the asteroid type or the effectiveness of a specific nuclear device, more yield is presumed to produce better results. The problem vis-à-vis disruption using a nuclear explosion is that “P’ is for plenty” is currently the only rule available. There is no body of knowledge relating the efficiency of a specific device for disrupting asteroids of various compositions and constructions.

This research will examine the neutron yield coupling efficiency (i.e. the fraction of the total incident neutron energy from a nuclear explosion which is deposited in the target) for a range of neutron energies and target compositions and the resulting energy deposition profiles. Furthermore, some energy deposition profiles will also be used as a source term to investigate their effect on the target material’s hydrodynamic response.

1.4 Hypothesis

Examining how and where neutrons deposit their energy, the neutron yield coupling efficiency, and the sensitivity of the material response to energy deposition profiles will provide valuable insights to potentially tailoring a nuclear device output to achieve a specific effect with the greatest efficiency. This will help in determining factors such as yield vs. weight for the delivered weapon. Yield and weight considerations are a critical potential concern since the device would have to meet the cargo limitations of available delivery platforms such as the Atlas V rocket that has a launch vehicle capability of 1955 kg. The Atlas V will be used in September 2016 to send

a spacecraft to the asteroid Bennu [12]. The results of this study will also inform the selection of a nuclear device from among the available designs for a particular scenario.

1.5 Assumptions and Limitations

The majority of the neutrons are emitted from a nuclear explosion in the final few generations over times scales of a few shakes (10^{-8} seconds), and travel with a speed on the order of 10^7 m/s [13]. The time required to travel into the material and deposit their energy is therefore non-zero. Instantaneous neutron energy deposition is assumed, however, because it is presumed to be much shorter than the time scales associated with the hydrodynamic response of the material, and the energy deposited is assumed to be fully coupled with the material prior to simulating the hydrodynamic response.

1.6 Approach

Neutron yield coupling efficiency and energy deposition profiles will be examined using MCNP6, a Monte Carlo N-Particle transport code developed by the Los Alamos National Laboratory [14]. The nuclear cross section data used is from the ENDF/B-VII.1 US Evaluated Nuclear Data Library [15]. Simulations to determine neutron yield coupling efficiency will be conducted for neutron energies of 0-15 MeV in eight different material as well as the neutron reactions and material properties that may cause any variations. Mono-energetic 2.45 and 14.1 MeV neutrons, as well as a representative thermonuclear spectrum will also be used. These will be the source energies for developing energy deposition profiles in four of the eight materials initially examined.

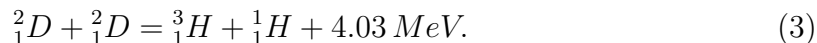
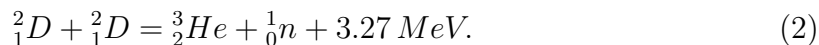
The sensitivity of the material response to the energy deposition profile will

be evaluated using Spheral, a smoothed-particle hydrodynamics code developed by Lawrence Livermore National Laboratory. Disruption effectiveness will be evaluated using novel metrics.

II. Theory

2.1 Neutron Energy

The neutron energies from deuterium-deuterium (D-D) and deuterium-tritium (D-T) fusion were the two of the source energies chosen for simulating the energy deposition profiles in MCNP. The D-D reaction has two possible outcomes, (2), where a neutron is produced and (3) where no neutron is produced.



Through conservation of energy and momentum, the neutron from (2) has an energy of 2.45 MeV. The D-T reaction has only one outcome,



and the resulting neutron has an energy of 14.1 MeV [13].

2.2 Neutron Interactions

A classification system for neutron interactions is shown in Figure 2.1. The two primary mechanisms through which a neutron interacts with an atom are scattering off the nucleus or absorption by the nucleus. Since the neutron is an uncharged particle, its interactions with electrons are negligible [16]. Absorption reactions include capture, where one or more particle may be emitted, and fission, where the nucleus splits.

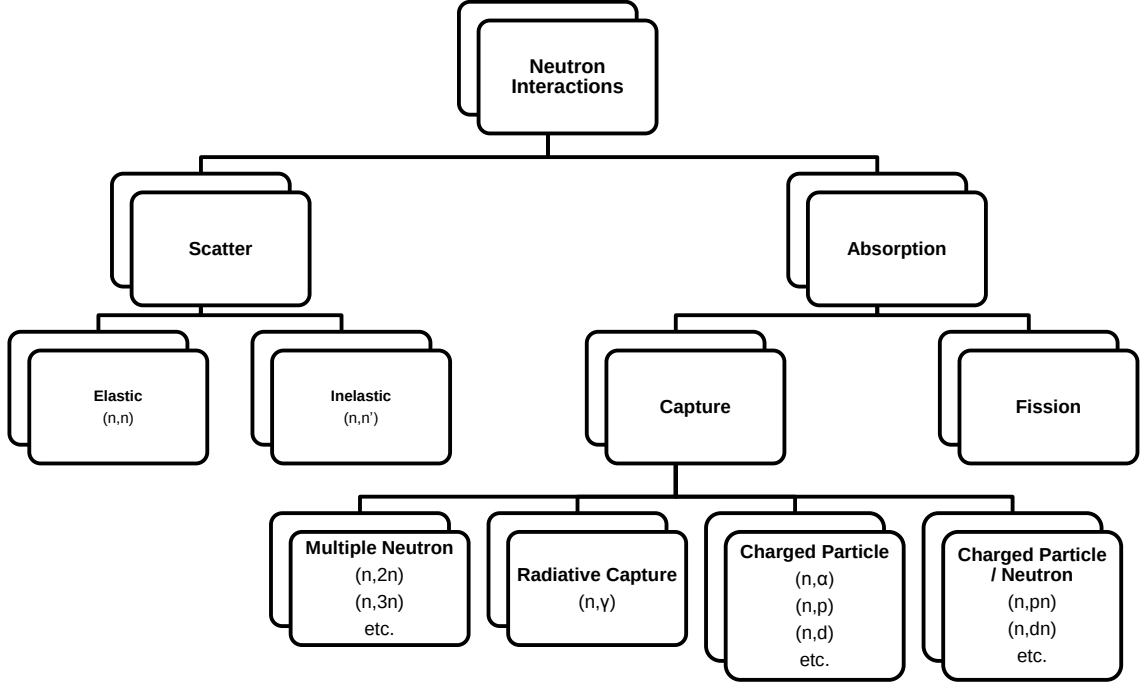


Figure 2.1. Hierarchy of neutron interactions.

2.2.1 Scattering

When a neutron scatters off a nucleus, it transfers some portion of its kinetic energy to the nucleus. If the energy and momentum are conserved in the interaction, it is considered an elastic scattering event represented as (n,n) . For a neutron undergoing elastic scatter, the maximum energy it can transfer to the nucleus, ΔE_{max} depends on the atomic mass, A , of the target nucleus and is given by

$$\Delta E_{max} = E \left[1 - \left(\frac{A-1}{A+1} \right)^2 \right] = E (1 - \alpha), \quad (5)$$

where E is the initial energy of the neutron, and α is defined by the equation. The minimum remaining energy, E_{min} , of the neutron following the collision is found from

$$E_{min} = E - \Delta E_{max} = \alpha E. \quad (6)$$

Therefore

$$\alpha = \frac{E_{min}}{E}, \quad (7)$$

indicating that the smallest possible remaining fraction of the neutron's energy is α [17]. The average logarithmic energy decremented, ξ , is defined as

$$\xi = \ln \left(\frac{\overline{E_2}}{E_1} \right) = 1 + \frac{\alpha}{1 - \alpha} \ln \alpha, \quad (8)$$

where E_1 is the neutron energy before the collision and E_2 after the collision [18]. From this, the average fraction of its energy that the neutron loses per collision is

$$\frac{\overline{E_2}}{E_1} = e^{-\xi}. \quad (9)$$

Table 2.1 provides a summary of scattering properties of nuclei representing the range of atomic masses for elements studied in this paper. Also included is the number of elastic scatters for a 14.1 MeV neutron to reach 1 eV.

Table 2.1. Neutron scattering properties of nuclei.

Isotope	$\frac{E_{max}}{E}$	$\alpha = \frac{E_{min}}{E}$	ξ	$\frac{\overline{E_2}}{E_1}$	Collisions to 1 eV
^1H	1.0000	0	1.0000	0.3679	17
^{16}O	0.2215	0.7785	0.1199	0.8870	138
^{23}Na	0.1597	0.8403	0.0845	0.9190	195
^{28}Si	0.1332	0.8668	0.0698	0.9326	236
^{40}Ca	0.0952	0.9048	0.0492	0.9520	335
^{58}Ni	0.0667	0.9334	0.0341	0.9665	483

Inelastic scatter occurs when kinetic energy is not conserved, and instead some of the neutron's energy is absorbed by the nucleus, putting it in an excited nuclear state

[16]. Inelastic scattering is only possible when the neutron's energy exceeds the energy of the lowest nuclear excited state of the target atom. Following an inelastic scatter, the nucleus will almost instantaneously emit excess energy to transition to a more energetically favorable state by emitting a gamma of energy equal to the difference in energy of the states minus a small fraction for nuclear recoil, $E_r = E_\gamma^2/2 * m_r * c^2$. In some instances, however, the decay is delayed, and these longer lived nuclear excited states are known as isomers. The effect of isomers are not accounted for in the MCNP simulations.

2.2.2 Capture

When a neutron is captured by an atom, it forms a temporary excited state known as a compound nucleus, C^* , which exists until one or more particles are emitted [19]. The compound nucleus will experience a change in energy both from the energy of the incident neutron, but also due to the difference in mass between the compound nucleus, and the neutron and nucleus that formed it (a result of a change in binding energy). For any nuclear reaction, the change in energy, Q , can be found by

$$Q = (m_{initial} - m_{final})c^2, \quad (10)$$

where $m_{initial}$ is the total mass of the reactants and m_{final} is the total mass of the products. One possible result of a capture is the emission of photon(s) as the nucleus decays back to the ground state. A shorthand representation of this reaction is (n, γ) where n represents the incident particle, and γ represents the emitted particle. An example of this is the reaction

$$n + {}^1\text{H} \rightarrow ({}^2\text{H})^* \rightarrow {}^2\text{H} + 2.225 \text{ MeV}, \quad (11)$$

where the 2.225 MeV is the Q-value of the reaction. Another possibility is the emission of one or more nucleons. In this case, the reaction is of the form

$$M_1 + M_2 \rightarrow C^* \rightarrow M_3 + M_4, \quad (12)$$

where M_1 and M_2 are the mass of the neutron and target atom, and M_3 and M_4 are the mass of the resultant atom and emitted nucleon(s) as shown in Figure 2.2.

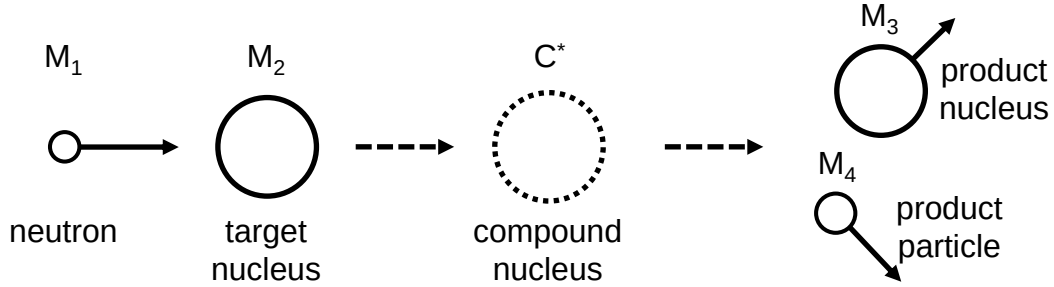


Figure 2.2. Nuclear reaction.

If $M_1 + M_2 > M_3 + M_4$, then the reaction is energetically possible for any incident neutron energy. However if $M_1 + M_2 < M_3 + M_4$, there is an energy threshold which must be overcome for the reaction to take place.

The Q values, in MeV, for all the reactions and isotopes examined in this paper are shown in Table 2.2. If the value is positive, then the reaction is possible for any incident neutron energy. However, a negative value represents the energy deficit of the reaction. This energy deficit does not, however, represent the threshold energy that the reaction requires to occur. According to Turner, “The neutron must have enough energy to supply both the increase in mass, $-Q$, and also continued motion of the center of mass of the colliding particles after the collision [16].” This threshold energy, E_{th} is given by

$$E_{th} = Q \left(1 + \frac{M_1}{M_3 + M_4 - M_1} \right). \quad (13)$$

The threshold energies for some of the reactions listed in Table 2.2 are given in Table 2.3. Threshold energies for the (n,3n) reaction are not included since the Q values for all materials examined exceed 15 MeV, which is higher than the neutron energies examined herein.

Table 2.2. Neutron reaction Q values (MeV).

Isotope	Reaction						
	(n, γ)	(n,p)	(n,d)	(n,t)	(n, α)	(n,2n)	(n,3n)
¹ H	2.225	-	-		-	-	
¹⁶ O	4.143	-9.128	-9.903	-14.479	-2.216	-15.664	-28.887
²³ Na	6.959	-3.082	-6.570	-10.677	-3.866	-12.420	-23.488
²⁴ Mg	7.331	-4.222	-9.468	-15.631	-2.555	-16.532	-29.676
²⁵ Mg	11.093	-2.542	-9.839	-10.541	0.478	-7.331	-23.862
²⁶ Mg	6.443	-8.060	-11.921	-14.675	-5.414	-11.093	-18.424
²⁷ Al	7.725	-1.317	-6.047	-10.882	-3.132	-13.058	-24.423
²⁸ Si	8.474	-3.349	-9.360	-16.161	-2.654	-17.180	-30.494
³⁹ K	7.800	0.728	-4.157	-9.738	1.361	-13.078	-25.15
⁴¹ K	7.534	-1.199	-5.584	-9.196	-0.115	-10.095	-17.895
⁴⁰ Ca	8.363	-0.018	-6.104	-12.924	1.748	-15.635	-28.931
⁵⁴ Fe	9.298	0.596	-6.629	-12.425	0.844	-13.378	-24.064
⁵⁶ Fe	7.646	-2.402	-7.959	-11.928	0.326	-11.197	-20.495
⁵⁷ Fe	10.045	-1.402	-8.335	-9.348	2.399	-7.646	-18.843
⁵⁸ Ni	8.999	0.912	-5.948	-11.067	2.899	-12.216	-22.464
⁶⁰ Ni	7.820	-1.529	-7.308	-11.504	1.355	-11.388	-20.387
⁶¹ Ni	10.596	-0.030	-7.636	-8.871	3.580	-7.820	-19.208
⁶² Ni	6.838	-4.029	-8.913	-11.975	-0.435	-10.596	-18.416

When reactions with a positive Q value occur, more energy is released in the material than was carried by the neutron which lead to the reaction. This results in an

Table 2.3. Neutron reaction threshold energy (MeV).

Isotope	Reaction				
	(n,p)	(n,d)	(n,t)	(n, α)	(n,2n)
¹⁶ O	-9.669	-10.527	-15.391	-2.355	-16.651
²³ Na	-3.212	-6.858	-11.145	-4.036	-12.964
²⁴ Mg	-4.393	-9.866	-16.287	-2.663	-17.226
²⁵ Mg	-2.64	-10.236	-10.967	-	-7.626
²⁶ Mg	-8.362	-12.384	-15.244	-5.624	-11.524
²⁷ Al	-1.364	-6.273	-11.289	-3.249	-13.546
²⁸ Si	-3.466	-9.698	-16.743	-2.749	-17.799
³⁹ K	-	-4.264	-9.99	-	-13.416
⁴¹ K	-1.228	-5.722	-9.422	-0.118	-10.344
⁴⁰ Ca	-0.018	-6.258	-13.25	-	-16.029
⁵⁴ Fe	-	-6.753	-12.658	-	-13.629
⁵⁶ Fe	-2.445	-8.103	-12.143	-	-11.399
⁵⁷ Fe	-1.426	-8.482	-9.514	-	-7.782
⁵⁸ Ni	-	-6.051	-11.259	-	-12.429
⁶⁰ Ni	-1.555	-7.431	-11.698	-	-11.579
⁶¹ Ni	-0.031	-7.762	-9.018	-	-7.95
⁶² Ni	-4.093	-9.058	-12.17	-0.442	-10.768

increase in neutron yield coupling efficiency. Conversely, if the incident neutron energy exceeds the threshold energy for a negative Q reaction, and that reaction occurs, there is a reduction in the energy deposited in the material, and a corresponding reduction in neutron yield coupling efficiency.

2.3 Reaction Cross Section

Neutron yield coupling efficiency is not only dependent on the types of reactions that are energetically possible, but also on the probability of them occurring. This probability can be expressed as a cross section, traditionally measured in barns, which is a unit of area equal to 10^{-28} m^2 or 10^{-24} cm^2 . A cross section can be conceptualized as the size of a target for a neutron traveling through the material to hit. Just like a larger target is more likely to be hit, a larger cross section represents an increased probability for a specified reaction to occur.

Using ^{28}Si and ^{16}O (the constituent elements of quartz) as an example, the total neutron cross section, as well as the cross section for elastic and inelastic scatter and the (n,2n), (n, γ), (n,p), (n,d), and (n, α) capture reactions, are shown in Figures 2.3-2.6.

In Figures 2.3 and 2.5, all the cross sections become linear (in log-log space) at low energies, and have the same slope. This behavior is known as the “1/v law”, due to the inverse relationship between velocity and cross section. Because of this relationship, if the cross section for one neutron energy or velocity is known, then the cross sections for the rest of this low energy region can be calculated using

$$\frac{\sigma}{\sigma_0} = \frac{v_0}{v} = \sqrt{\frac{E_0}{E}}, \quad (14)$$

where σ is the cross section at velocity, v , or energy, E , and σ_0 is the cross section at

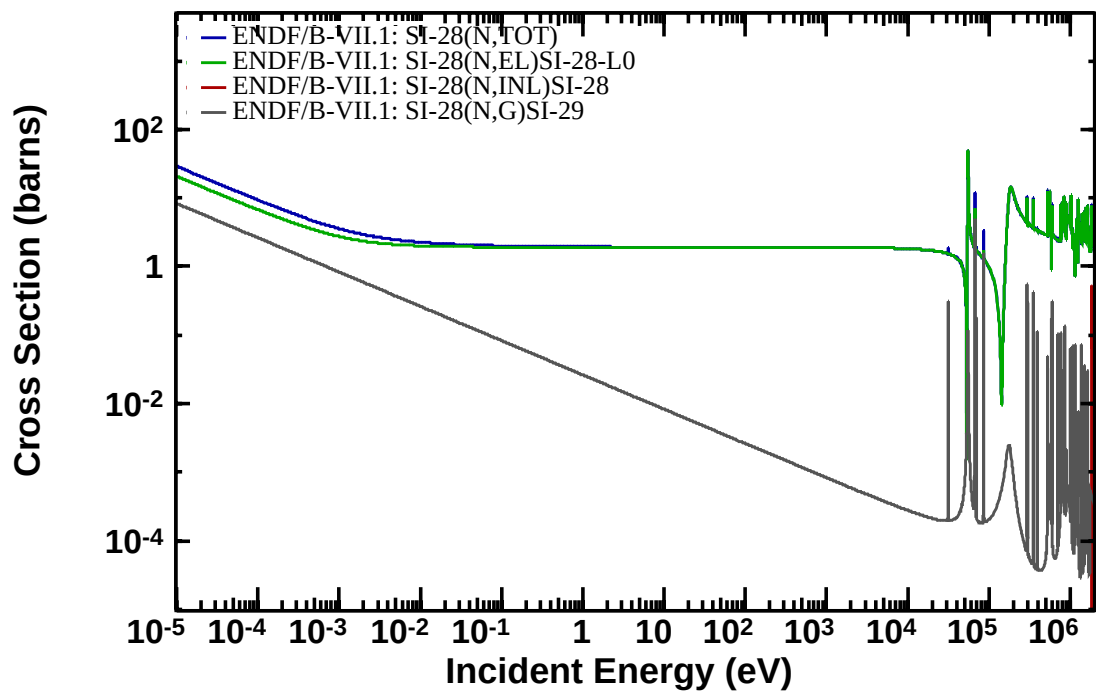


Figure 2.3. Neutron cross sections in ^{28}Si for reactions occurring at energies below 2 MeV. Created in ZVView with data from [20].

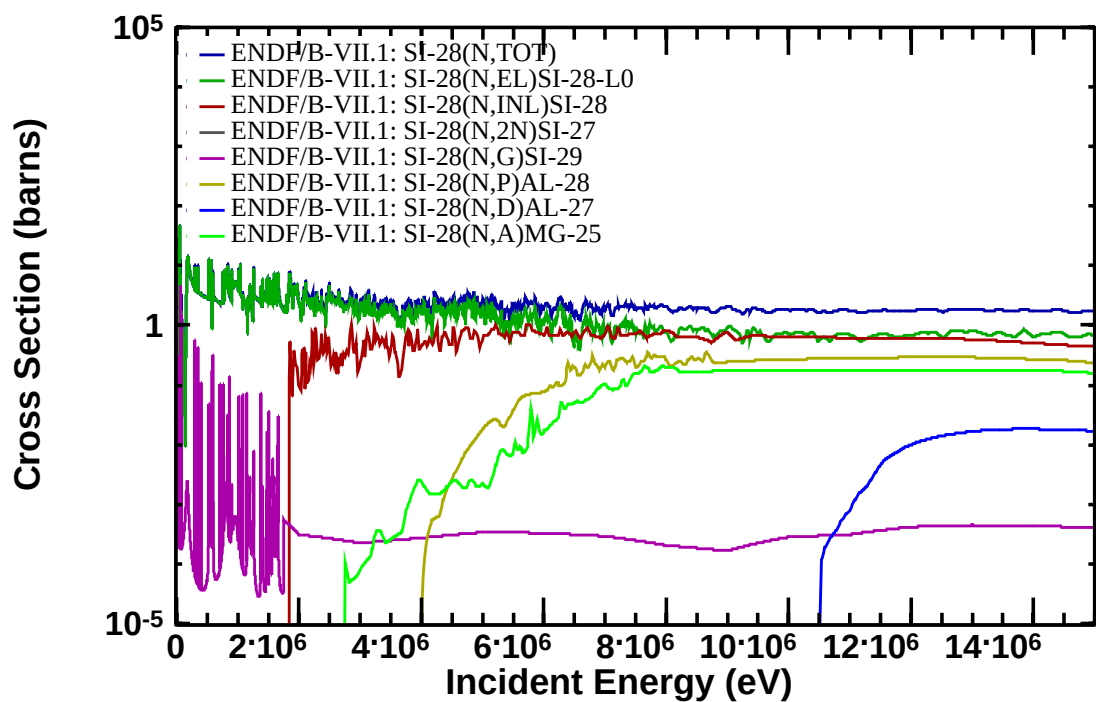


Figure 2.4. Neutron cross sections in ^{28}Si for reactions occurring at energies below 15 MeV. Created in ZVView with data from [20].

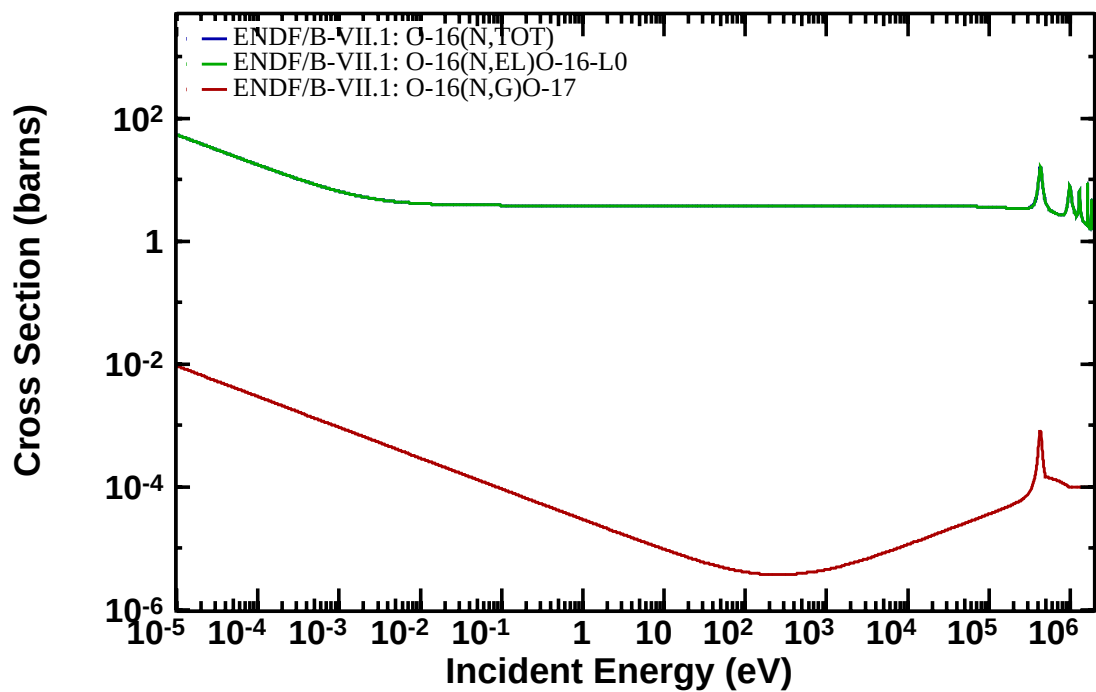


Figure 2.5. Neutron cross sections in ^{16}O for reactions occurring at energies below 2 MeV. Created in ZVView with data from

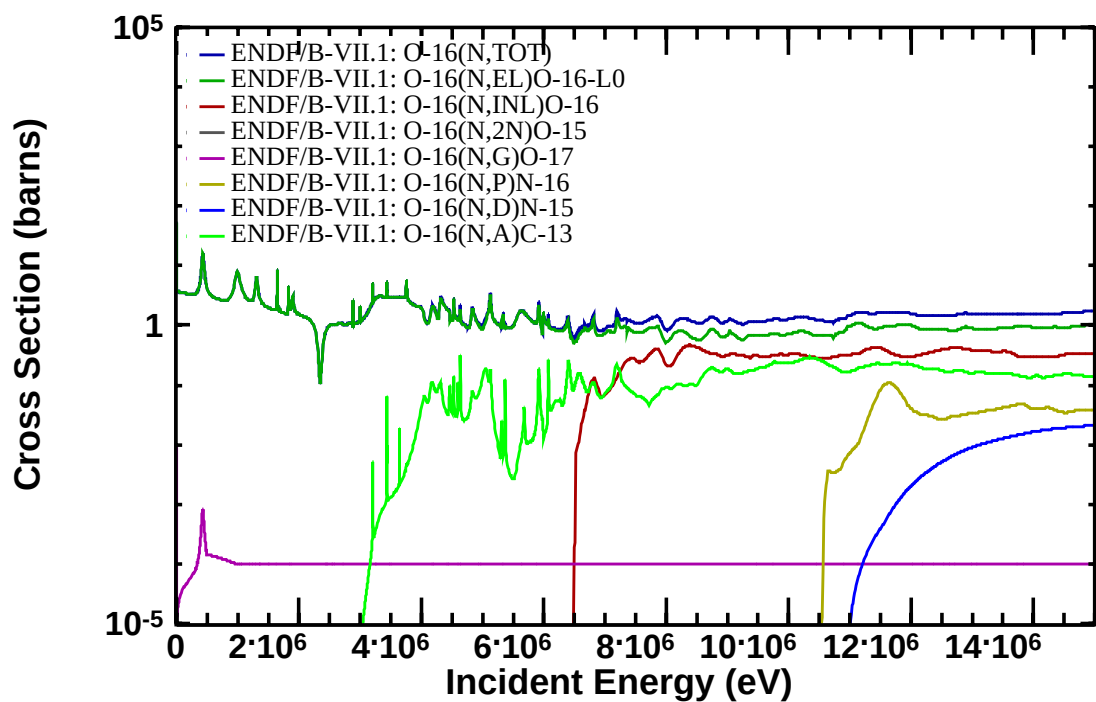


Figure 2.6. Neutron cross sections in ^{16}O for reactions occurring at energies below 15 MeV. Created in ZVView with data from [20].

velocity, v_0 , or energy, E_0 [16].

III. Methodology

The computational work in this research consisted of two components. MCNP6 is used to study how variations in neutron energy, material composition, and height of burst (the distance between the asteroid surface and the nuclear explosion or neutron source) affect neutron yield coupling efficiency, and create a set energy deposition profiles. Spheral is used to assess the sensitivity of disruption effects to the energy deposition profile.

3.1 MCNP-6

3.1.1 Model

For most computations, the asteroid was modeled as a sphere with a radius of 25 meters. This size was chosen since it is within the size range of objects too small to successfully deflect and it also is within the size range of objects where a significant fraction of the population has not yet been discovered, leading to the potential of an object being detected with less than the necessary time for a deflection to achieve the necessary offset to avoid impact with the earth. Finally, it represented an upper limit on the size of model that could be evaluated in Spheral with sufficient resolution given the limited computational capacity available. The basic geometry is shown in Figure 3.1.

The neutron output from a nuclear explosion is modeled as an isotropic point source located on the z axis at a distance of 0.01-800 cm from the surface.

Materials

Eight different material compositions were evaluated in MCNP. They are listed in Table 3.1 along with the mass fractions of their constituent elements or isotopes. The

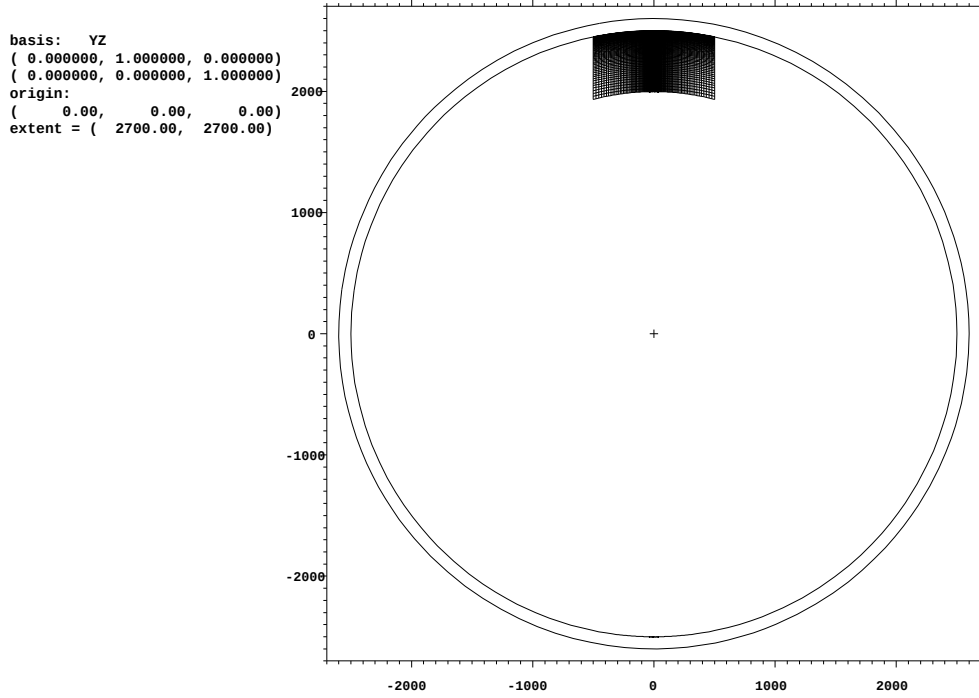


Figure 3.1. Cross section view of the MCNP asteroid model in the YZ plane, with the Y axis in the vertical direction. Units on vertical and horizontal scale are length in centimeters. The inner circle represents the physical asteroid, and the outer circle represents the limit of the MCNP universe, beyond which particles are no longer tracked. The cross-hatched region near the top of the figure represents the maximum extent of the tally cells extending in 5 meters from the surface and out to 5 meters from the Z axis.

composition for the Allende meteorite are from measurements made from collected samples. While it is categorized as a carbonaceous chondrite, the amount of carbon it contains is only 0.25% of the total mass, and was therefore not included in the MCNP model [1]. The approximate terrestrial naturally occurring isotopic composition for each element were used for all materials, although some of the isotopes evident in only trace amounts were excluded. Also, for elements that were only minor constituents of the material, only the most common isotope(s) were included.

The materials were chosen with the intent of studying a wide range of responses to neutrons, and with the exception of the Allende meteorite, are not necessarily representative of any specific asteroid composition.

Table 3.1. Materials with mass fraction of constituents. Allende Meteorite composition from [1].

Material	Constituents																			Density($\frac{g}{cm^3}$)
	¹ H	¹⁶ O	²³ Na	²⁴ Mg	²⁵ Mg	²⁶ Mg	²⁷ Al	²⁸ Si	³⁹ K	⁴¹ K	⁴⁰ Ca	⁵⁴ Fe	⁵⁶ Fe	⁵⁷ Fe	⁵⁸ Ni	⁶⁰ Ni	⁶¹ Ni	⁶² Ni		
Ice	.1120	.8881	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.917
Wet Tuff	.0258	.6146	-	-	-	-	-	.3595	-	-	-	-	-	-	-	-	-	-	-	2.3
Quartz	-	.5326	-	-	-	-	-	.4708	-	-	-	-	-	-	-	-	-	-	-	2.65
Granite	-	.4835	.0274	.0043			.0763	.3392	.0319	.0023	.0130	-	.0216	-	-	-	-	-	-	2.7
Allende Meteorite	-	.6663	-	.1167	.0148	.0163	.0170	.1605	-	-	.0184	-	.2351	-	.0095	.0032	-	-	-	2.997
Olivine (Mg)	-	.4549	-	.2729	.0346	.0380	-	.1666	-	-	-	-	-	-	-	-	-	-	-	3.2
Olivine (Fe)	-	.3141	-	-	-	-	-	.1378	-	-	-	0.318	.5027	.0121	-	-	-	-	-	4.49
Meteoritic Iron	-	-	-	-	-	-	-	-	-	-	-	.0348	.5503	.0132	.2723	.1049	.0046	.0145	-	7.5

Tally

MCNP6 has a number of standard tallies by which the user can record many different parameters over surfaces and volumes such as flux, energy densities, charge, current, etc. For all the simulations here, the +F6 tally was used. The +F6 tally records the collision heating for all particles in the model in units of MeV/g per source particle, averaged over the volume of the tally cell. Cross section libraries were used for heating values and dE/dx (change in energy per unit distance) was used when available for particles such as neutrons, photons, electrons, and protons. Physics models are automatically employed when tabular data is not available for the specific interaction, or for energy regimes that exceed the limits of available data [21]. The effects of physics modes are addressed in Appendix G. Figure B.1 in Appendix B is an example MCNP deck with a mono-energetic neutron source.

MODE

The MODE card lists the particles which are to be transported in the problem. For this simulation, MODE N P H D T A was used, to track neutrons, photons, protons, deuterons, tritons and alphas. MODE E was specifically not used for two reasons. First, it was not used in the examples provided to the author. Secondly, an annotation by K.Yip in a MCNP report from Brookhaven National Lab indicates that, “...when “e” (electron) is included in the MODE card, photon energy deposition is NOT included in +F6 [22].”

PHYS

Photonuclear particles are not automatically tracked, but was turned on using PHYS:P, with *ispn* set to -1. This causes one photon interaction per collision to be sampled. Cross section data is not available for all nucleotides. One way to partially

remedy this is to substitute another nucleotide's cross section data for the photon production instead. This is accomplished by adding a second materials card labeled MPNXX (where XX is the material number), and then specifying the nucleotide which does not have the cross section available, and the replacement to be used. For these simulations, the cross section for K have been replaced with those for Ca, the effect of which can not be known due to the lack of the K cross sections. Physics cards for all other particles were used, but were all set to default parameters. Figure B.2 in Appendix B is an example MCNP deck where the MPNXX card is used.

Tally cell

Two tally cell geometries were used in the simulations. The first was a single tally cell comprising the entire asteroid. This tally cell was used to determine the total energy deposited, the average number of secondary particles created, as well as the number of neutrons which escaped, and the average energy of the escaping neutrons. This cell geometry did not provide any spatial information regarding where the energy was deposited, or where the secondary particles were generated.

A second tally cell geometry was used to generate energy deposition profiles. The geometry was constructed using two sets of surfaces. Centered on the origin, and progressing inward from the exterior surface were a set of concentric spheres. Centered on the z axis and progressing outwards were a set of concentric cylinders. The intersection of these two sets of surfaces created tally cells with two different shapes. The cells along the z axis formed by the innermost cylinder are a set of stacked cylinders with spherical caps. Progressing outward, they are surrounded by toroids with two sides defined by spheres, and two sides defined by cylinders. This geometry is not suitable for describing the entire volume of a sphere, but was suitable for the dimensions over which it was used, and also provided some flexibility in adjusting the

size of the tally cells in relationship to their distance from the neutron source. The asteroid model had a 25 meter radius and the tally cells only extended 5 meters in from the surface, and 5 meters from the z axis. This distance was chosen because it exceeded the maximum energy deposition for all materials as shown in the energy profiles in Appendix E. At this scale, the geometry is nearly rectangular (and in fact all 2D energy contours are presented in rectangular coordinates). Beyond giving flexibility in cell sizing, this configuration also helped improve the counting efficiency by maximizing the tally cell volume while retaining the required locational specificity due to the cylindrical symmetry of the problem. Figure 3.2 is a cross section view of the tally cell fine grid from the side, and Figure 3.3 is a cross section view from the top (i.e. the positive z axis).

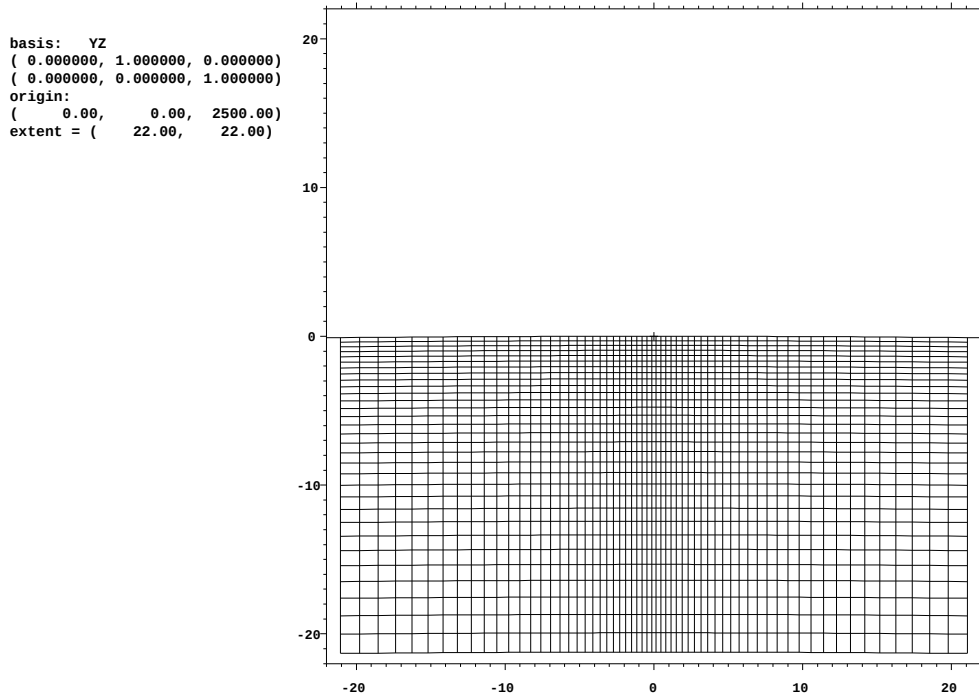


Figure 3.2. Cross section view of the MCNP tally cell fine grid from the side. The cells along z-axis are cylindrical, with the remaining cells in the shape of a toroid formed when the visible cross section is rotated around the z-axis.

Tally cell size was designed to approximately match the spatial distribution of

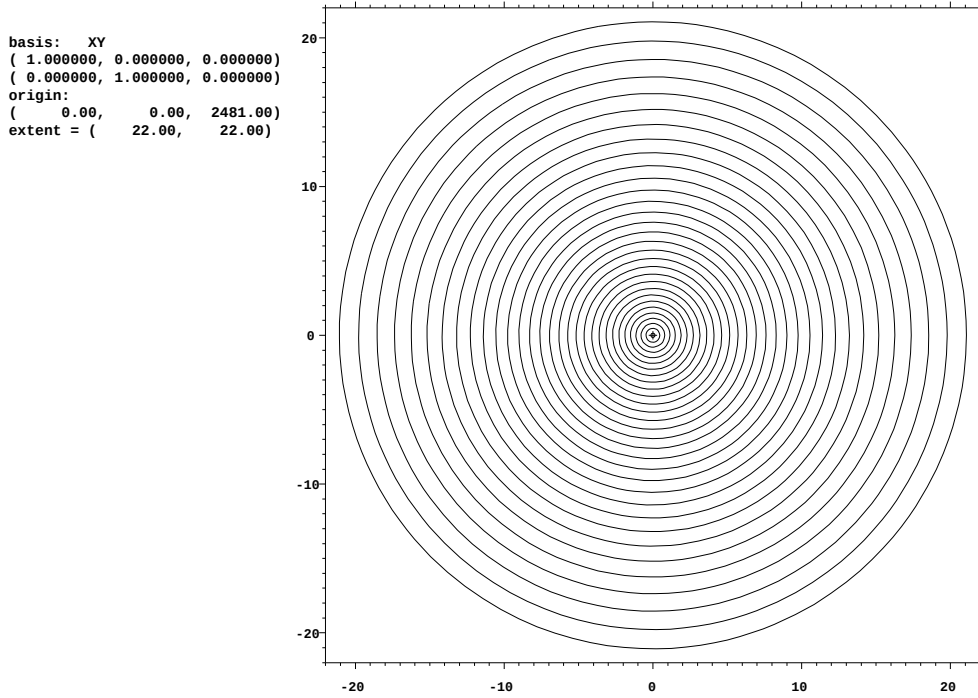


Figure 3.3. Top down view of the MCNP tally cells.

the nodes used in Spheral. Logarithmic spacing was used to increase the distance between adjacent spheres the farther they were from the surface, and increase the spacing between adjacent cylinders the farther they were from the z axis. This raised the problem of very thin cylinders (i.e. with a small radius) and toroids (i.e. with inner and outer surface close together) near the z axis far from the surface, and very flat toroids near the surface far from the z axis. The first issue this caused is that the energy deposition over the volume of the cell varied much more in one dimension than another. Also, they presented a small total volume compared to the distance from the neutron source so that the number of neutrons reaching those cells was very low compared to other cells the same distance from the source.

The remedy was to have two sets of cells created. One was for regions near the neutron source, and the other was for regions farther away. The minimum dimension for the fine grid was 0.3 cm, with a ratio of 1.05 between adjacent surfaces. The

dimension for transitioning from the fine to the course grid was 1.3 cm. The minimum dimension was the diameter of the inner cylinder, and the thickness of the outermost spherical shell. The thicknesses of subsequent shells increased by the ratio of 1.05. The limit of the fine grid was when the difference in radius for two adjacent surfaces exceeded the transition dimension.

The coarse grid minimum radius for the cylinders was 1.143 cm, which is the size of the fourth smallest cylinder of the fine grid ($.15 + \sum_{n=1}^3 0.3 * 1.05 = 1.143$). The course grid maximum radius was 2498.71 cm ($\sum_{n=0}^3 0.3 * 1.05 = 1.29$, $2500 - 1.29 = 2498.71$). The extent of the coarse grid was 5 m. Figures 3.1 and 3.4 are examples of the coarse grid, and Figures 3.2 and 3.3 are examples of the fine grid.

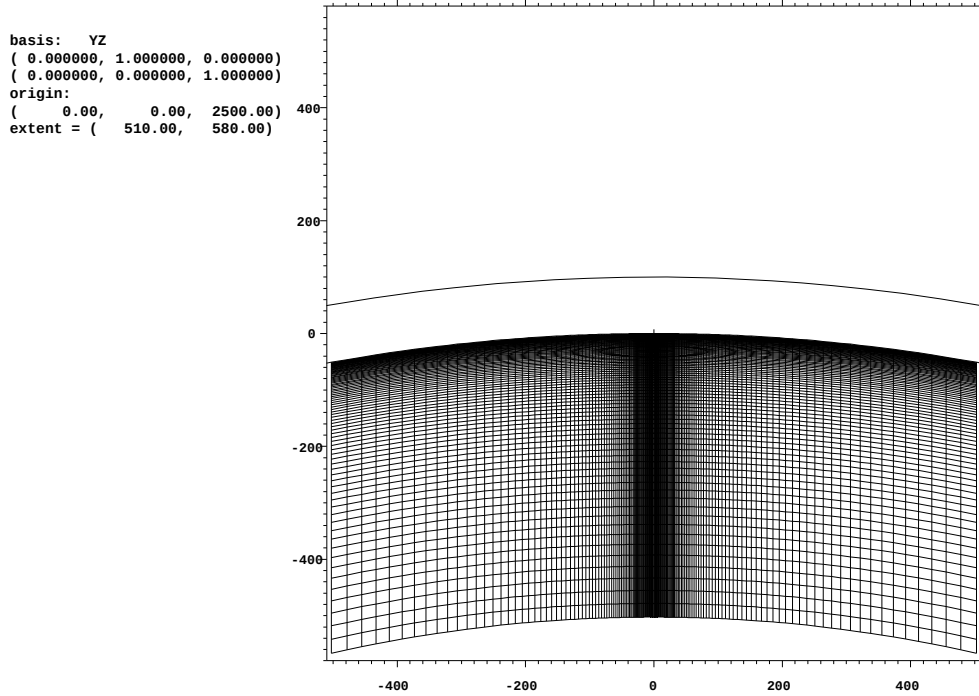


Figure 3.4. Cross section view of the MCNP tally cells. The cells along z-axis are cylindrical, with the remaining cells in the shape of a toroid formed when the visible cross section is rotated around the z-axis.

3.1.2 Procedures

Neutron yield coupling efficiency and secondary particle creation

This set of simulations explored how varying the incident neutron energy would impact the neutron yield coupling efficiency and the number and type of secondary particles created. For each of the eight materials, a set of 72 energy bins were used to cover the energy spectrum from 0-15 MeV. For 0-2 MeV, 100 keV wide bins were used. From 2-15 MeV, 250 keV wide bins were used. The total fraction of incident energy deposited was recorded, as well as the number of secondary particles created such as photons, neutrons, protons, deuterons and alphas. In addition to the 72 energy bins, a representative thermonuclear spectrum, shown in Figure 3.5 was used and compared to the the results from neutrons at the average energy of the thermonuclear spectrum. Figure B.2 in Appendix B is an example MCNP deck using the thermonuclear spectrum.

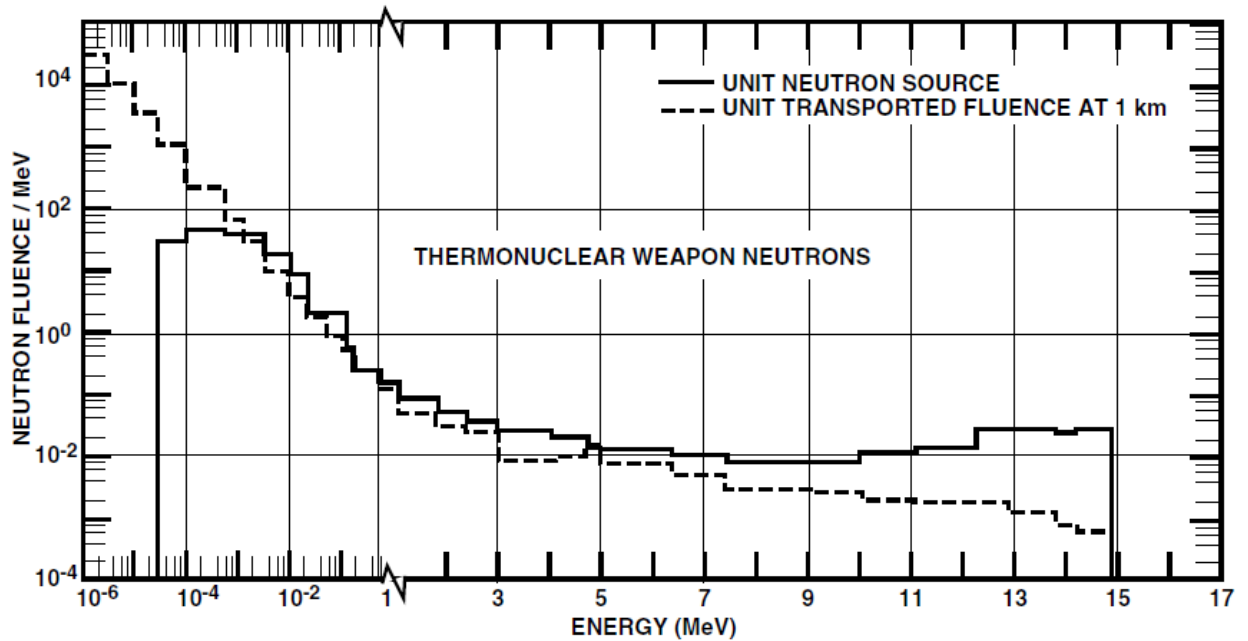


Figure 3.5. Generic thermonuclear weapon neutron energy spectrum. Reproduced from [23].

To generate the thermonuclear energy spectrum, the GetData graph digitization tool was used to determine the coordinates for the neutron source energy bin boundaries in Figure 3.5. The area of each bin was then computed, which was used as a weight for the energy bin in the MCNP simulation. The SI1 H card establishes the boundaries of the energy bin in MeV. The SP1 D card gives the relative weight for each bin. Since there is one more boundary than there are bins, the first value in the SP1 D card is zero. If the sum of the weights does not add to one, they are automatically normalized. The average neutron energy for this representative thermonuclear spectrum is 1.42 MeV.

A script was written using SciPy, the scientific computing tool for the Python programming language, to automate the process of creating the 584 MCNP input decks. Additionally a Windows batch file was created with the execution commands for all 72 MCNP decks per material. A second SciPy script was used to extract the relevant data from the MCNP output file, and the results were plotted using the Matplotlib module. The eight decks for the thermonuclear spectrum were created by a separate script since the neutron energy source had a different format from the individual energy bins.

A final set of 16 simulations were conducted to find the total energy deposited by 2.45 and 14.1 MeV neutrons in all eight materials.

Energy Deposition Contours

Initial Simulations. An initial set of sixteen simulations were conducted using 2.45 and 14.1 MeV neutrons for all eight material. A single tally cell grid was used extending 2 meters in from the surface, and 5 meters from the z-axis. In addition to the parameters specified in 3.1.1, a PRDMP card was added to the input deck to specify the creation of a separate MCTAL output file which contains only the values

of each cell for the indicated tally type. This card was added to all input decks that specified multiple tally cells.

The process for generating the input decks for simulations with multiple cells was similar to that used to generate the examples in Appendix B, however, additional cards were added to create the boundaries of each tally cell, define the cell, and specify its inclusion in the tally.

Source for Spheral. While the initial energy profile simulations were able to adequately represent the energy profile near the surface, the noise in the results prevented a suitable analysis of the entire volume over which the energy was deposited, and would not be ideal for use as the energy source for Spheral. For those simulations, a set of two tally cell grids were used to maintain a high resolution near the source and also to reduce the noise in areas of the model where fewer neutrons would travel.

Of the eight initial materials examined, four were selected for further study. Ice and meteoric iron were chosen both because they were the most and least dense and also because they had the lowest and highest average atomic mass. Quartz was chosen since it is a well studied and characterized material, and the results could be compared to other studies. Finally, the Allende Meteorite was chosen since it is an example of an actual asteroid's composition.

Three neutron source energies were used for these simulations, 2.45 MeV, 14.1 MeV, and a thermonuclear spectrum. These three neutron energies, the four materials, and the two tally cell regions resulted in a total of 24 simulations.

Height of Burst

Two sets of simulations were conducted to explore the effects of moving the neutron source away from the asteroid surface. These were only done for quartz using 2.45 MeV neutrons. The first set used a single tally cell to determine the total energy

deposited with varying Height of Burst (HoB), which is the distance between the source and the surface of the asteroid. Simulations for HoB of -400, -200, -100, -50, -25, -12.5, 0.1, 12.5, 25, 50, 100, 200, 400, and 800 cm were conducted.

The second set of simulations for the positive HOB values mapped the energy profiles created using a single set of tally cells extending to a depth of 3 m from the surface, and a distance of 5 m from the z axis. A total of 22 simulations were conducted.

3.2 Spheral

Spheral is an open source Adaptive Smoothed Particle Hydrodynamics (ASPH) code developed by Mike Owen and Lawrence Livermore National Labs. It is built using C++ and has a python user interface [24]. It is designed for massively parallel systems and was run on the Livermore Computing Center (LC) restricted zone (RZ) machine RZZeus. All LC Linux clusters use the TOSS (Tri-Laboratory Operating System Stack) operating system, which was developed from the CHAOS (Clustered High Availability Operating System) project derived from Red Hat [25]. RZZeus has a total of 267 nodes with 8 Intel Xeon E5530 processors per node for a total of 2,144 cores. The CPU speed is 2.4 GHZ, and there is 24 GB of memory per node for a total of 6.4 TB of total memory. Each simulation was run using 16 nodes (256 cores) [26].

All simulations used the same equation of state and strength setting. The intent was to examine how variation in energy profile altered the hydrodynamic response for a generic asteroid model. To simplify the computation, asteroid rotation and self gravity were not included and the model comprised a solid internal structure. Spheral supports a number of equation of state models, and for this simulation, the Tillotson Equation of State (TEOS) for granite was used. The TEOS was originally developed by Tillotson in 1962 to predict shock pressures in metals during hypervelocity impact

[27]. A material density of 2.68 was specified with no porosity. The strength model depended on only two constant parameters, cohesion (100 MPa) and shear modulus (22.7 GPa) although the code does support using a three dimensional strength model developed by Gareth S. Collins which also takes into account the coefficient of internal friction and strength at infinite pressure to adjust the strength for varying conditions [28].

The initial flaws or damage within the material was defined using a Weibull distribution. The initial damage serves as nucleation points for fractures to form during the hydrodynamic response. The code does not explicitly define fractures, but damage between adjacent nodes reduces their influence on each other, resulting in increasingly independent motion that led to greater damage and eventually separation.

3.2.1 Model

As in MCNP, the asteroid is modeled as a sphere with a radius of 25 meters. Figure 3.6 gives an exterior view of the model. All figures of the asteroid model in Spheral were generated using the visualization tool VisIt developed by LLNL [29]. Since nodes in a ASPH code do not have defined size or shape, the figures shown here are a somewhat non-physical representation. The icosohedral shape of the nodes was chosen to visually approximate a solid object without incurring the rendering time required to display them as spheres. The size of the nodes is scaled proportional to the cube root of the mass in order to approximate a solid without gaps or overlaps between adjacent nodes.

There were two competing requirements present in developing the node spacing for the Spheral model. On one hand, there was a need for high resolution (achieved through close node spacing) in order to accurately represent the significant spatial variation of energy deposited, especially near the neutron source, which were observed

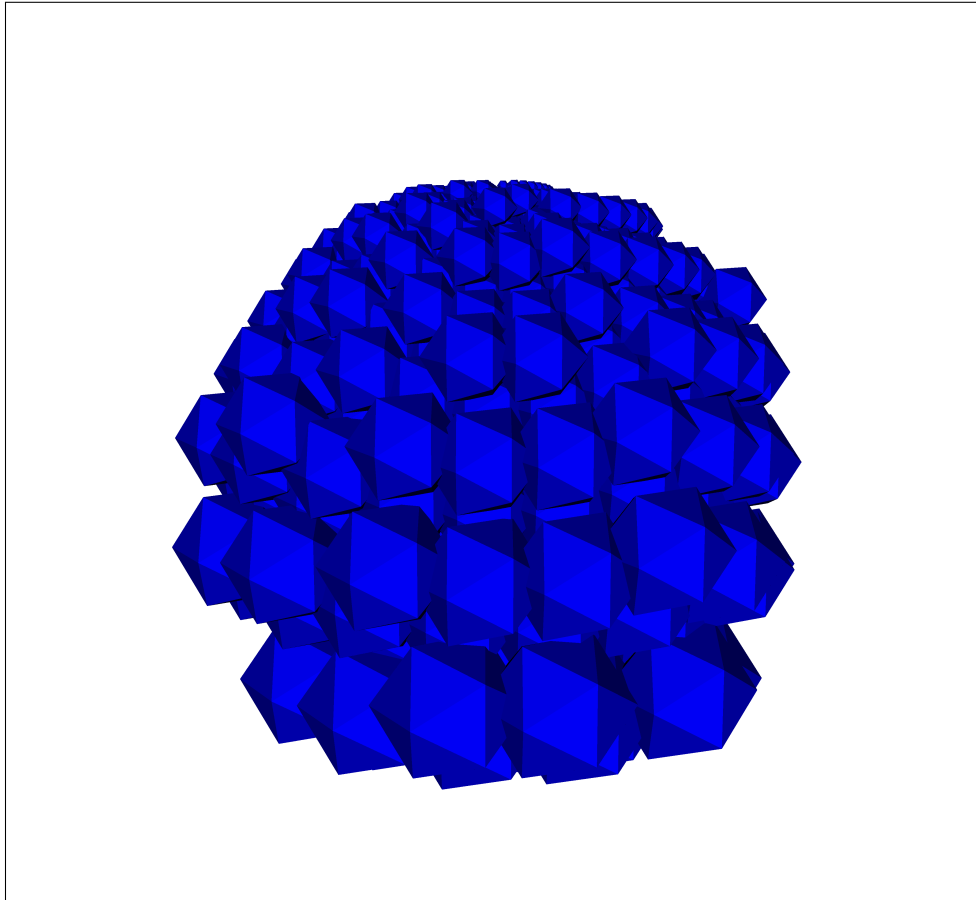


Figure 3.6. Asteroid model in Spheral, side view.

in the MCNP result. On the other hand, a 50 meter asteroid modeled entirely with small nodes would be incredibly computationally intensive to simulate. As a compromise, a model was developed where the nodes were smallest at the location of maximum energy density, and got progressively larger with increasing distance from that point. The minimum node spacing was 4 mm, and increased by a factor of 1.2 for each successive spherical shell. This spacing is shown in Figure 3.7 which is a cross-sectioned view from the side, and Figure 3.8 which is a top down view. This variable spacing not only matched the decreasing spatial variation in energy deposition, but also minimized the total number of nodes in the model, which helped reduce the computational load. The total number of nodes was 5216. If a uniform node spacing of 4 mm had been used instead, it would have resulted in approximately 2×10^{12} nodes in the model.

3.2.2 Simulation inputs

The inputs for the hydrodynamic simulations were the energy deposition profiles for four materials, with three different neutron energy spectra for each material. The materials were quartz, meteoric iron, ice, and the Allende meteorite, and the neutron energies were 2.45 MeV, 14.1 MeV, and a thermonuclear spectrum neutron source.

The nodes in Spheral are defined in (x,y,z) coordinates, with the origin at the center of the asteroid model. The MCNP energy deposition profiles employed (r,R) coordinates, where r is the distance from the z axis, and R is the distance from the origin, also located at the center of the asteroid model. To determine the energy deposition for each node, the coordinates of the nodes were first converted into (r,R) coordinates. The coordinate conversions used were

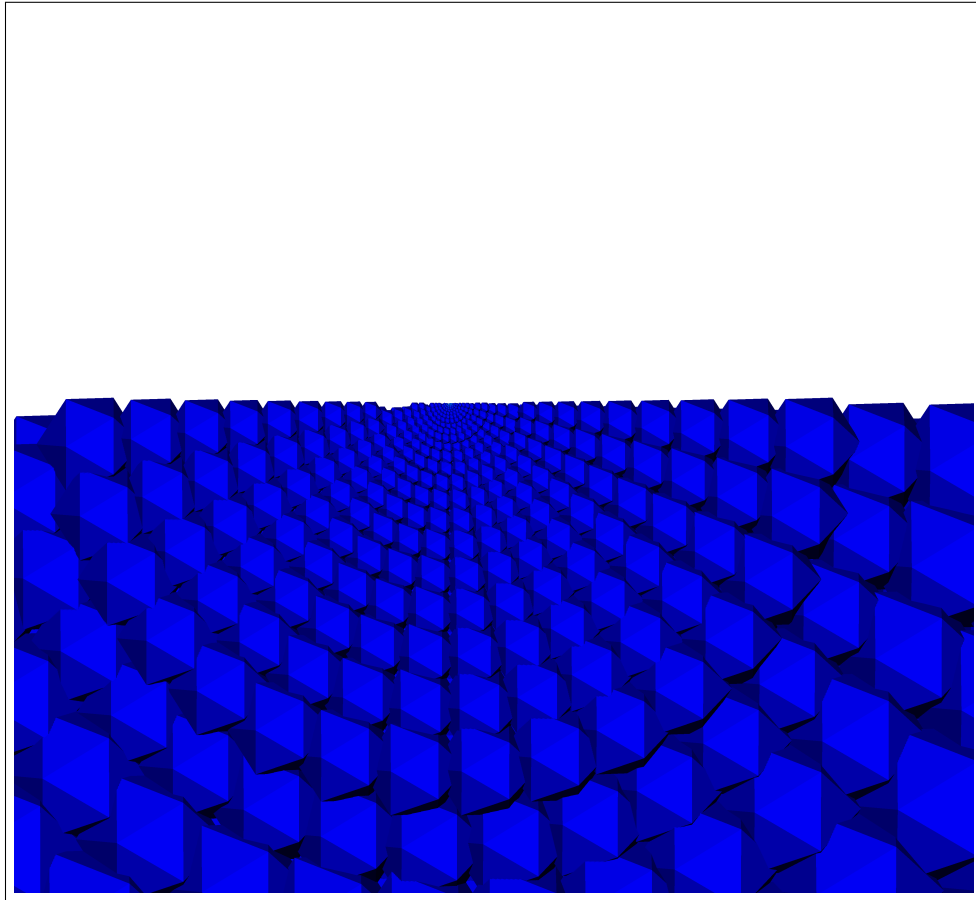


Figure 3.7. Asteroid model in Spheral, side cross section zoomed in.

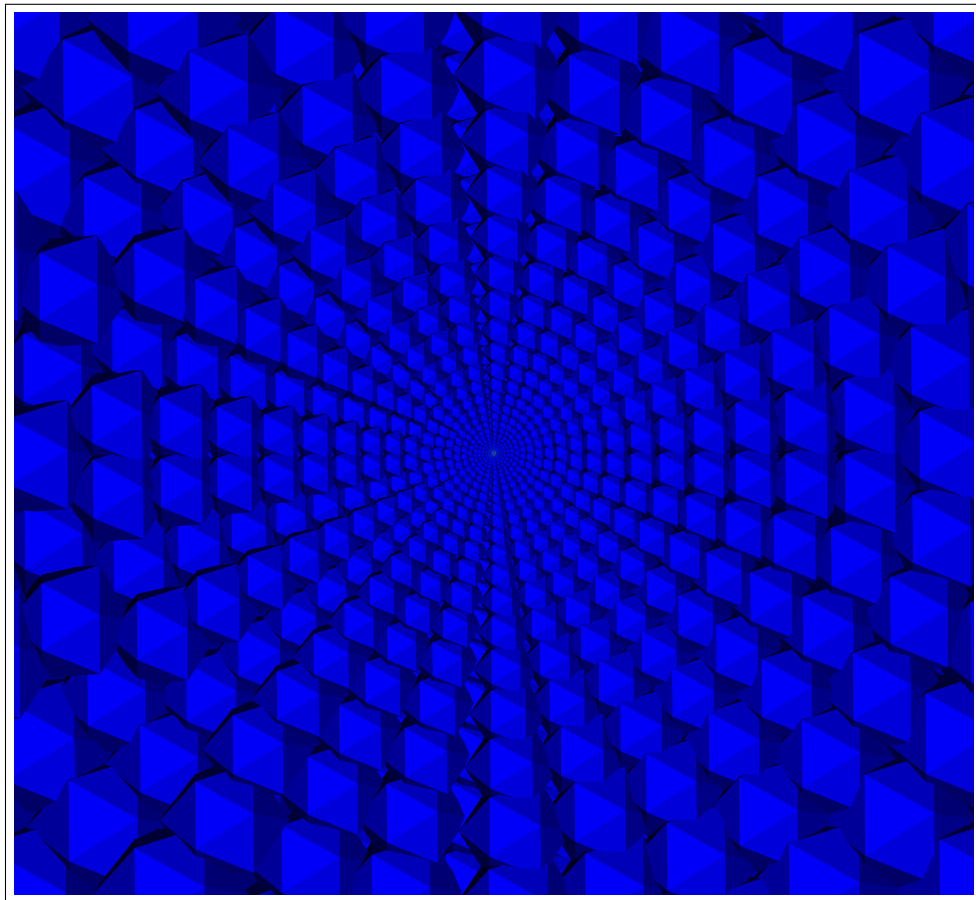


Figure 3.8. Asteroid model in Spheral, top view, zoomed in.

$$r_{node} = \sqrt{x^2 + y^2}, \quad (15)$$

$$R_{node} = \sqrt{x^2 + y^2 + z^2}, \quad (16)$$

where (r_{node}, R_{node}) is the coordinate for the Spheral node.

Once the location for the center of the Spheral node was converted into (r, R) coordinates, then linear interpolation was used to find the energy fraction per gram. A limitation of Spheral is that it does not have Scientific Python modules installed, so the mathematical tools for interpolation were limited. Interpolation was done in three steps. First, the r and R values representing the center of MCNP tally calls which bracket the location of the Spheral node were identified, giving four values which bound (r_{node}, R_{node}) . Then, using linear interpolation, the value representing the fraction of the total neutron source energy per gram for the node was determined.

The units for MCNP energy deposition profiles are in MeV/gram per source particle, relative to the material density in the MCNP model. The Spheral simulations used a single neutron yield, $Y_n = 10 \text{ kt}$, for all the simulations. To account for any total neutron source energy, the heating values were divided by the incident neutron energy, or average incident neutron energy, resulting in energy densities in units of g^{-1} .

Once this value was calculated, it had to be converted into the appropriate units for Spheral. The energy units for MCNP are MeV, mass is gram, and length is centimeter. In Spheral, length is centimeters, mass is grams, and time is microseconds; this results in energy units of 10^5 J .

The total neutron source energy used was 10 kt. The energy density for a node is

$$E_{dep}^{Spherical} = \frac{E_{dep}^{MCNP}}{\bar{E}_{neutron}} * \frac{\rho_{MCNP}}{\rho_{Spherical}} * Y_n * 4.184 \times 10^7 \quad [10^5 \text{ J/g}], \quad (17)$$

where $E_{dep}^{Spherical}$ is the energy density for the node, E_{dep}^{MCNP} is the interpolated energy density from MCNP (MeV/g), ρ_{MCNP} is the density used in the MCNP simulation (g/cm³), $\rho_{Spherical}$ is the density used in the Spherical simulation (g/cm³), Y_n is the neutron yield in kilotons, and 4.184×10^7 is a unit conversion from kt to 10^5 J.

IV. Results and Analysis

4.1 MCNP

4.1.1 Data Acquisition

A SciPy script was used to extract the relevant data from the MCNP output files. For the simulations using a single tally cell, this was done from the standard output format. For the energy profiles, the data was extracted from an MCTAL file.

4.1.2 Energy Coupling

The following information was extracted from the MCNP output files:

- Energy deposited in the entire asteroid in MeV/gram
- Mass of the asteroid model
- Weight per incident neutron for escape
- Average energy of escaping neutrons

The total energy deposited per incident neutron was calculated by multiplying the heating value for the entire asteroid, in MeV/gram, by the mass of the asteroid in grams. This was done for all 72 energy bins as well as the thermonuclear spectrum. Figure 4.1 is a comparison of the heating per neutron for all eight materials for a surface neutron source. One clear result is that higher neutron energies result in more neutron heating. This trend holds for all the materials except for neutron energies above 12 MeV in meteoric iron. There are two results from iron that are consistent with this behavior. The slight increase in slope in the energy per neutron lost to escape shown in Figure 4.3, which corresponds to a decrease in the probability of capture shown in Figure 4.10, as well as the sharp rise in the number of neutrons

produced as shown in Figure 4.2. The number of neutrons produced is an indication of the (n,2n) reaction. The sharp rise occurs near the threshold energy for the (n,2n) reaction for three of the constituents of meteoric iron, ^{56}Fe , ^{58}Ni , and ^{60}Ni as shown in Table 4.1. The meteoric iron is the only material where the isotopic composition is observed to influence the energy deposition results. A second feature can be seen in all the materials containing silicon, which is the dip in E_{dep} per neutron between 2 and 3.5 MeV. This decrease is matched in the decreased fraction of neutrons captured, as shown in Figure 4.10, which is due to the decreased capture cross section for (n, γ) above 2 MeV shown in Figure 2.4.

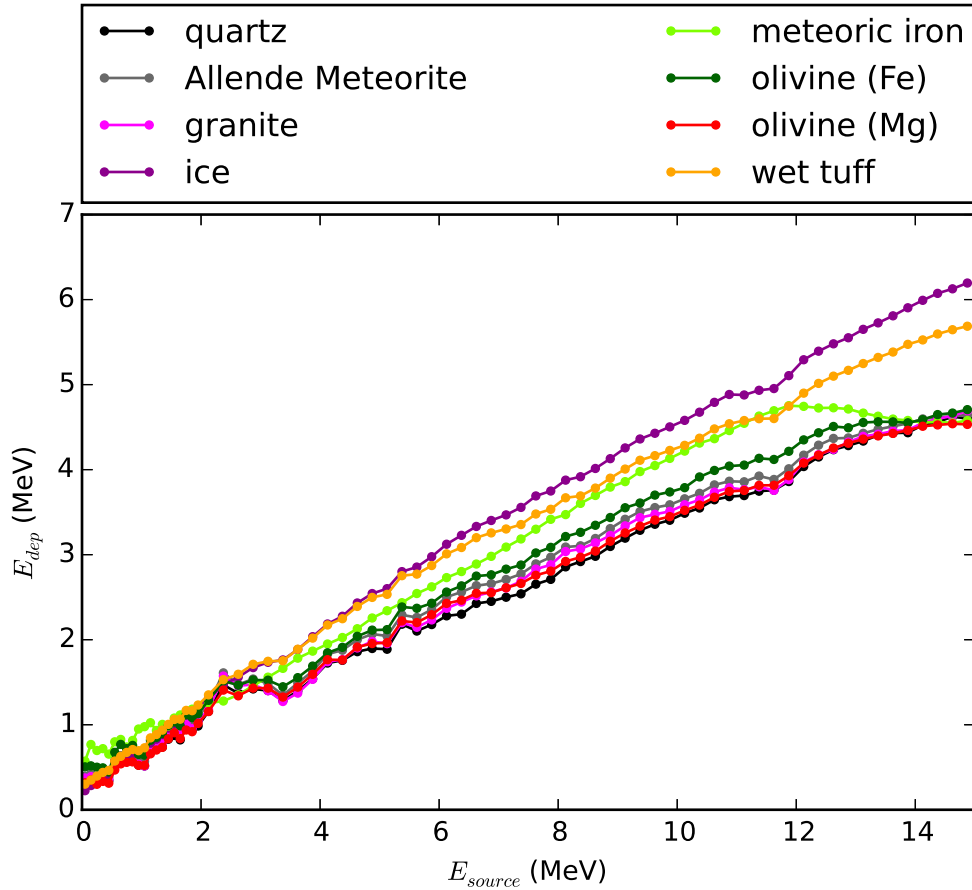


Figure 4.1. Total energy deposited per source neutron for a surface source.

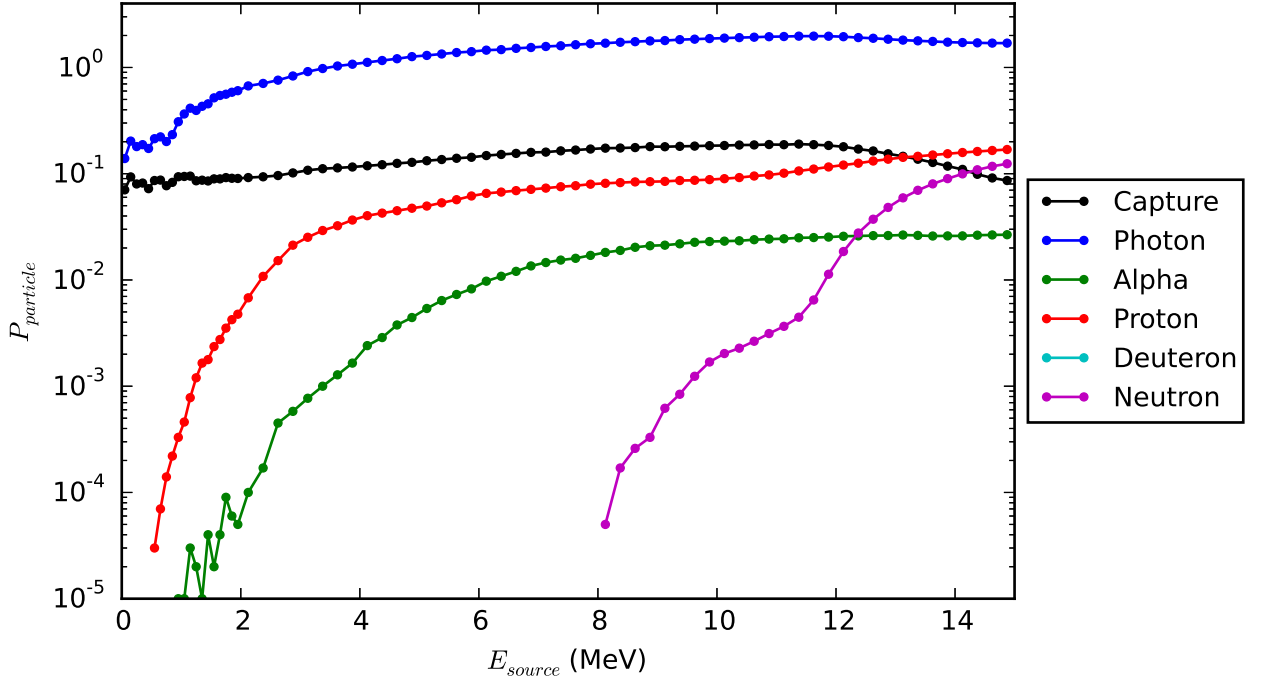


Figure 4.2. Iron Secondary Particles.

Table 4.1. Reaction Q values (+) or threshold energies (-) in meteoric iron.

Isotope	Reaction						First Nuclear Exited State (MeV)	Mass Fraction
	(n, γ)	(n,p)	(n,d)	(n,t)	(n, α)	(n,2n)		
⁵⁴ Fe	9.298	0.596	-6.753	-12.658	0.844	-13.629	1.4082	.0348
⁵⁶ Fe	7.646	-2.445	-8.103	-12.143	0.326	-11.399	0.8468	.5503
⁵⁷ Fe	10.045	-1.426	-8.482	-9.514	2.399	-7.782	0.0144	.0132
⁵⁸ Ni	8.999	0.912	-6.051	-11.259	2.899	-12.429	2.4592	.2723
⁶⁰ Ni	7.820	-1.555	-7.431	-11.698	1.355	-11.579	1.3325	.1049
⁶¹ Ni	10.596	-0.031	-7.762	-9.018	3.580	-7.95	0.0674	.0046
⁶² Ni	6.838	-4.093	-9.058	-12.17	-0.442	-10.768	1.1730	.0145

Figure 4.3 compares the energy lost per neutron to escape for a surface source.

This energy lost, E_{lost} , is found from

$$E_{lost} = P_{escape} * \bar{E}_{escape}, \quad (18)$$

where P_{escape} is the probability that a neutron will be lost to escape, and $\bar{E}_{escape}$ is the average energy of the escaped neutron.

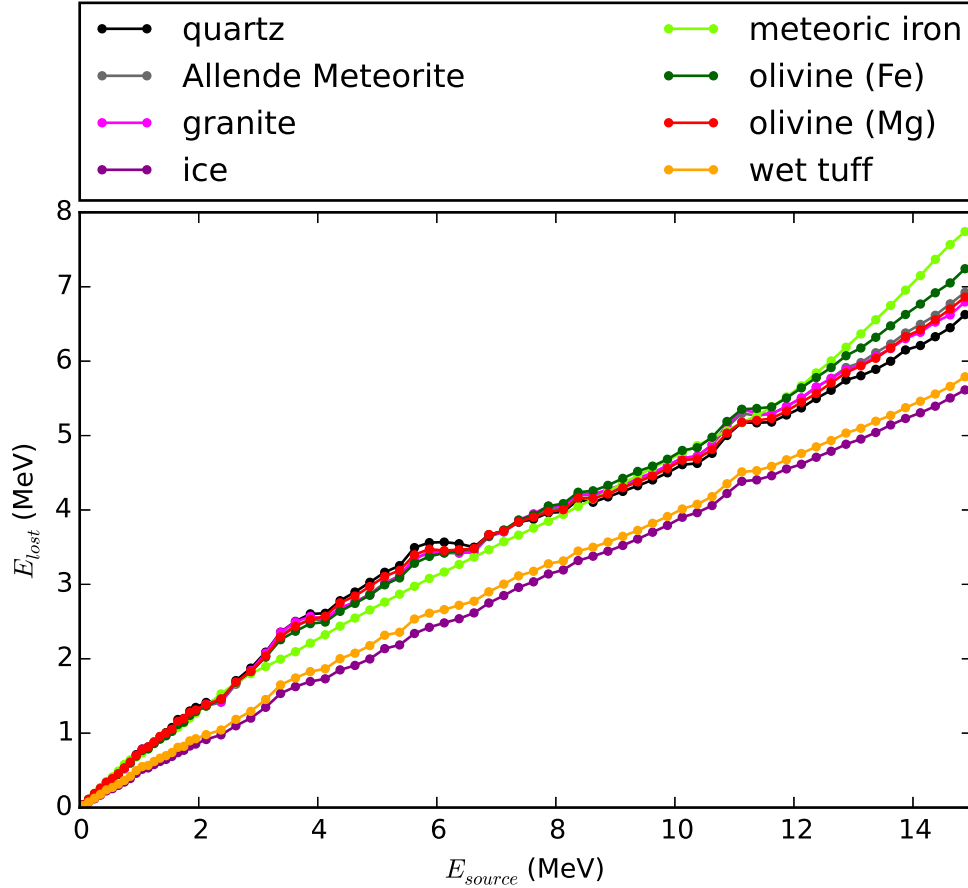


Figure 4.3. Energy lost to escape for a surface source.

Besides the aforementioned increase observed in meteoric iron (and also to a lesser extent in iron rich olivine), another noticeable feature is that the hydrogenous materials, ice and wet tuff, lose consistently less energy to escape for all incident neutron energies.

The energy not lost to escape is the energy available to heat the asteroid. This

energy, $E_{available}$, is found by

$$E_{available} = Y_n - E_{lost}, \quad (19)$$

where Y_n is the neutron yield.

The efficiency, $\eta_{available}$, by which the available neutron energy is coupled to the asteroid model is

$$\eta_{available} = \frac{E_{dep}}{E_{available}}. \quad (20)$$

For $\eta_{available} > 1$ there is a net gain in energy from positive Q reactions, for $\eta_{available} < 1$, there is a net loss due to threshold (negative Q) reactions. Figure 4.4 shows $\eta_{available}$ for the eight materials for a surface neutron source. Below 3 MeV in hydrogenous materials or 4.5 MeV in non-hydrogenous materials there is a net gain in energy, and above those thresholds there is a net loss of energy.

The neutron yield coupling efficiency, η_y , is a measure of the fraction of the neutron yield which is deposited in the asteroid. It is found by

$$\eta_y = \frac{E_{dep}}{Y_n}. \quad (21)$$

Figures 4.5 and 4.6 show η_y for all eight materials for a surface source. Again, the anomalous effects of hydrogenous materials is evident, as well as the influence of variations in the cross section of silicon at low energies. For a subsurface source, where none of the neutrons escape, η_y is significant higher as seen in Figure 4.7 and 4.8. By dividing $\eta_y^{subsurface}$ by $\eta_y^{surface}$ the relative energy gains of a subsurface source can be determined as shown in Figure 4.9.

The increase in energy deposition for a subsurface source are clearly significant, especially at low incident neutron energies.

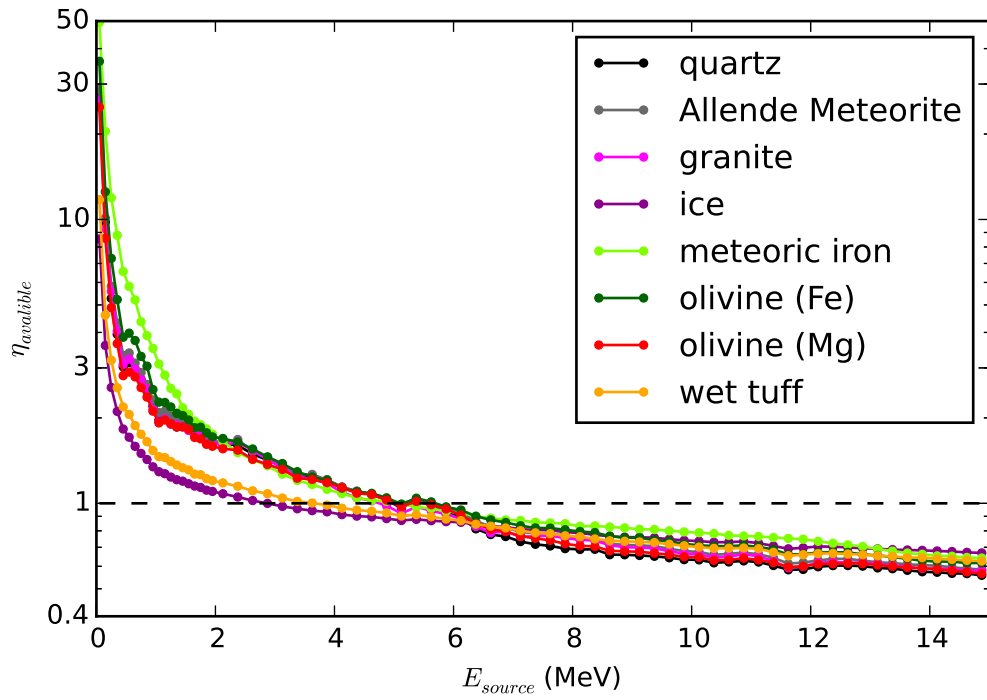


Figure 4.4. Available neutron energy coupling efficiency for a surface source.

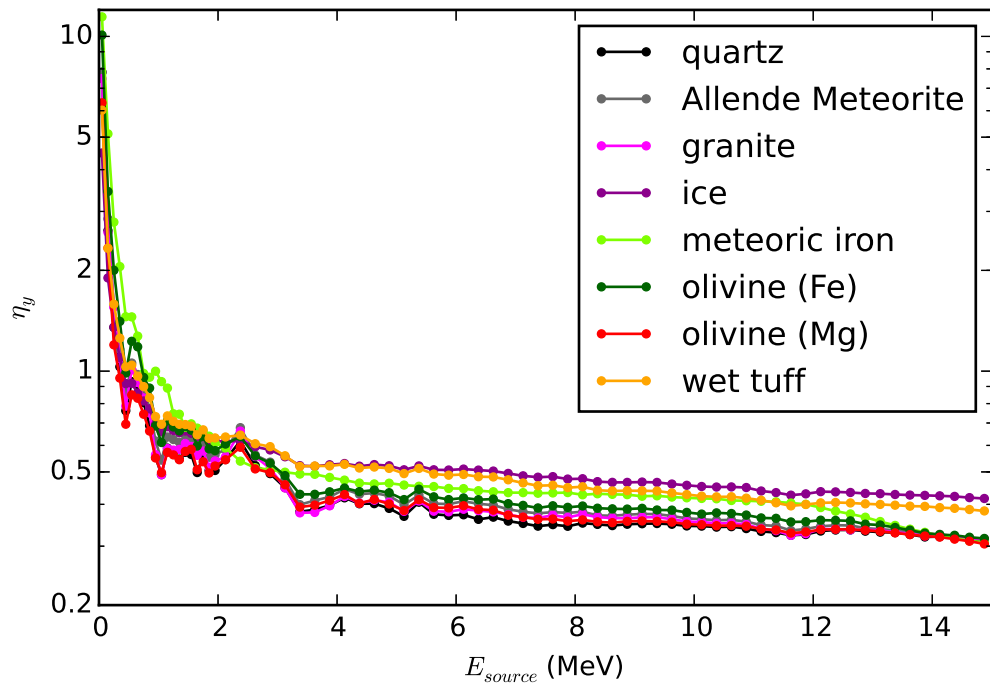


Figure 4.5. Neutron yield coupling efficiency for a surface source.

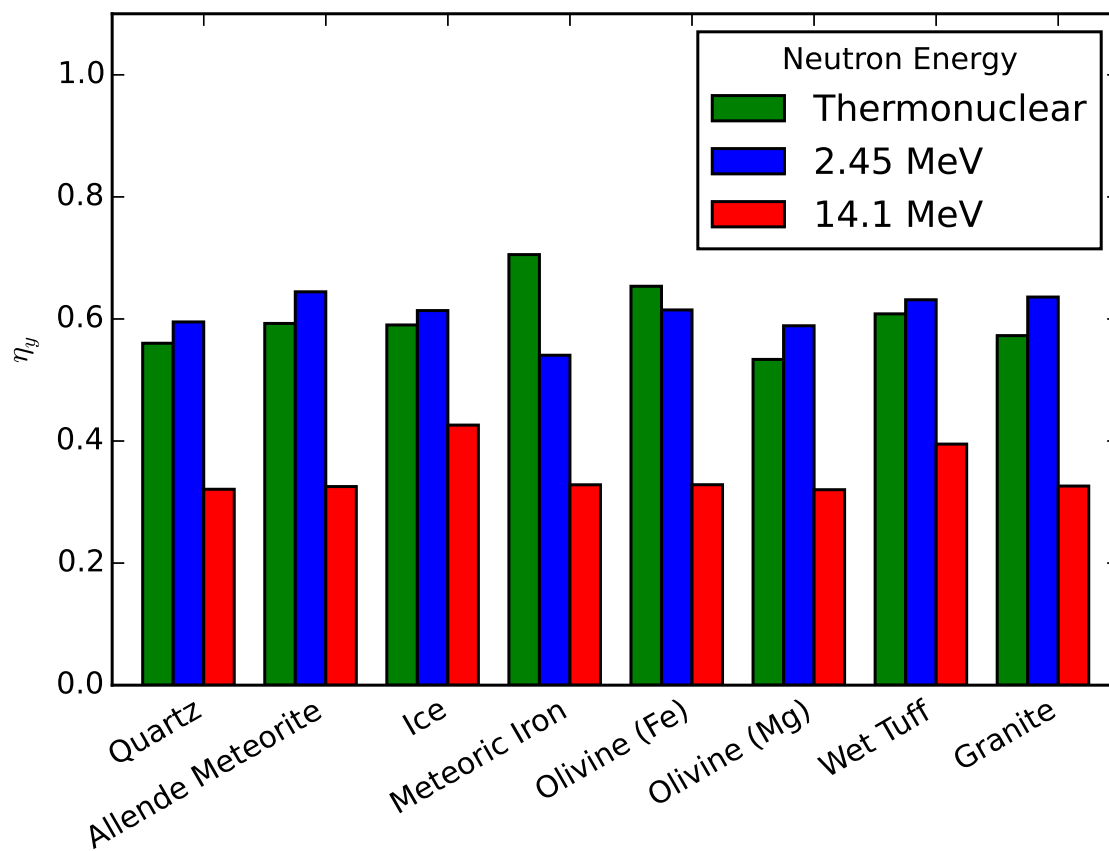


Figure 4.6. Neutron yield coupling efficiency for a surface source.

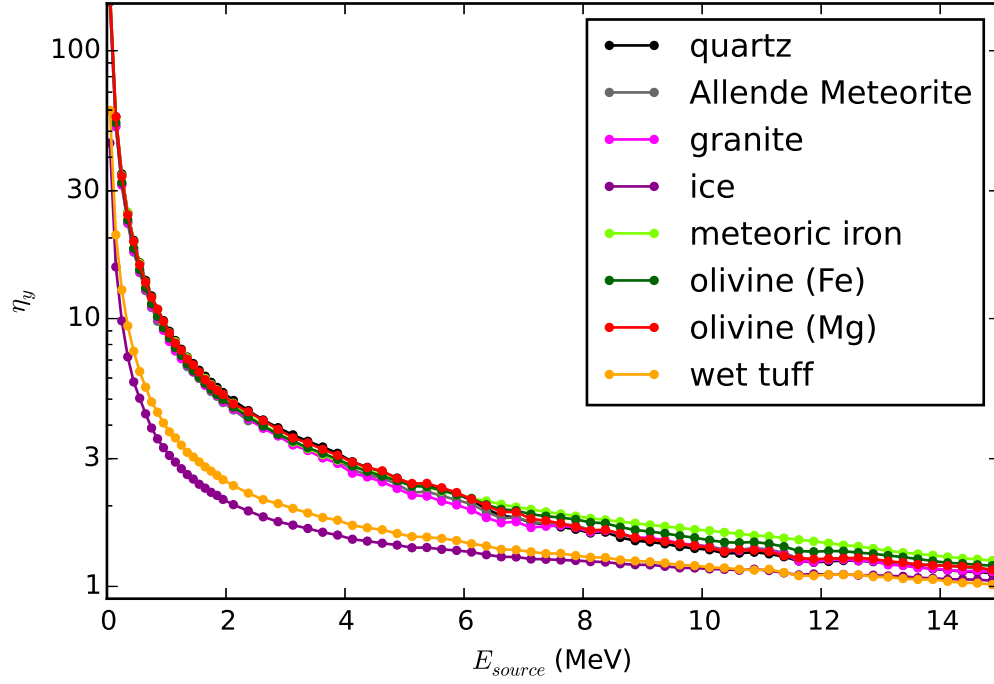


Figure 4.7. Neutron yield coupling efficiency for subsurface source.

4.1.3 Neutron Capture and Secondary Particle Creation

The following information was extracted from the MCNP output files:

- Weight per incident neutron of neutrons created in the (n,xn) reaction
- Weight per incident neutron for photons created from neutrons
- Weight per incident neutron for total proton, deuteron, triton, and alpha creation
- Weight per incident neutron for capture

The photons created from neutrons includes both the (n,γ) reaction, as well as the gamma emitted following inelastic scatter. The (n,γ) reaction is possible for all neutron energies, but the inelastic (n,n') reaction only occurs for neutron energies exceeding the energy level of the first excited nuclear state. MCNP can produce and

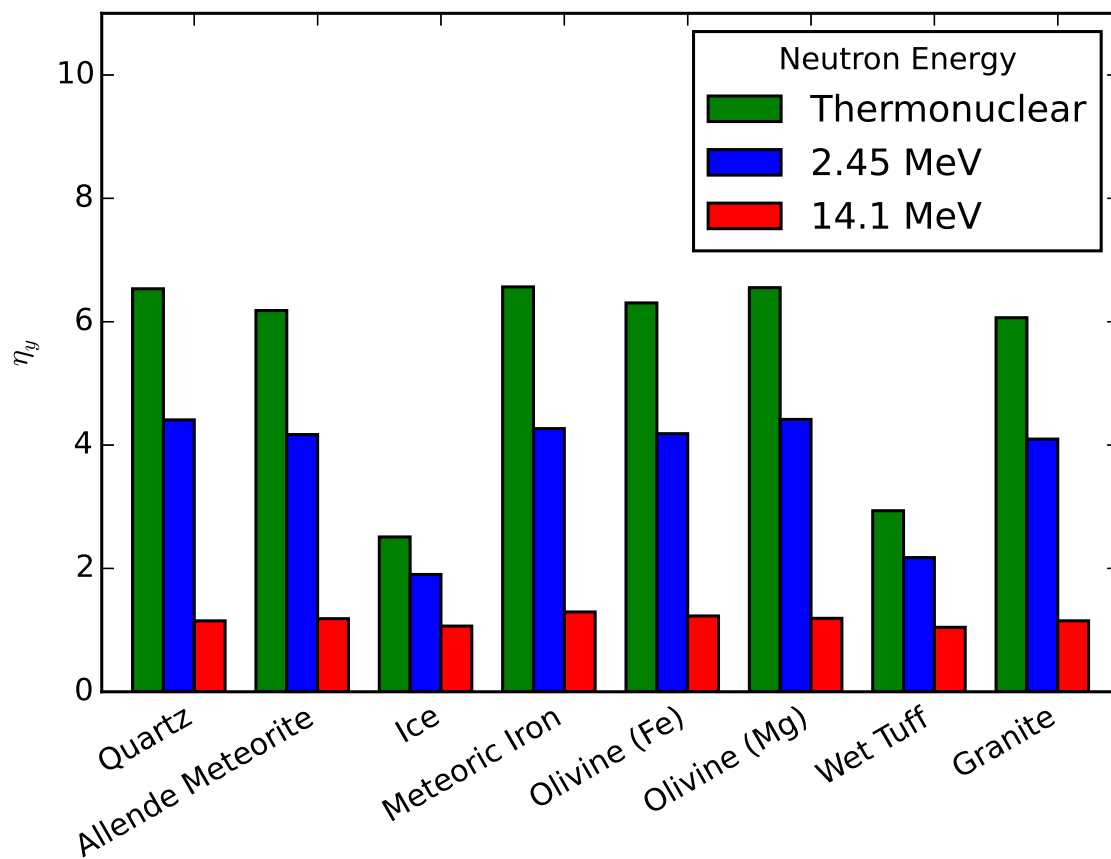


Figure 4.8. Neutron yield coupling efficiency for a subsurface source.

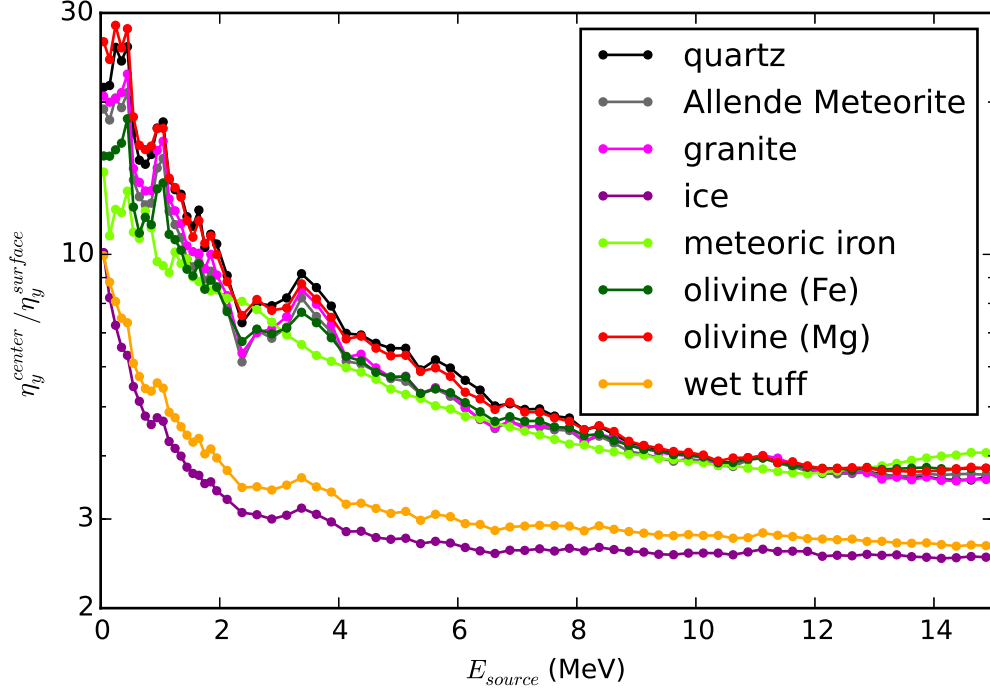


Figure 4.9. Neutron yield coupling efficiency ratio for a subsurface versus a surface source.

track ions created by elastic recoil from neutrons with light nuclei such as H, D, T, ^3He , and ^4He [21]. This is the source of the protons created in ice for energies below the threshold energy for the (n,p) reaction in oxygen, which is 9.67 MeV (Appendix C, section C.1). For all materials not containing H, the proton creation is an indication of the (n,p) reaction. The creation of deuterons, tritons, and alphas are an indication of the (n,d), (n,t), and (n, α) reactions, since none of the materials contain D, T or ^4He . MCNP tracks the number of neutrons created and lost during a (n,xn) reaction (where $x \geq 2$). When the number of neutrons is created is twice that of those lost, then the (n,2n) reaction is the only one taking place. Since the (n,3n) reaction is not energetically possible for the materials and neutron energies examined, the incidence of the (n,2n) reaction on the following figures is half the number of neutrons created in (n,xn) reactions as listed in the MCNP output file.

Figure 4.10 shows the fraction of source neutrons captured. While materiel prop-

erties influence the fraction of neutrons captured, geometry and density can also have an affect. The increase in capture probability for materials with hydrogen matches the lower values for energy lost to escape observed in Figure 4.3.

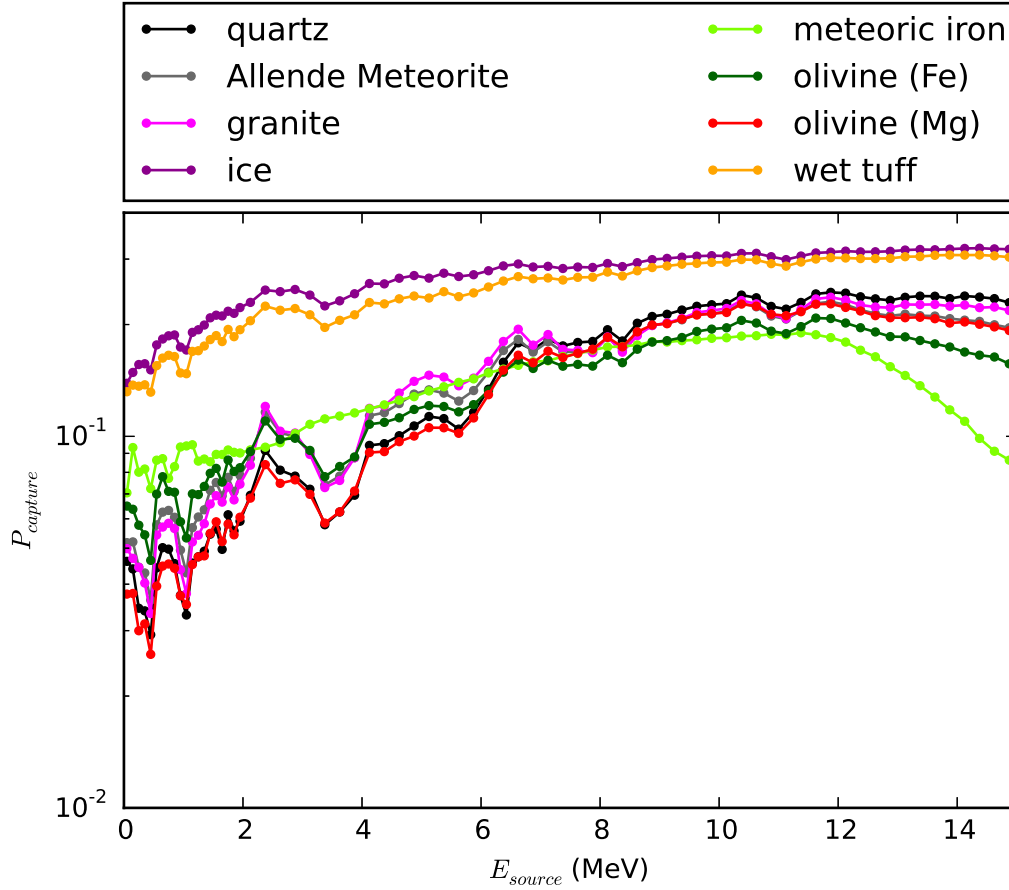


Figure 4.10. Probability of capture for neutrons.

Figure 4.11 shows the fraction of source neutrons captured as well as the secondary particle creation in quartz. The Q values for the energetically favorable reactions, the threshold energies for the threshold reactions and the corresponding particles created are listed in Table 4.2. Table 4.2 also displays the energy level of the first excited nuclear state (which is the lower limit for inelastic scatter) and mass fraction of each element indicating its relative contribution to the materials characteristics.

As expected, the probability of particle creation in Figure 4.11 is a linear combi-

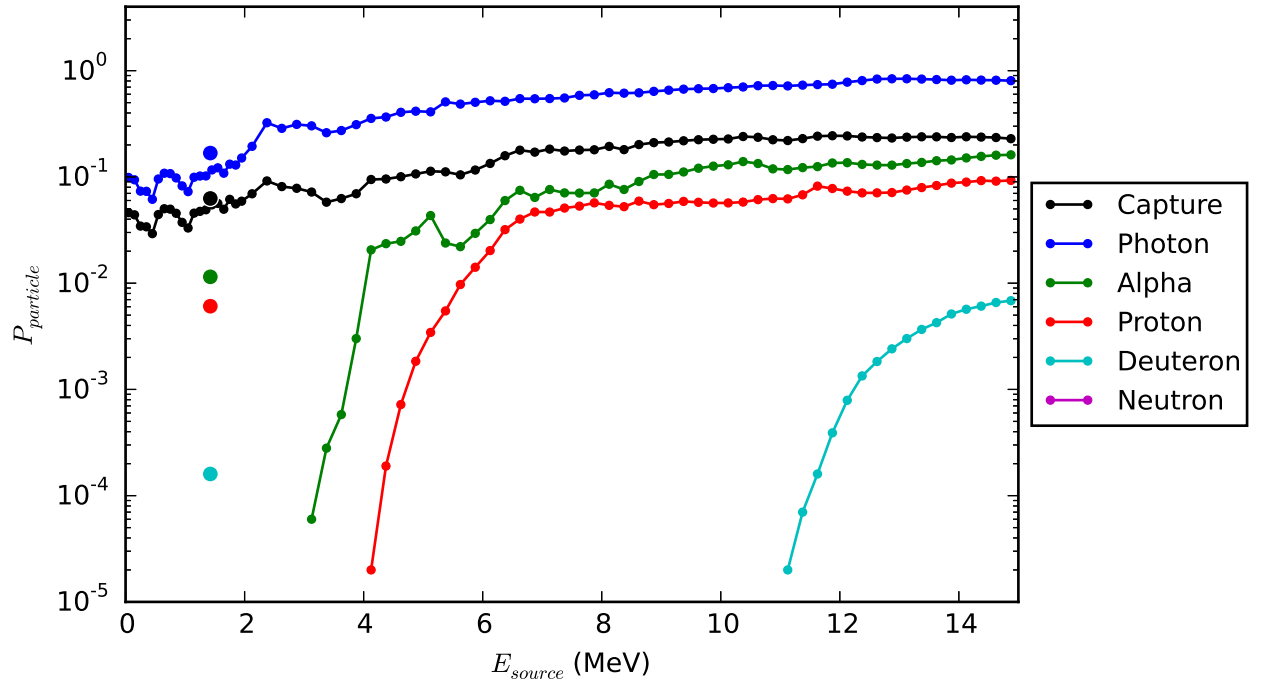


Figure 4.11. Neutron capture and secondary particle creation in quartz.

Table 4.2. Q values (+) or threshold energies (-) for neutron reactions in quartz (MeV).

Isotope	Reaction						First Nuclear Exited State (MeV)	Mass Fraction
	(n, γ)	(n,p)	(n,d)	(n,t)	(n, α)	(n,2n)		
¹⁶ O	4.143	-9.669	-10.527	-15.391	-2.355	-16.651	6.0494	.5326
²⁸ Si	8.474	-3.466	-9.698	-16.743	-2.749	-17.799	1.7790	.4708

nation of the cross sections for the reactions which generate them for the constituent materials shown in Figures 2.4 and 2.6. However, the reaction energies and secondary particle creation and neutron capture probabilities do illuminate the reason for the variations on energy coupling observed in section 4.1.2. Results for all eight materials are provided in Appendix C.

4.1.4 Geometric Losses from Curvature

The theoretical maximum fraction of neutrons captured would occur for $R \rightarrow \infty$ so that there would be no loss due to the curvature of the asteroid. However, as R goes to zero, the fraction captured would also go to zero. The cause of the variation in capture fraction is the geometry illustrated in Figure 4.12. A neutron source indicated in yellow is shown at the surface of an infinite sphere ($R \rightarrow \infty$) in red, with a finite sphere in gray superimposed. Neutrons captured in the red region would (predominantly) be lost to escape in the finite gray sphere.

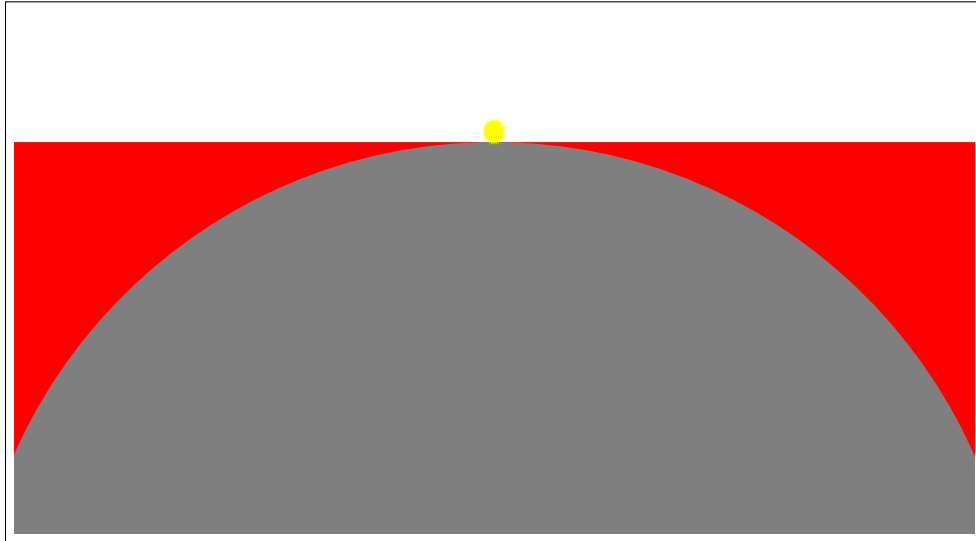


Figure 4.12. Illustration of geometric loss.

A set of simulations was conducted for seven different radii varying incrementally by a factor of 4. The relative curvature is shown in Figure 4.13.

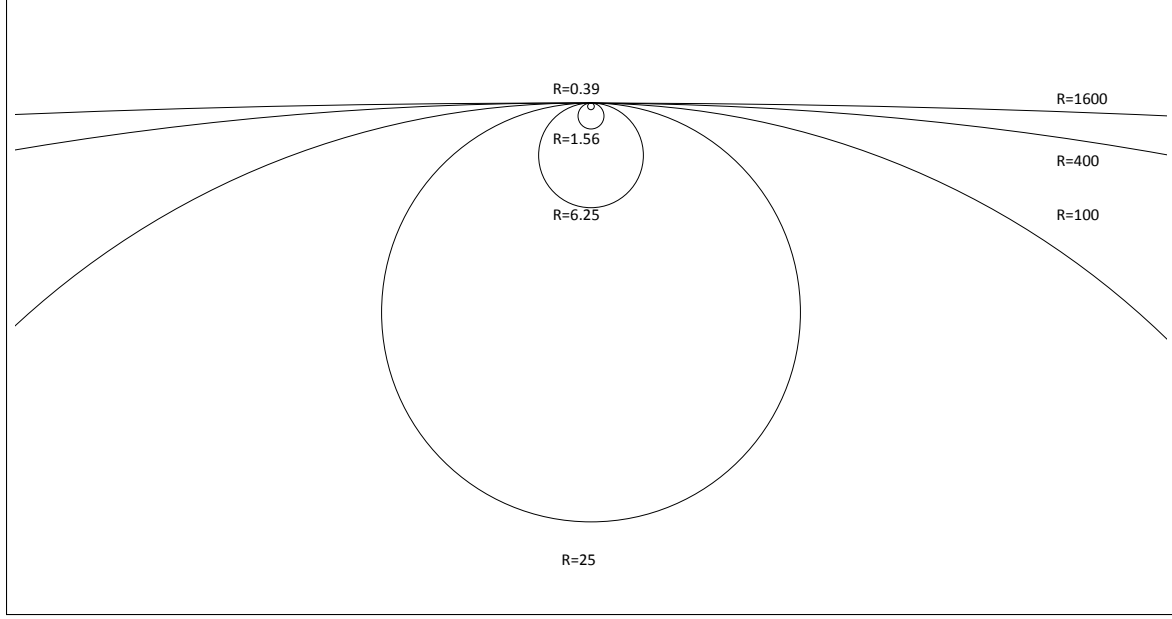


Figure 4.13. Relative curvature for specified radii.

The effects can be clearly seen in Figure 4.14 where the fraction of neutrons captured decreases at small radii and converges at large radii. In this example the material is quartz with $\rho_0 = 2.45 \text{ g/cm}^3$ and $R_0 = 2500 \text{ cm}$, but similar behavior would occur in all materials, albeit with different energy dependent variations and convergence values. The reason that the capture fraction does not go to zero is that the size scales in which that would be observed are so small as to be irrelevant to the the current discussion. This is demonstrated in Figure 4.25 where E_{dep} decreases by a few orders of magnitude within the first centimeter beneath the surface.

Paralleling the decrease in the fraction of neutrons captured is a decrease in η_y as shown in Figure 4.15. The reduction in η_y is predominantly due to the energy carried by escaped neutrons. However, that is not the entire reason since a slight variation in $\eta_{available}$ is observed as seen in Figure 4.16.

The effect of radius is not only due to the physical dimensions, but also the density. The physical radius is not the determining factor, but rather the radius in relationship to the mean free path of the incident neutron. When the radius varies as $\frac{1}{\rho}$, then the

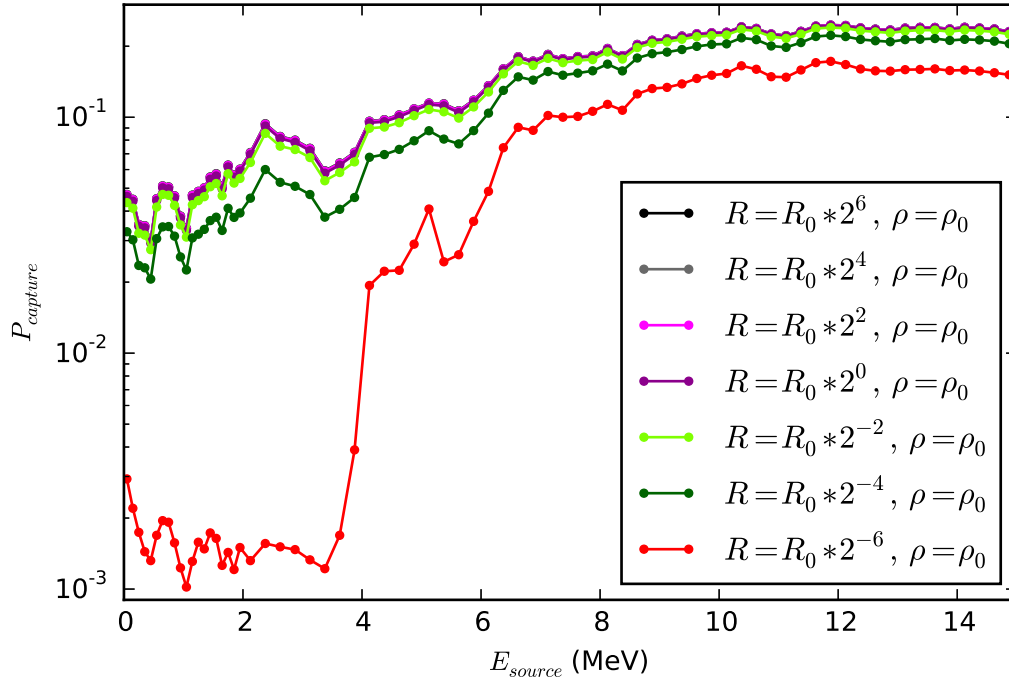


Figure 4.14. Fraction of source neutrons captured in quartz. $R_0 = 2500 \text{ cm}$, $\rho_0 = 2.45 \text{ g/cm}^3$.

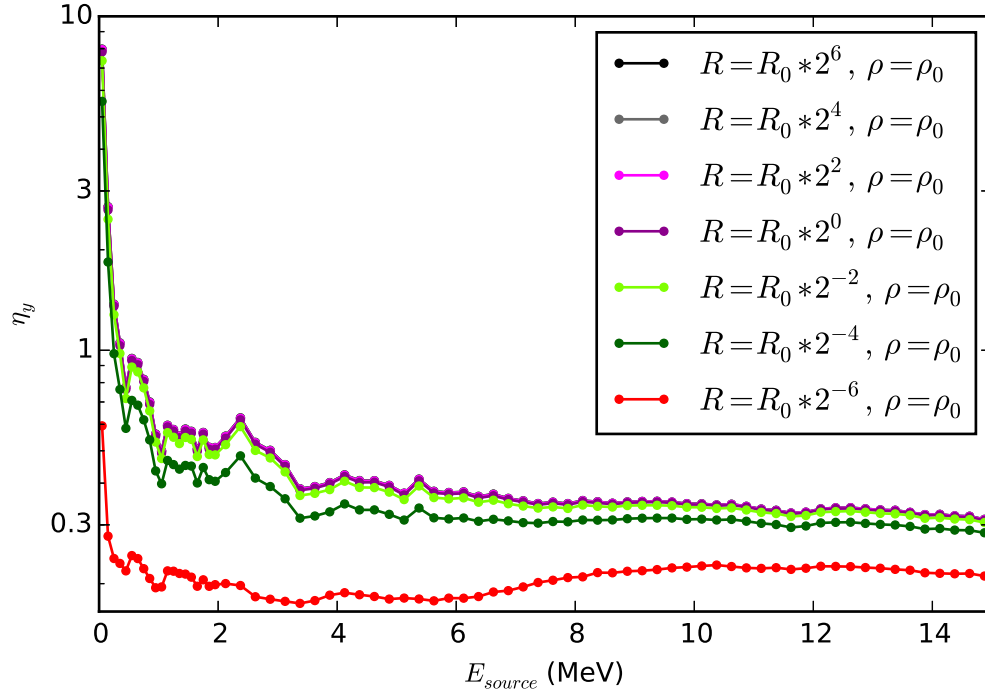


Figure 4.15. Neutron yield coupling efficiency in quartz. $R_0 = 2500 \text{ cm}$, $\rho_0 = 2.45 \text{ g/cm}^3$.

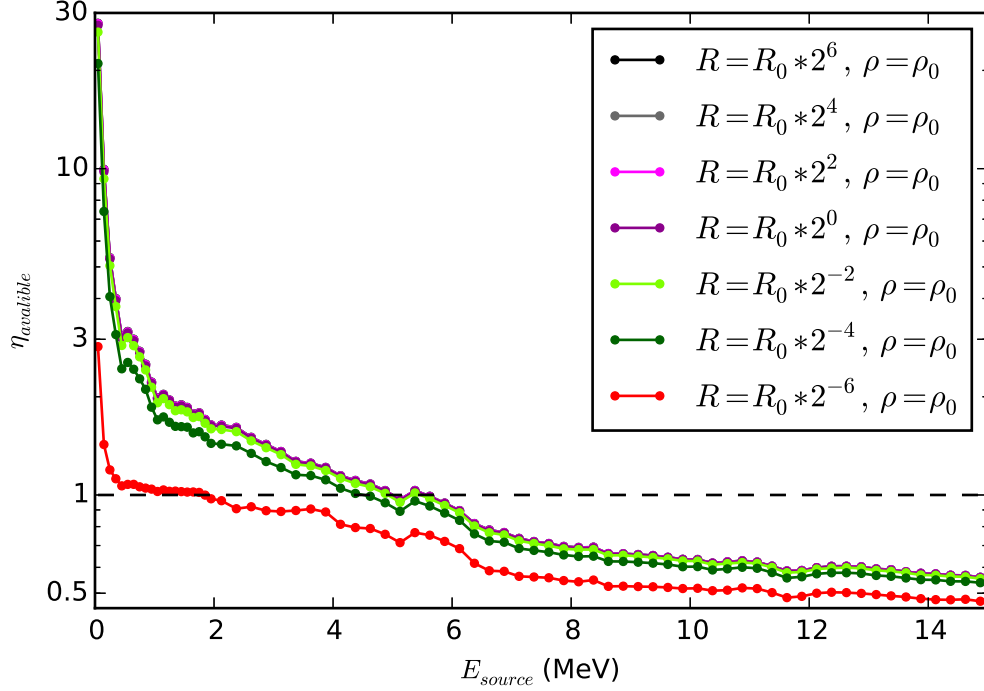


Figure 4.16. Available neutron energy coupling efficiency in quartz. $R_0 = 2500 \text{ cm}$, $\rho_0 = 2.45 \text{ g/cm}^3$.

radius remains a constant multiple of the mean free path. This effect can be seen in Figure 4.18, where the capture fraction is constant even as the radius and density vary by over three orders of magnitude. For this reason, η_y does not change when the radius is a constant multiple of the mean free path as seen in Figure 4.18. The mean free path for all eight materials examined is shown in Figure 4.19.

4.1.5 Geometric Loss due to Location of the Neutron Source

For a body of infinite radius, the height of the neutron source above the surface will have no impact on the total energy transferred since there will be no change in the number of neutrons which impact the surface and there is no effect from curvature. For a finite radius, the solid angle in which source neutrons interact with the surface decreases with distance from the surface. This decrease in neutrons can be seen in a decrease in η_y . Figure 4.20 shows the decrease in η_y as the neutron source varies from

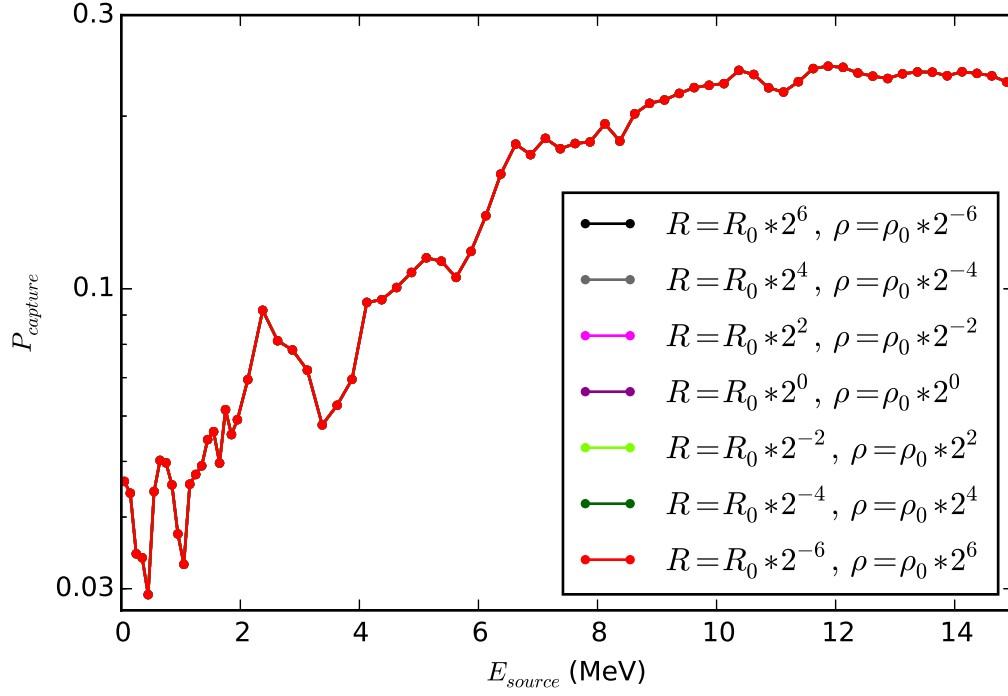


Figure 4.17. Fraction of source neutrons captured in quartz. $R_0 = 2500 \text{ cm}$, $\rho_0 = 2.45 \text{ g/cm}^3$.

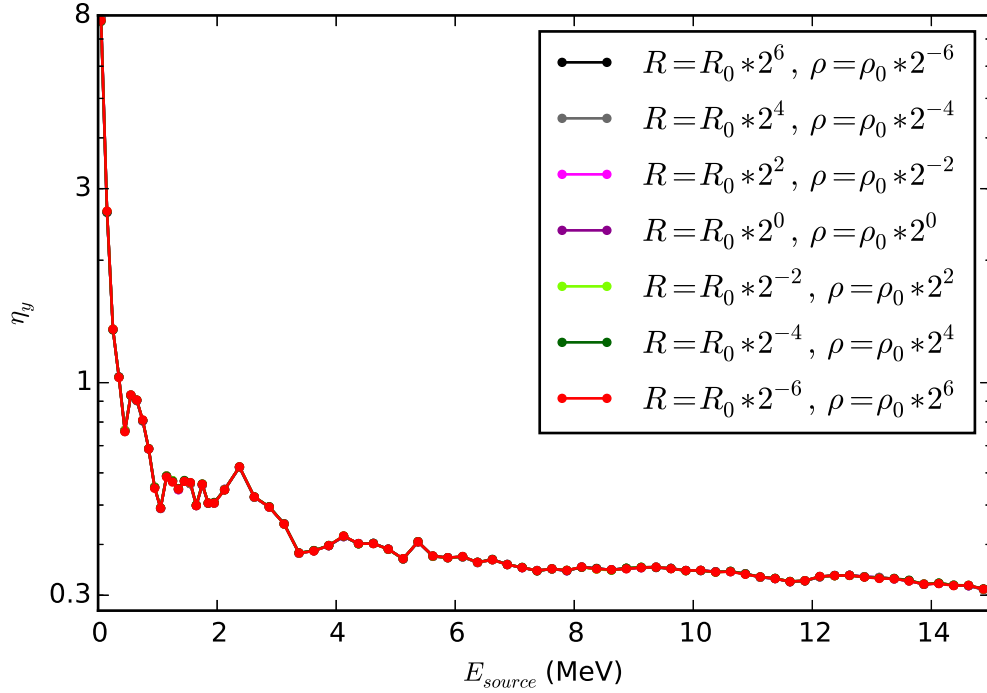


Figure 4.18. Neutron yield coupling efficiency in quartz. $R_0 = 2500 \text{ cm}$, $\rho_0 = 2.45 \text{ g/cm}^3$.

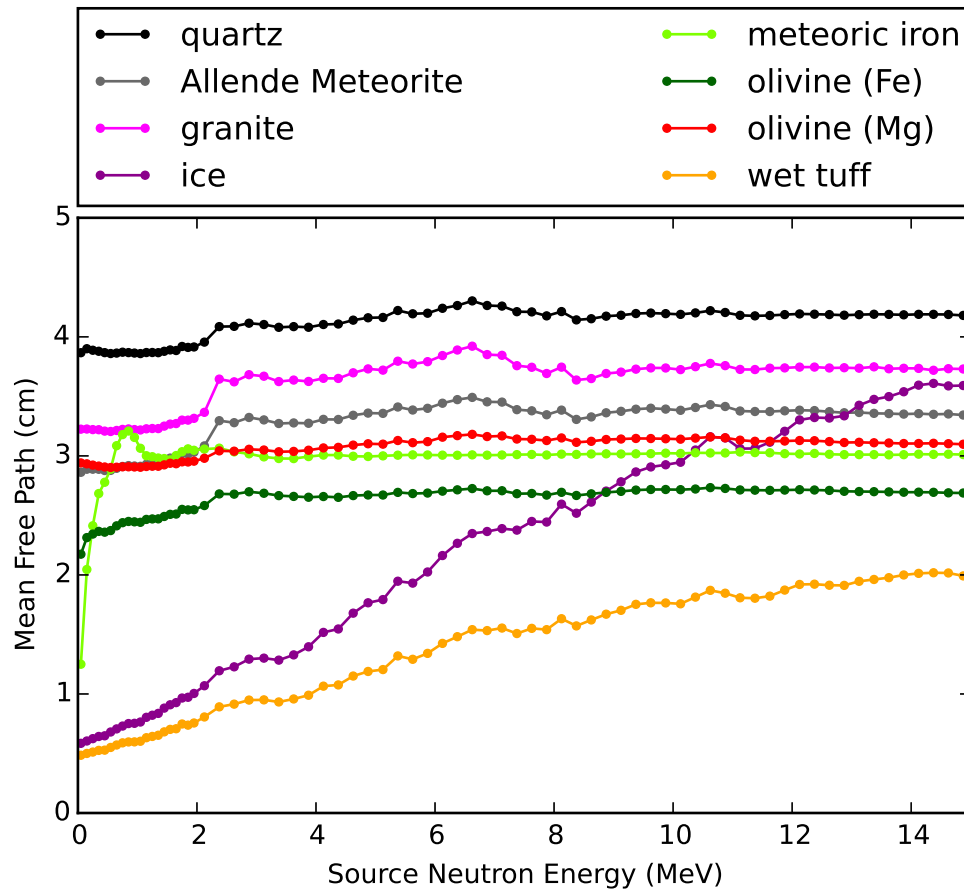


Figure 4.19. Neutron mean free path.

8 meters above the surface to 4 meters below the surface for a quartz asteroid and 2.45 MeV neutrons. The E_{dep} contours are shown in Appendix F for HOB greater than 0.

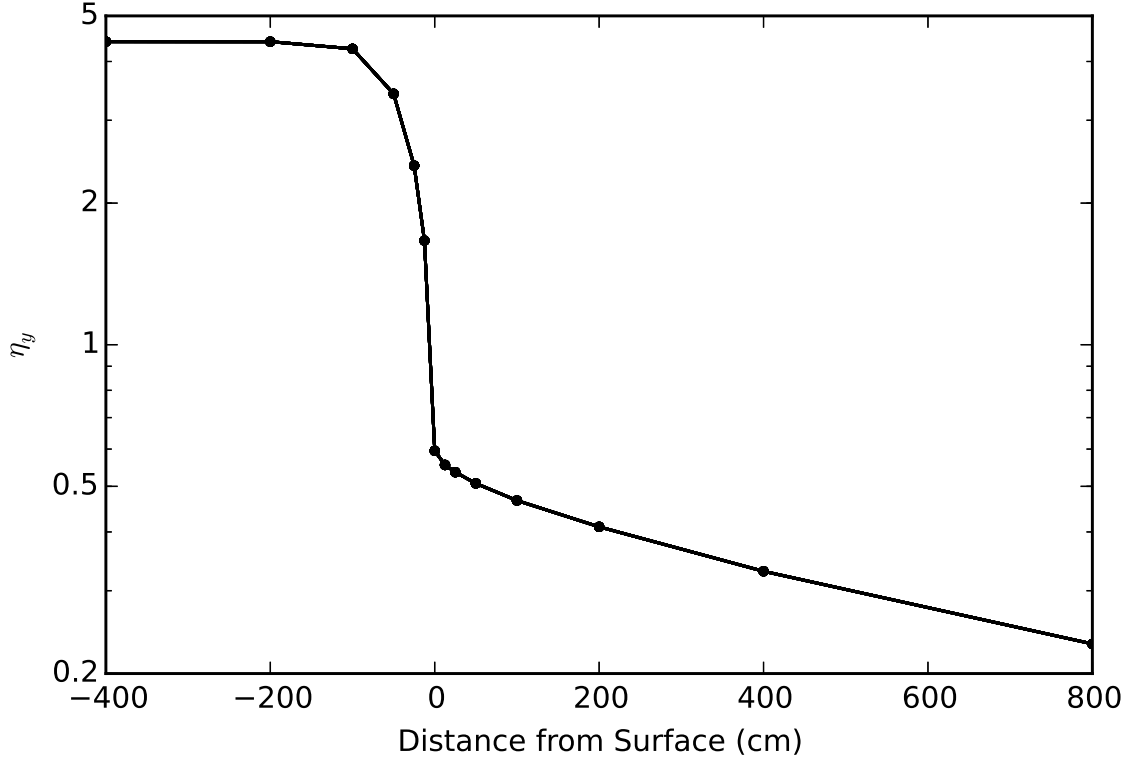


Figure 4.20. Neutron yield coupling efficiency in quartz.

Paralleling the η_y values is the fraction of neutrons captured, shown in Figure 4.21.

4.1.6 Timing

An assumption underlying the validity of the hydrodynamic calculations is that the time scales in which the energy is coupled to the asteroid is short in comparison to the time scales over which the material response occurs. MCNP provides the average time for capture and escape, and the average for both capture *and* escape. Since over half the neutrons never interact with the asteroid and the time for escape is

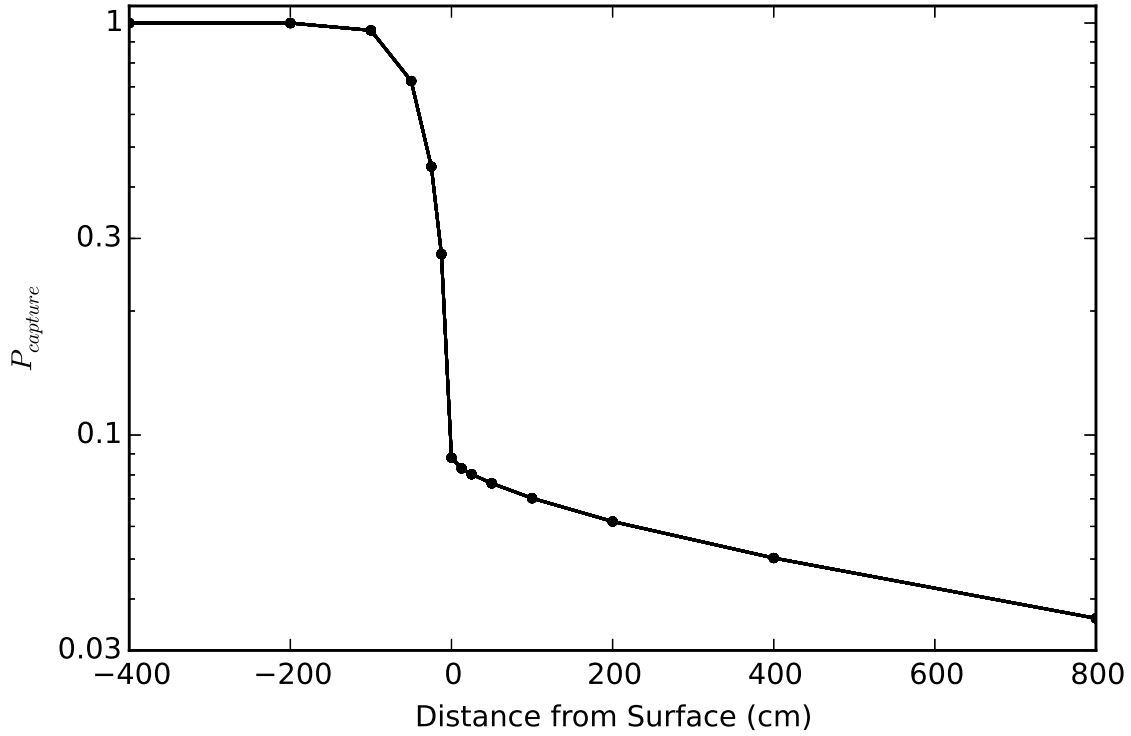


Figure 4.21. Fraction of neutrons captured in quartz.

determined by the arbitrarily chosen universe for the problem, the average lifetime of the neutrons which are captured is used to provide an estimate of the time period energy deposition. This time could be considered a lower bound since it does not include the duration for which neutrons are emitted from the source (non-zero for a nuclear explosion) or the lifetime of the secondary particles created and only accounts for the average time from emission to capture. Figure 4.22 shows the mean lifetime for capture.

The neutron lifetime is influenced by the cross sections for capture and scatter, and the density of the material. The ratio between the scattering cross section and the capture cross section influences the neutron lifetime where an increase in the average number of scatters results in an increased neutron lifetime. The influence of density is seen in Figure 4.23 which shows the mean lifetime for capture in quartz for seven densities. Clearly seen is that the lifetime is inversely proportional to the

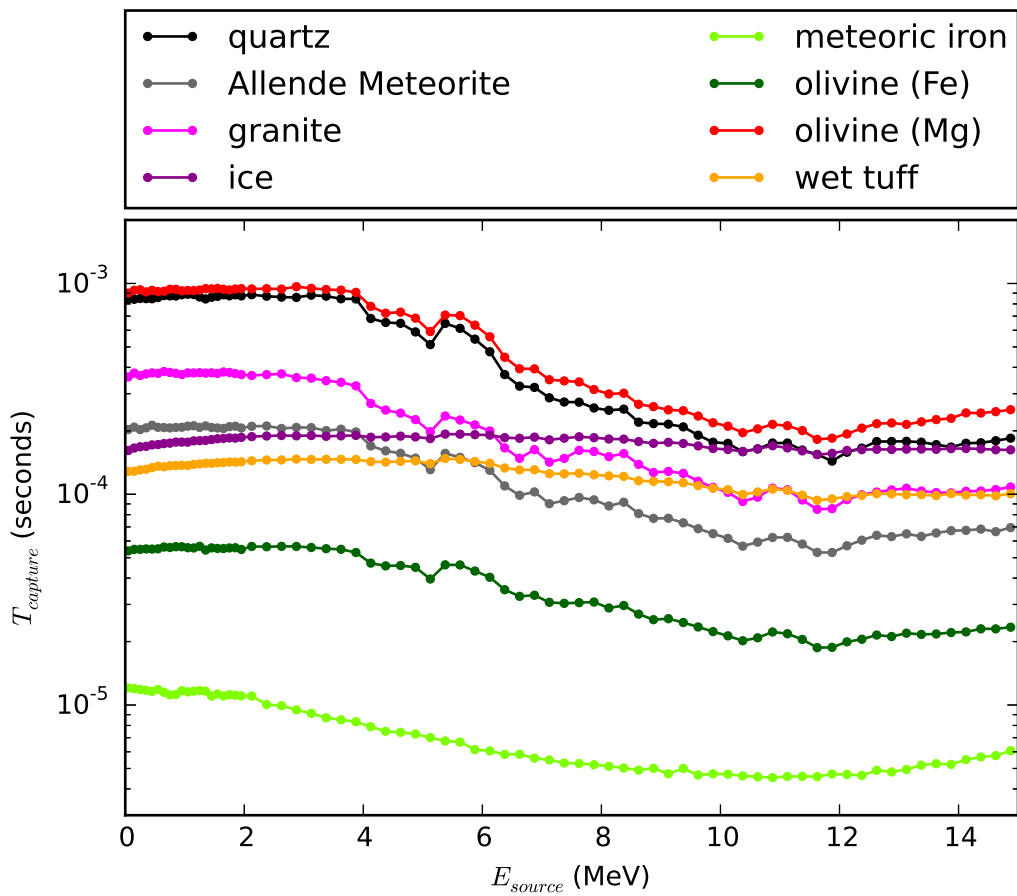


Figure 4.22. Mean lifetime for captured neutrons.

density, which means it is proportional to the mean free path.

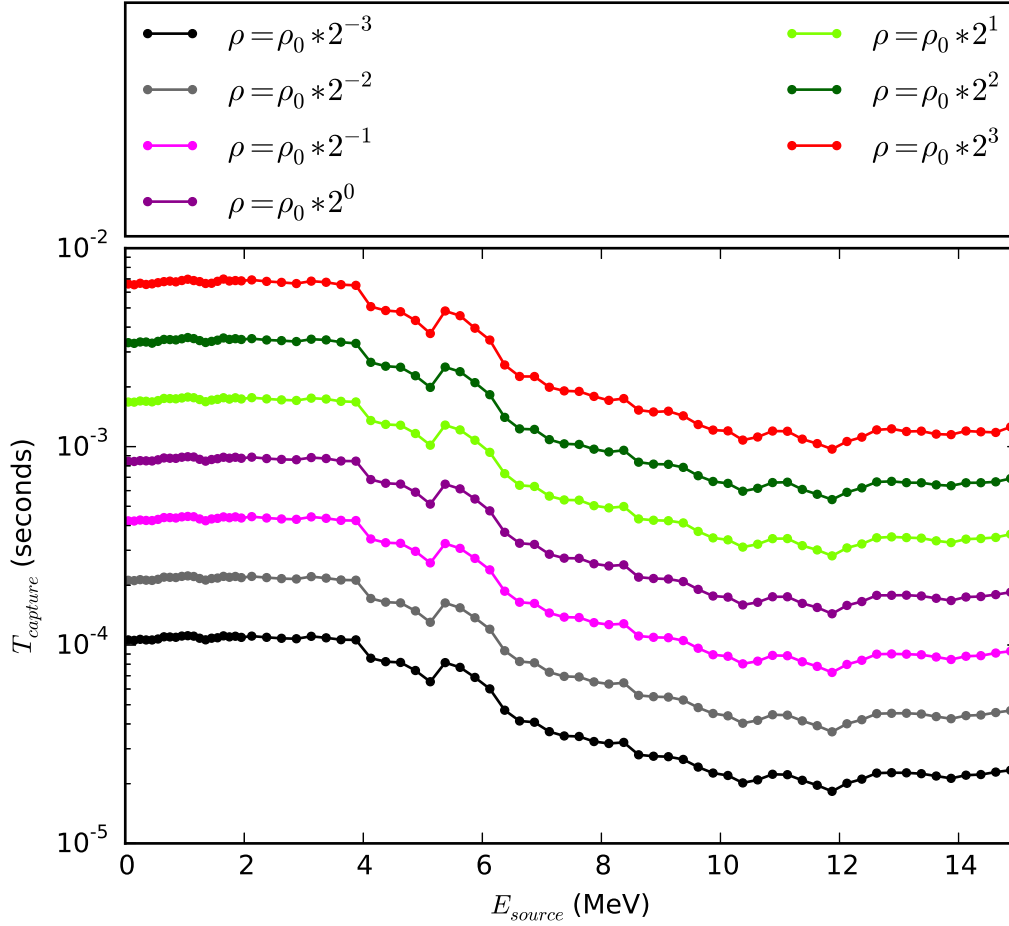


Figure 4.23. Mean lifetime for captured neutrons in quartz. $R_0 = 2500 \text{ cm}$, $\rho_0 = 2.45 \text{ g/cm}^3$.

4.1.7 Energy Contours

The results up to this point have examined average values for a single tally cell comprising the entire asteroid. This next section will explore where the energy is deposited within the asteroid. Energy values from MCNP are in $\frac{\text{MeV}}{\text{gram neutron}}$. To compare energy densities relative to Y_n and not $\frac{\bar{E}}{\text{neutron}}$ in materials with different densities, the energy values from MCNP are converted to volumetric energy densities using

$$\frac{E_{dep}}{cm^3} = Y_n \frac{\frac{E_{dep}}{gram\ neutron}}{\frac{\bar{E}}{neutron}} \rho. \quad (22)$$

Since the MCNP results are independent of Y_n , the results are given here are $\frac{E_{dep}}{cm^3 Y_n}$. Figures 4.24 and 4.25 compare E_{dep} along the z-axis of the asteroid for ice, quartz, meteoric iron, and Allende Meteorite for 2.45 and 14.1 MeV mono-energetic neutrons and a thermonuclear spectrum. The two dimensional energy deposition profiles that these figures represent are shown in Appendix E. Additional centerline energy deposition profiles from preliminary simulations for quartz, meteoric iron, olivine (Fe), and wet tuff which extend only to a depth of 150 cm are shown in Appendix D.

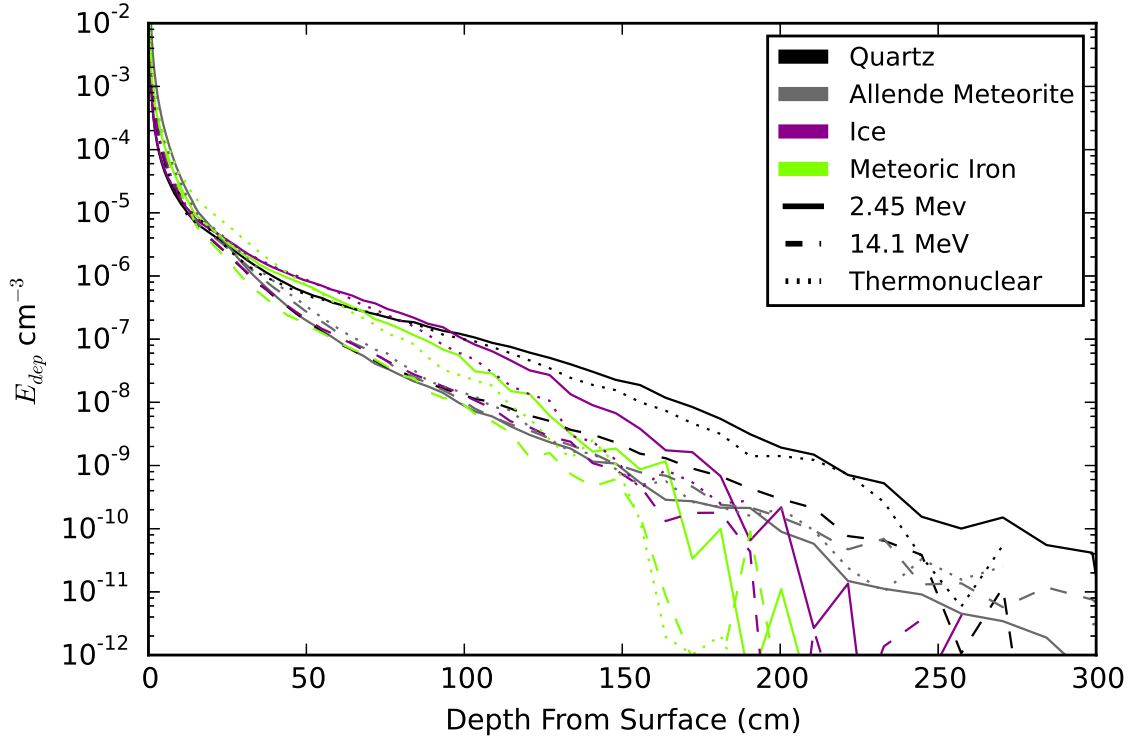


Figure 4.24. Energy deposition contour centerline profile.

The energy contours shown here for quartz and meteoric iron represent the energy source term for two of the Spherical simulations. The energy contours for ice and Allende Meteorite do not, however, represent the energy source terms for those

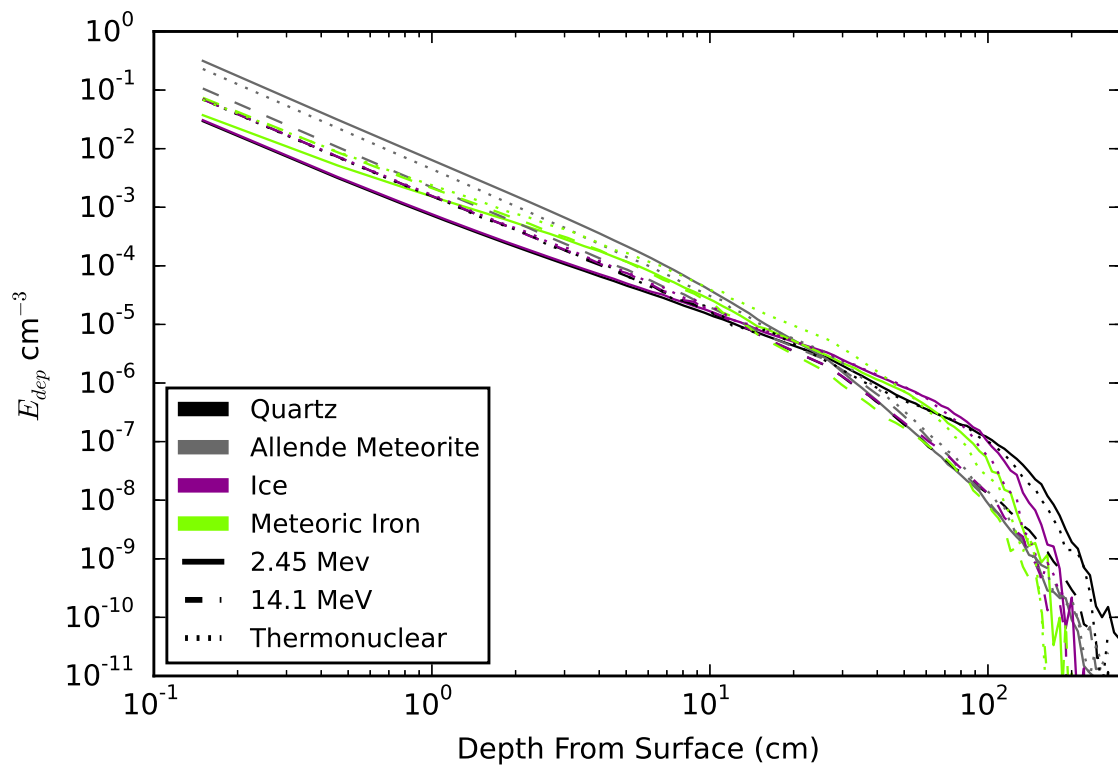


Figure 4.25. Energy deposition contour centerline profile.

materials. All energy profiles presented here were generated using cross section tables in MCNP. The energy contours for ice and Allende Meteorite were generated using physics models for some constituents. Some of the discrepancies in the results for the use of cross section tables and physics models are shown in Appendix G.

4.2 Spheral

4.2.1 Disruption Assessment

Simplifying Assumptions

Before examining the disruption effects resulting from the Spheral simulations, a few simplifying assumptions of the disruption assessment methodology must be addressed. First, gravity is neglected (apart from its use in calculating the escape velocity), which tends to overestimate the disruption. However, this overestimation is only significant for particles near the escape velocity, which is typically very low. Second, escape velocity is calculated at the average radius of the per-disrupted asteroid, even though it would actually be lower once the material became dispersed. This second factor will tend to underestimate the disruption, although the degree to which it offsets the neglect of gravity is not evaluated. Third, only the magnitude of fragment velocity is accounted for and not direction. Fourth, all orbital mechanics are ignored. Fifth, the size and cohesion of the resulting fragments does not affect the outcome.

Methodology

The initial measure of disruption was the fraction of material ejected from the asteroid. A node was considered disrupted if the following condition was met

$$\sqrt{x^2 + y^2 + z^2} \geq R + v_{esc} * t, \quad (23)$$

where (x, y, z) are the coordinates for the center of the node relative to the center of the asteroid prior to disruption, R is the radius of the asteroid, v_{esc} is the escape velocity measured at the surface of the undisturbed asteroid, and t is the time following the disruption. The escape velocity was calculated using

$$v_{esc} = \sqrt{\frac{2GM}{R}}, \quad (24)$$

where

$$M = \frac{4}{3}\pi R^3 \rho, \quad (25)$$

leading to

$$v_{esc} = 7.477 \times 10^{-10} * \rho^{0.5} * R \quad (26)$$

in c,g, μ s units. The escape velocity was 3.09 cm/s for all simulations since the density of the Spheral model was used (2.68 g/cm³), and not the density of the materials in MCNP which generated the energy distribution profiles.

Results

In addition to the limitations due to the disruption assessment methodology, the hydrodynamic simulation has its own limitations. Initially the code was set up to redistribute the nodes every 5000 cycles. However, the simulation would consistently crash at that point, possibly because this is the first instance of ratioed zoning used in a Spheral simulation and the node redistribution function may not account for varying node size. Because of this, that step was removed, and no redistribution of nodes took place. This resulted in some non-physical outcomes. Specifically, it enabled a large fraction of the material to be compressed into a bowl shaped shell opposite the site of

the explosion without the material registering an increase in density. To demonstrate this effect, the simulation results for quartz disrupted with a thermonuclear neutron spectrum will be examined. In this instance, after 5 seconds, 20.94% of the asteroid had been ejected. Figure 4.26 shows a cross section view of the asteroid before and after disruption. The color scale is arbitrary and merely serves as a way of tracking the particles between sub-figures (a) and (b). A cursory visual inspection could leave the impression that more than 20% of the material had been ejected from the asteroid, but that is not the case here. What has taken place is that the nodes colored yellow, orange, and red have been compressed into the area formerly occupied by only the red nodes.

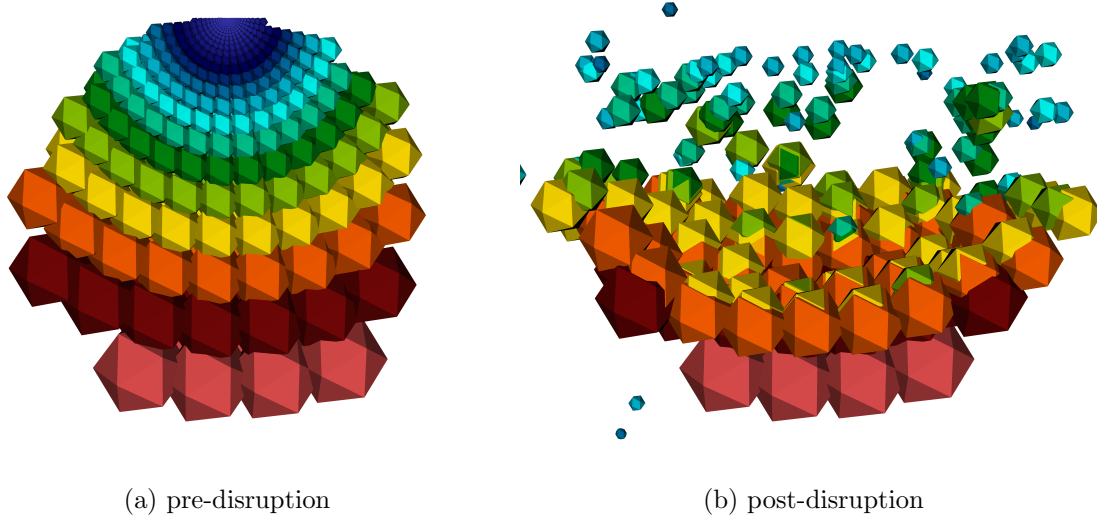


Figure 4.26. Node location before and after disruption for an energy profile from thermonuclear neutrons in quartz.

The material properties for this same post-disrupted state are shown in Figure 4.27. On the left the density is shown, which is 2.68 g/cm^3 for all nodes. On the right is the pressure. The pressure scale is in units of 10^{11} Pa , so the green represents 1 kPa (about 0.14 psi). These pressure and density values are obviously not representative of the actual material response when it is compressed into a smaller volume, and are

indicative of inherent limitations of the simulation as implemented.

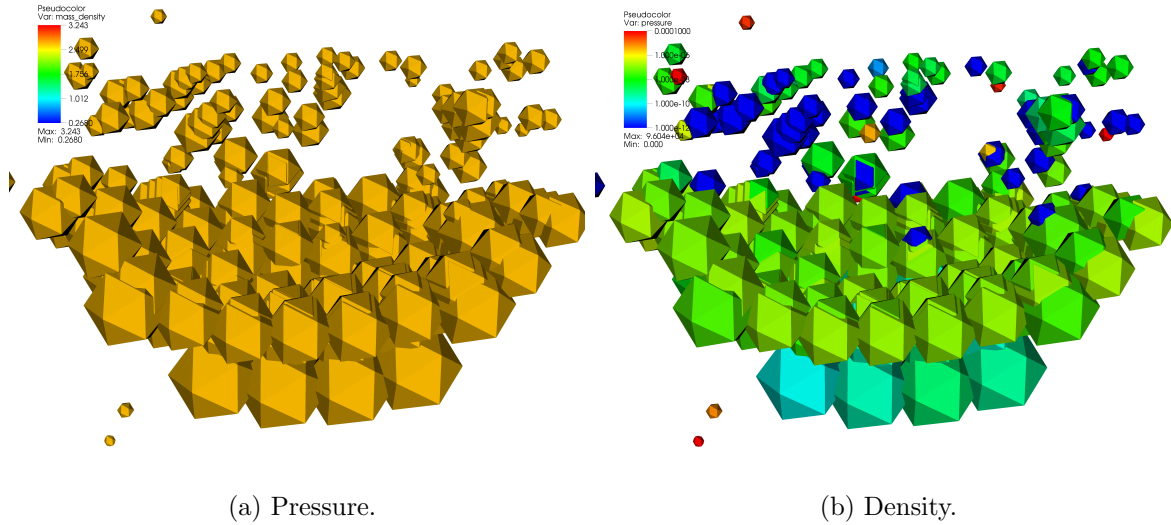


Figure 4.27. Material parameters following disruption.

The theoretical total energy deposited in the asteroid model is the neutron yield coupling efficiency multiplied by the neutron yield, which is 10 kt. These values are shown in Figure 4.3 under the columns labeled $Y_n \eta_y$. Due to the variation in cell and node sizes, as well as the limitations of the energy interpolation algorithm, the actual total energy deposited varied slightly from these values, and are shown in the E_{dep} column of Table 4.3. These E_{dep} values are used in all subsequent analysis. For quartz and meteoric iron, the values for η_y used are the same as shown in Figure 4.6, which is based on MCNP simulations using cross section tables for all the materials. The energy deposition profiles for ice and Allende Meteorite used for the hydrodynamic simulations were based on MCNP simulations that used physics models for some of the elements instead of cross section tables. Because of this, the values of η_y used to calculate the theoretical energy deposition are different that what is shown in Figure 4.6. Also, because the energy deposition profiles for ice and Allende Meteorite are partially based on physics models, the material responses presented below are

potentially suspect.

Table 4.3. Theoretical and actual energy deposited in the Spheral model (kt).

	2.45 MeV		14.1 MeV		Thermonuclear	
	$Y_n\eta_y$	E_{dep}	$Y_n\eta_y$	E_{dep}	$Y_n\eta_y$	E_{dep}
quartz	5.95	6.39	3.21	3.39	5.60	6.02
Allende Meteorite	5.28	5.68	2.94	3.10	5.32	5.71
ice	4.61	4.76	3.97	4.13	4.24	4.39
meteoric iron	5.41	5.76	3.28	3.39	7.05	7.48

The disruption effect is thought to be proportional to the square root of the energy deposited. A least squares fit of the form

$$f(E_{dep}) = a * \sqrt{E_{dep}} \quad (27)$$

was made for the disruption effect of each of the four materials examined. The results are shown in Figure 4.28 and the values of a , the fitting parameter, are shown in Table 4.4.

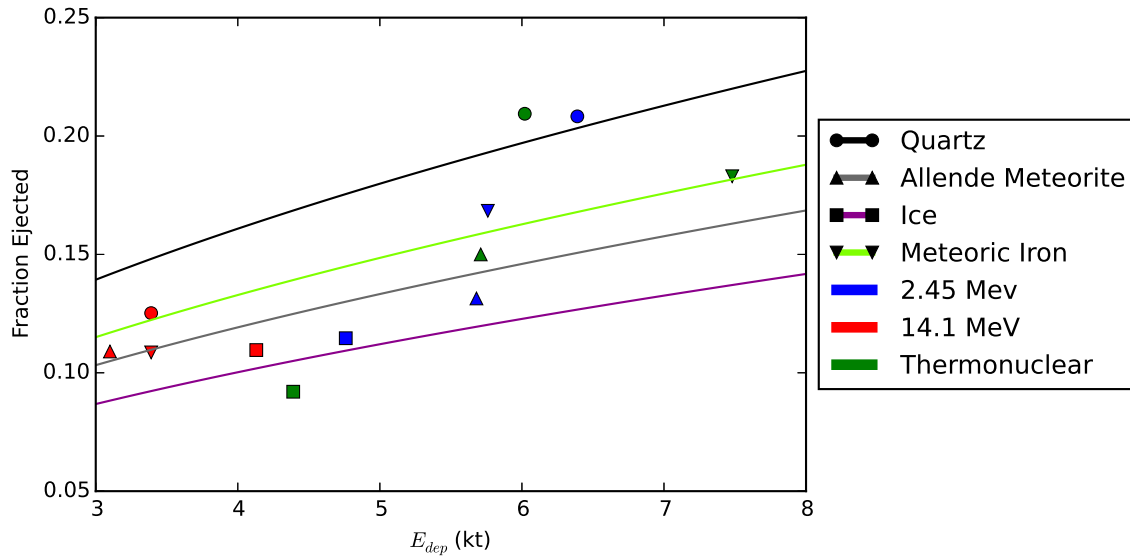


Figure 4.28. Least squares fit by material for fraction ejected.

Table 4.4. Fitting parameter for materials.

Material	a
quartz	0.080
Allende Meteorite	0.060
ice	0.050
meteoric iron	0.066

It is immediately evident, at least in these simulations, that the profile of the energy deposition can significantly influence the material response, even when the material properties for the hydrodynamic model are held constant. Since the energy deposition profiles are sensitive to the elemental or even isotopic composition of the material, accurate characterization of the composition is necessary for meaningful results of a disruption simulation for a real world event.

The same technique was applied to the three different neutron energies. The curves fit to the results for each neutron energy for all materials are shown in Figures 4.29 and for just quartz and Allende Meteorite are shown in 4.30. The neutron energy curve fitting parameters for both figures are given in Table 4.5. While the fitting parameter for each neutron energy varies depending on the group of materials selected, their relationship to each other is consistent, with the results for 2.45 MeV and thermonuclear neutrons being almost identical and the results for 14.1 MeV neutrons displaying a somewhat reduced disruption effect. This reduced effectiveness does not account for the decreased neutron yield coupling efficiency for high energy neutrons, so the combined result is a significant reduction in the effectiveness of high energy neutrons for disruption.

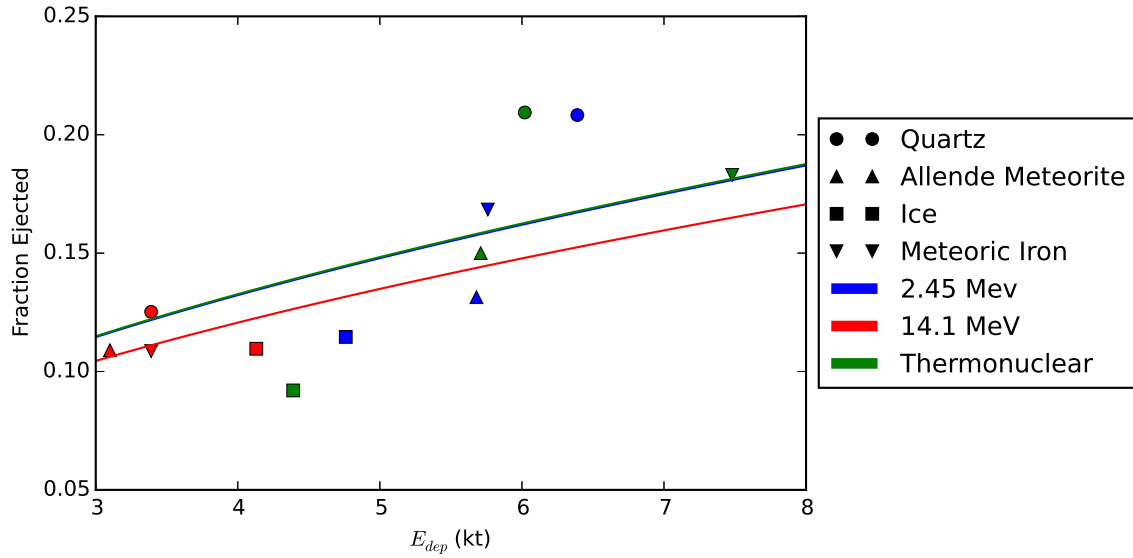


Figure 4.29. Least squares fit by neutron energy for fraction ejected with energy deposition simulated using both cross section data and physics models.

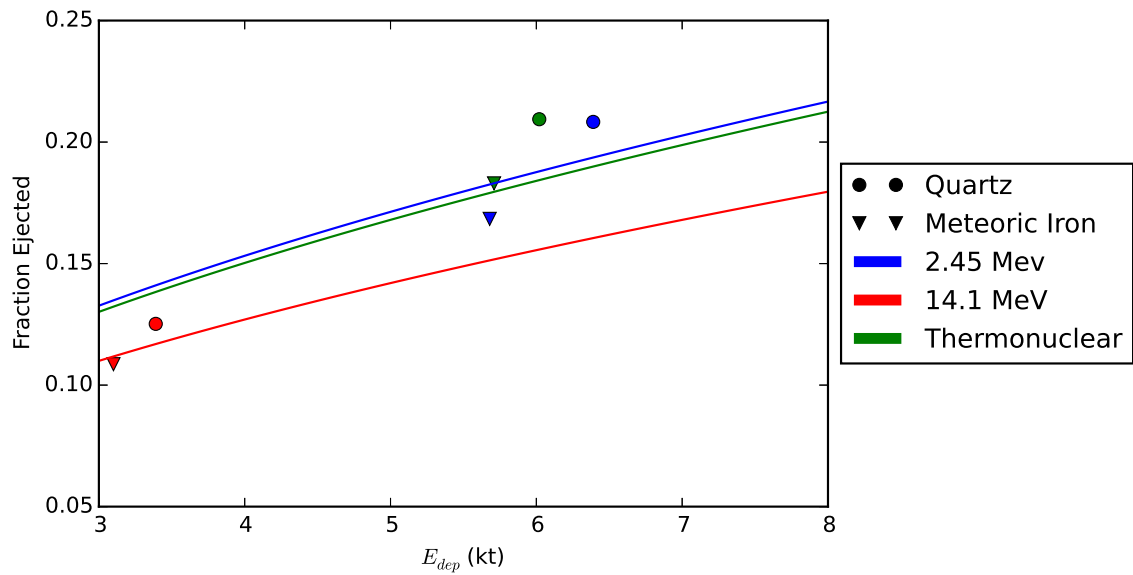


Figure 4.30. Least squares fit by neutron energy for fraction ejected for materials with energy deposition simulated using cross section data.

Table 4.5. Fitting parameter for neutron energy.

Neutron Energy	<i>a</i>	
	Figure 4.29	Figure 4.30
2.45 MeV	0.066	0.766
14.1 MeV	0.060	0.064
thermonuclear	0.066	0.075

In comparing the energy profiles for quartz and meteoric iron in Figures 4.24 and 4.25 with the disruption results shown in Figure 4.28, the increased disruption effect from the quartz energy profiles as compared to the meteoric iron energy profiles may be due to the increased energy deposition at depth in quartz as compared to meteoric iron. However, any conclusions drawn from the result of these simulations using Spheral must be considered preliminary. The validity of the the ratio node zoning in Spheral has not been established by comparing the results from multiple input energy profiles with results from high fidelity models with the same inputs. Also, a set of simulations using the ratio zoning with different initial node spacing and spacing ratio variations were not conducted to determine the convergence or divergence of results based on values chosen.

4.2.2 Alternate Disruption Assessment Methodology

A second disruption assessment methodology is presented here, although the techniques are not applied to the preliminary simulation results for the hydrodynamic response presented thus far.

Simplifying Assumptions

In addition to the simplifying assumptions listed for the disruption assessment presented above, this alternative method requires additional assumptions to be made.

First, any material that does not achieve escape velocity relative to the center of mass frame of reference prior to disruption is considered to not have been disrupted. Second, the trajectory of the asteroid is assumed to pass through the center of the earth. Third, the approach velocity is much greater than the velocity of the disrupted particles.

Methodology

Two parameters are used to evaluate the disruption. The first is the fraction not disrupted, ND , which is similar in concept to the fraction not ejected, but calculated based on node velocity instead of position such that

$$ND = \sum_{i=1}^n \frac{m_i}{m_0} \text{ for } v_i \leq v_{esc}, \quad (28)$$

where m_i and v_i are the mass and velocity of node i , m_0 is the total mass of the asteroid, and n is the total number of nodes in the simulation.

The evaluation of the disrupted portion of the asteroid is not quite so straightforward. Since directionality is ignored, each particle, i , can be thought of existing with equal probability anywhere at radius $v_{esc}t$ at time, t , following the disruption. For $t \leq R_{earth}/v_i$, the particle is guaranteed to hit earth, as shown in Figure 4.31.

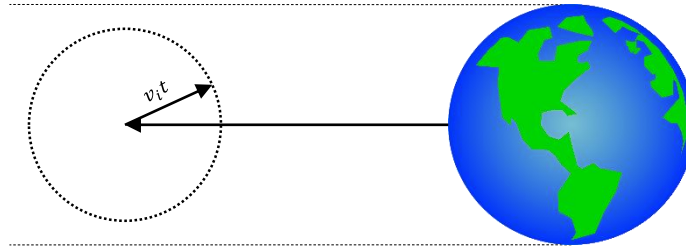


Figure 4.31. Earth's intersection with the spherical shell representing the possible location of particle i at time $t < R_{earth}/v_i$ [30].

For $t > R_{earth}/v_i$, the probability of the particle hitting earth is proportional to

the area of the spherical shell that intersects the path of the earth divided by the total surface area of the shell. This area of intersection is shown in Figure 4.32.

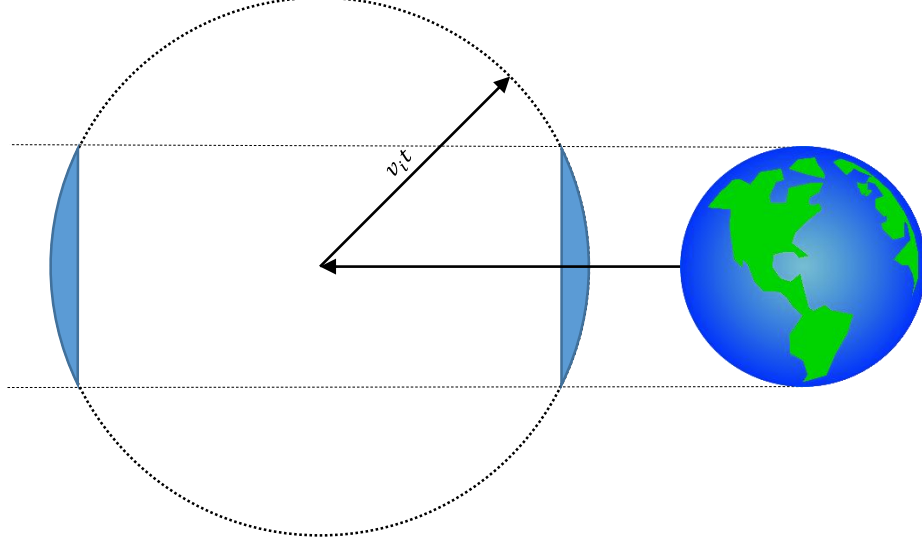


Figure 4.32. Earth's intersection with the spherical shell representing the possible location of particle i at time $t > R_{earth}/v_i$ [30].

With the constraint that $v_i \ll \text{approach speed}$, both areas of intersection are the same size, so the calculations will only examine a hemisphere. The surface area of a hemisphere is $2\pi r^2$, so for particle i , it would be $2\pi(v_i t)^2$. The area of a spherical cap defined by a circle of intersection with radius A , is $\pi(A^2 + H)^2$, for the dimensions indicated in Figure 4.33.

The probability of the earth striking a particle at radius $R = (v_i t)^2$, where $A = R_{earth}$, and $H = tv_i - \sqrt{(tv_i)^2 - R_{earth}^2}$ is

$$P_{hit}(i, t) = \frac{R_{earth}^2 + \left(tv_i - \sqrt{(tv_i)^2 - R_{earth}^2} \right)^2}{2(tv_i)^2}. \quad (29)$$

For $R \ll tv_i$, H approaches zero, and this simplifies to

$$P_{hit}(i, t) = \frac{R_{earth}^2}{2(tv_i)^2}, \quad (30)$$

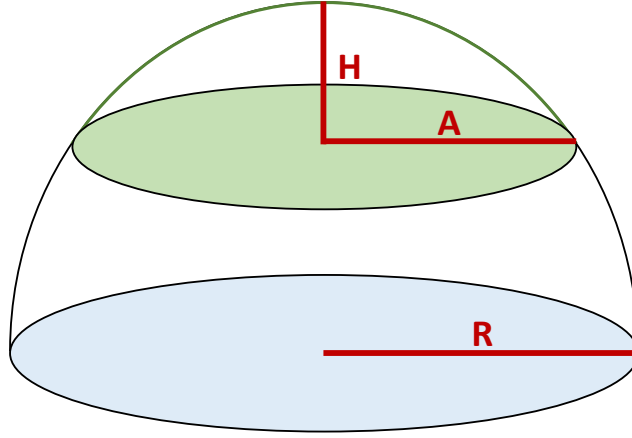


Figure 4.33. Spherical Cap

and this simplification will be used for all subsequent calculations. For n fragments, the mass, m_E , expected to hit earth at time t can be found from

$$m_E(t) = \sum_{i=1}^n P_{hit}(i, t) m(i). \quad (31)$$

This is cumbersome, however, because it requires summing over all fragments for each time. A simplification can be made by calculating the disruption factor, D , such that

$$D = \sum_{i=1}^n \frac{m_i}{m_0} \frac{v_{esc}^2}{v_i^2} \text{ for } v_i > v_{esc}, \quad (32)$$

which once calculated, enables $m_E(t)$ to be calculated with the simple equation

$$m_E(t) = \frac{D \rho v_{esc} R_{earth}^2}{2t^2} + ND \cdot m_0 \text{ for } t \geq \frac{R_{earth}}{v_{esc}}. \quad (33)$$

For $t < \frac{R_{earth}}{v_{esc}}$, $m_E(t)$ can not be calculated due to the inherent ambiguity of the disruption factor. However, the maximum areal density, ρ_A , of disrupted fragments impacting earth can serve as a proxy for the potential hazard and can be calculated

by

$$\rho_A = \frac{D\rho v_{esc}}{2\pi t^2}. \quad (34)$$

Obviously, ρ_A does not account for the non-disrupted portion, since that presents a deterministic rather than probabilistic threat.

V. Conclusion

5.1 Summary

The presence of hydrogen in a material results in a significantly smaller increase in η_y for a subsurface burst compared to a surface burst. This is due to the lower relative reaction Q value of radiative capture in hydrogen. This distinction is not observed for a surface burst since the lower Q value is off set by the decreased energy lost to scatter. Less energy is lost to scatter from a hydrogenous material since the initial scattering event with a hydrogen nucleus can transfer a much larger fraction of its energy than is possible with the other materials.

In all materials, for a fixed neutron yield, lower neutron energies were associated with higher total energy deposition. This is due to the gain in energy deposited from positive Q reactions which become counterbalanced by loss in energy due to threshold reactions for higher neutron energies. For all materials except meteoric iron, an increase in neutron energy resulted in an increase in energy deposited per neutron. In meteoric iron, however, a noticeable drop in energy deposited per neutron occurred above 12 MeV. This corresponded to the threshold energy for the (n,2n) reaction in three of the constituent isotopes, and was also seen as a distinct second hump in the (n,2n) reaction occurrence. This was the only observed case where the isotopic variations were evident in a threshold reaction occurrence in any of the materials. This indicates that isotopic composition, and not just elemental composition, of an asteroid could influence the total energy deposited by neutrons from a nuclear explosion.

The preliminary hydrodynamics simulations conducted suggest that the spatial variations in energy deposition in an asteroid can have a significant effect on the resulting degree of disruption. While a correlation between energy profiles and fraction of material ejected (one measure of disruption) could not be identified, a consistent

trend based on energy deposition profiles was observed. Using a 14.1 MeV neutron energy deposition profile as a source term for Spherical hydrodynamics simulation resulted in a significantly reduced disruption efficiency (i.e. a lower mass ejected per unit of energy deposited) than resulted from the use of 2.45 MeV and thermonuclear spectrum neutron sources to generate the energy profiles.

5.2 Future Work

The results presented in this work represent a preliminary exploration of the effects of neutrons for asteroid disruption. Further simulations work could explore a wide variety of paths to better understand asteroid disruption. A next step could be using EOS and strength models corresponding to the materials used to generate the energy deposition profiles. Size, shape and internal structure variation, rotation and self gravity could be added to approximate known hazards. Neutron and x-ray yields could be combined to explore the total effects of a nuclear explosion. The hydrodynamic response of a subsurface burst could be modeled, and combined with the effects of a kinetic impactor in the form of a Nuclear Asteroid Penetrator. The output of the hydrodynamic simulations could be propagated using orbital models to determine the optimum axis for disruption. Neutron transport could be integrated with the hydrodynamics to explore the significance of the energy deposition time scales.

Appendix A. Asteroid Characterization

A.1 Definitions

Absolute Magnitude (H)-the visual magnitude an observer would record if the asteroid were placed 1 Astronomical Unit (AU) away, and 1 AU from the Sun and at a zero phase angle [31].

Albedo-The ratio of a body's brightness at zero phase angle to the brightness of a perfectly diffusing disk with the same position and apparent size as the body [31].

Astronomical Unit (AU)-The mean distance between the Earth and the Sun. In 2012, the International Astronomical Union defined the distance to be 149,597,870,700 meters [31].

Minimum Orbit Intersection Distance (MOID)-The closest possible approach of the two objects except where excluded by protective resonance [32].

Near Earth Objects (NEOs)-Asteroids and comets with perihelion distance less than 1.3 AU [31].

Perihelion-The closest point in an object's orbit about the Sun [31].

Potentially Hazardous Asteroids (PHAs)-Asteroids with an Earth Minimum Orbit Intersection Distance (MOID) of 0.05 AU or less and an absolute magnitude (H) of 22.0 or less [31].

A.2 Characterization

A.2.1 Size

The brightness of an NEO is the most readily measured parameter related to its size. The apparent magnitude, m , is calculated by

$$m = -2.5 \log \left(\frac{L}{L_0} \right), \quad (35)$$

where L is the luminosity of the body, and L_0 is the luminosity of a reference standard, which is the star Vega, given a value of $m = 0$ [33].

In order to compare objects observed at different locations, the absolute magnitude is calculated, which is an intrinsic value independent of the conditions under which the object was observed. The relationship between apparent magnitude, m , and absolute magnitude, H , is

$$m = H + 5\log(\Delta) + 5\log(r), \quad (36)$$

where Δ is the distance from the earth (AU) and r is the distance from the sun (AU) [33]. If the albedo, p_v , is known, the diameter of the body can be approximated from the absolute magnitude by

$$D = 1329 \times p_v^{-0.5} 10^{-0.2H}, \quad (37)$$

where D is the diameter in kilometers [34]. The uncertainty in diameter is principally due to an uncertainty the albedo, but also in H , which can be off by half a magnitude or more [34].

A.2.2 Density

Determining the mass of an asteroid is difficult, due to its small size. The two methods for determining the mass are observation of how the asteroid affects the orbit of another body, or how another body affects the orbit of the asteroid. The bulk density also requires an accurate determination of volume, which requires accurate three dimensional measurements. This information has become much more accessible with the advent of adaptive optics and space based sensors[35]. To date, the number of asteroids whose densities have been determined is 27 [36].

A.2.3 Mass Approximation

Assuming a homogeneous sphere with density ρ , the mass of an asteroid can be calculated by

$$M = \frac{\pi}{6} \rho D^3. \quad (38)$$

While there is significant uncertainty in both ρ , and p_v (which is used to approximate D), as a general rule, asteroids with lower albedo have lower densities, and those with higher albedo have higher densities. Because of this, the mass of an asteroid can typically be determined within a factor of ~ 2 from the calculated value H [34].

A.2.4 Composition

Analysis of reflectance spectra in the visible and near-infrared (VNIR) has provided the majority of knowledge about the mineralogy of asteroids[37]. Only about half of the 24 classes of asteroids, as defined by DeMeo et al. (2009), have a mineralogical interpretation; developed by linking an asteroid class with a specific meteorite mineralogy [37][38]. The composition of the remaining asteroid classes remains largely unknown [37].

A.2.5 Energy released in fireball

The energy of an asteroid, E , assuming a density of 2 and an impact velocity of 17 km/s is

$$E = 72334 * D^3, \quad (39)$$

where D is the diameter in km and E is in Megatons.

The total energy of a fireball event is several times larger than the observed total

radiated energy. The the following empirical formula was derived by Peter Brown and colleagues to convert the optical radiant energy E_O into an estimate of the total impact energy E [39].

$$E = 8.2508 * E_O^{0.885}. \quad (40)$$

A.2.6 Impact Interval

The average impact interval in year, t , for a population, N , of NEOs is given by

$$t = \frac{4.74 \times 10^8}{N(< H)} \quad (41)$$

[9]. Combined with (1), the impact interval for an NEO diameter D or larger is

$$t = \frac{4.74 \times 10^8}{942 D^{-2.354}}. \quad (42)$$

Appendix B. Example MCNP Decks

```
c *****
c CELL CARD
c *****
99990000 10 -2.65 -10000 imp:n,p,h,d,t,a=1
99990001 0 10000 -99999 imp:n,p,h,d,t,a=1
99990002 0 99999 imp:n,p,h,d,t,a=0

c *****
c SURFACE CARD
c *****
10000 so 2500
99999 so 2600.01

c *****
c DATA CARDS
c *****
sdef pos= 0 0 2900 erg=2.45 par=n
c Materials Cards
m10 8016.70c -0.5326 14028.70c -0.4708
+f6: 99990000
mode n p h d t a
phys:p 100. 0 0 -1 0
phys:h 100. 4j
phys:d 100. 4j
phys:t 100. 4j
phys:a 100. 4j
cut:n j j 0 0
cut:p,h,d,a,t j 0.001 0 0
nps 1e5
```

Figure B.1. MCNP Deck for total energy deposited in quartz for 2.45 MeV neutrons and a HoB of 400 cm.

```

c *****
c CELL CARD
c *****
99990000 10 -2.997 -10000 imp:n,p,h,d,t,a=1
99990001 0 10000 -99999 imp:n,p,h,d,t,a=1
99990002 0 99999 imp:n,p,h,d,t,a=0

c *****
c SURFACE CARD
c *****
10000 so 2500
99999 so 2600.01

c *****
c DATA CARDS
c *****
sdef pos= 0 0 2500.01 par=n erg=D2
      SI2 H 0.0 0.1
      SP2 D 0 1
c Materials Cards
m10 8016.70c -0.4835 12024.70c -0.0043 13027.70c -0.0763 14028.70c
-0.0763
      19039.70c -0.0319 19041.70c -0.0023 11023.70c -0.0274 20040.70c
-0.0130
      26056.70c -0.0216
mpn10 8016 12024 13027 14028 20040 20040 11023 20040 26056
+f6: 99990000
mode n p h d t a
phys:p 100. 0 0 -1 0
phys:h 100. 4j phys:d 100. 4j
phys:t 100. 4j phys:a 100. 4j
cut:n j j 0 0
cut:p,h,d,a,t j 0.001 0 0
nps 1e5

```

Figure B.2. MCNP Deck for total energy deposited in granite for 0-0.1 MeV spectrum of neutrons and a HoB of 0.01 cm.

```

c *****
c CELL CARD
c *****
99990000 10 -7.5 -10000 imp:n,p,h,d,t,a=1
99990001 0 10000 -99999 imp:n,p,h,d,t,a=1
99990002 0 99999 imp:n,p,h,d,t,a=0

c *****
c SURFACE CARD
c *****
10000 so 2500
99999 so 2600.01

c *****
c DATA CARDS
c *****
sdef pos= 0 0 2500.01 par=n erg=D1
SI1 H 3.21E-05 1.27E-04 7.50E-04 0.004829 0.016536 0.035796
      0.217151 0.305476 1 1.05392 1.83914 2.38632
      2.99317 4.01668 4.74265 6.36132 7.42067 9.99185
      11.1112 12.2661 13.8143 14.2071 14.8977
SP1 D 0 2.88E-03 2.95E-02 1.69E-01 2.27E-01 1.71E-01 3.78E-01
      5.07E-02 1.70E-01 7.97E-03 6.53E-02 2.75E-02 2.16E-02
      2.58E-02 1.42E-02 2.04E-02 1.08E-02 1.99E-02 1.28E-02
      1.54E-02 4.01E-02 8.86E-03 1.83E-02
c Materials Cards
m10 26054.70c -0.0348 26056.70c -0.5503 26057.70c -0.0132
      28058.70c -0.2723 28060.70c -0.1049 28061.70c -0.0046
      28062.70c -0.0145
+f6: 99990000
mode n p h d t a
phys:p 100. 0 0 -1 0
phys:h 100. 4j
phys:d 100. 4j
phys:t 100. 4j
phys:a 100. 4j
cut:n j j 0 0
cut:p,h,d,a,t j 0.001 0 0
nps 1e5

```

Figure B.3. MCNP Deck for total energy deposited in meteoric iron for a thermonuclear neutron spectrum and a HoB of 0.01 cm.

Appendix C. Material specific neutron yield coupling efficiency and secondary particle creation

Material specific information is presented here for a surface neutron source for all eight materials examined. The first figure in each series shows the energy deposited per neutron, E_{dep} , and the energy not lost to escape. The available neutron energy efficiency, shown in Figure 4.4, is the ratio of the two values. Superimposed is E_{dep} for the thermonuclear spectrum indicated by a green dot plotted at the average neutron energy of the thermonuclear weapons spectrum which is 1.42 MeV. The second figure in each section is the neutron yield coupling efficiency. Again, the green dot is the value for the thermonuclear spectrum for comparison. The final figure shows the secondary particle creation and neutron capture probability. Finally, the reaction Q-values or threshold energies for each constituent isotope are given, providing some insight into the energy gains or losses due to the reactions indicated by the particle production.

C.1 Ice

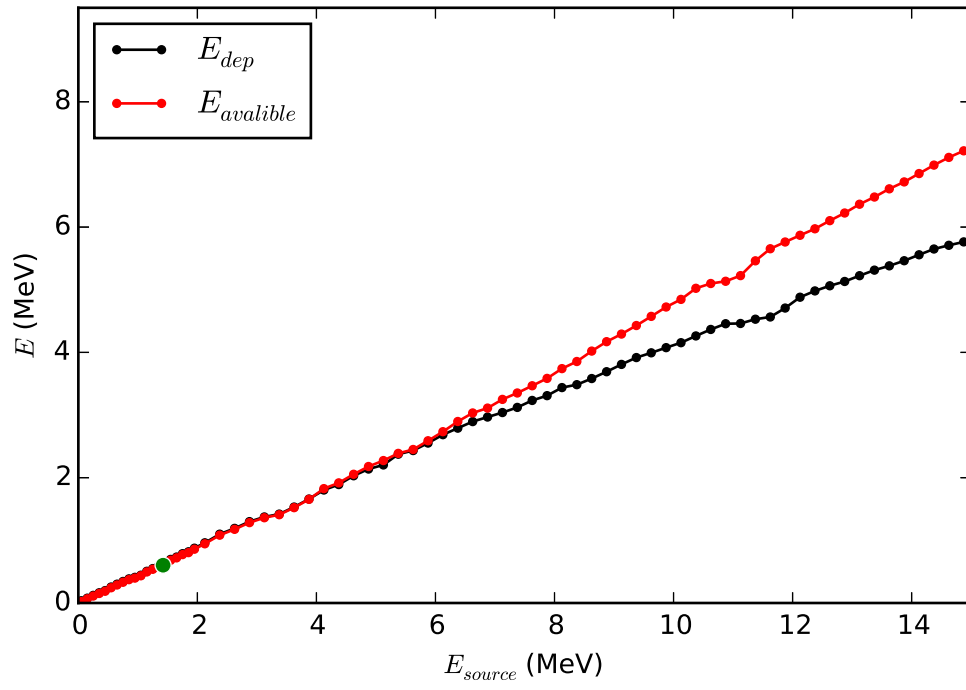


Figure C.1. Available neutron energy and energy deposited per neutron for ice.

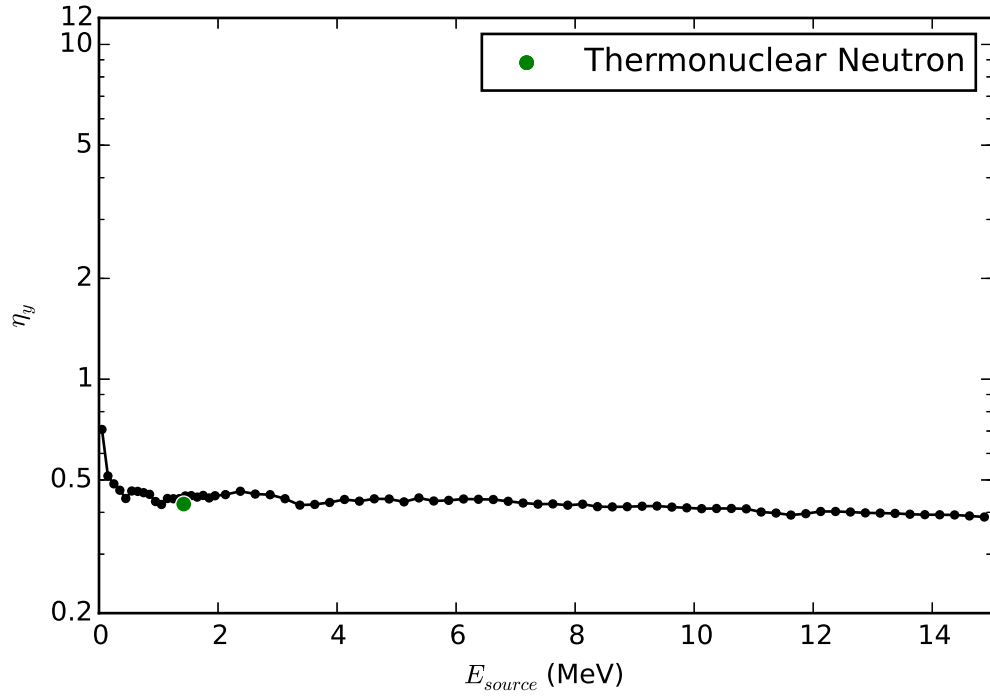


Figure C.2. Neutron yield coupling efficiency for ice.

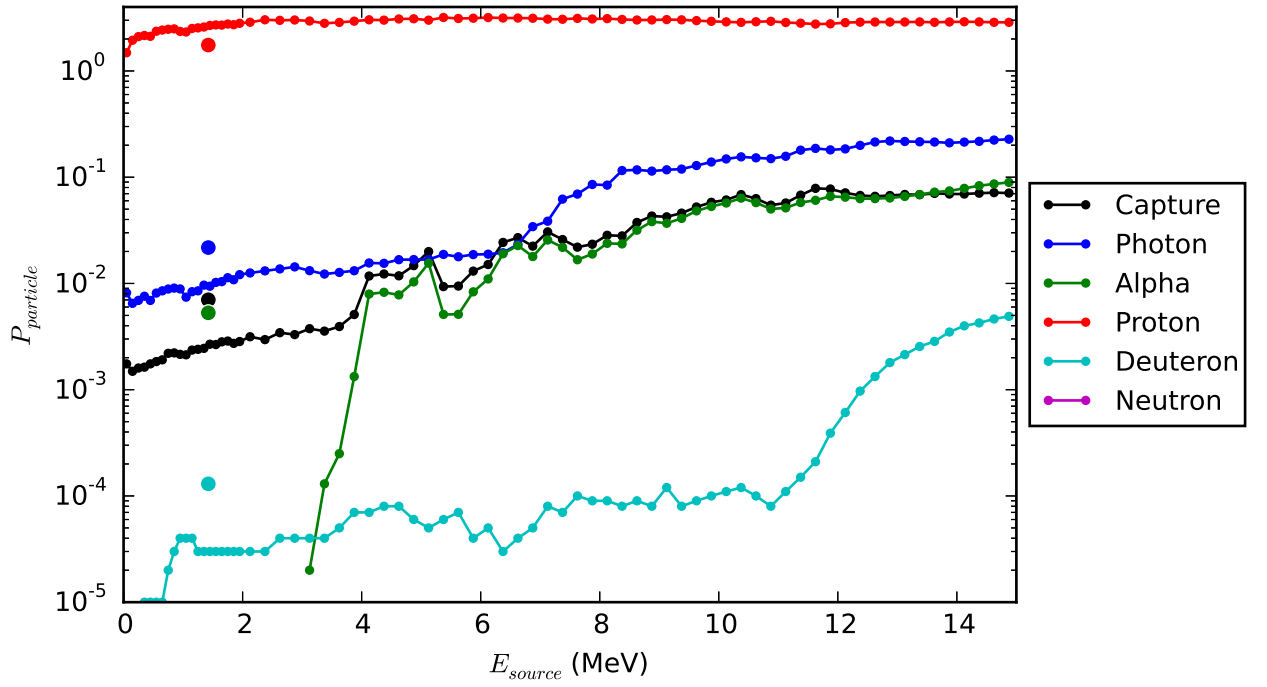


Figure C.3. Secondary particle creation and neutron capture probability for ice.

Table C.1. Reaction Q values (+) or threshold energies (-) for ice.

Isotope	Reaction						First Nuclear Exited State (MeV)	Mass Fraction
	(n, γ)	(n,p)	(n,d)	(n,t)	(n, α)	(n,2n)		
^1H	2.225	-	-	-	-	-	-	.1120
^{16}O	4.143	-9.669	-10.527	-15.391	-2.355	-16.651	6.0494	.8881

C.2 Wet Tuff

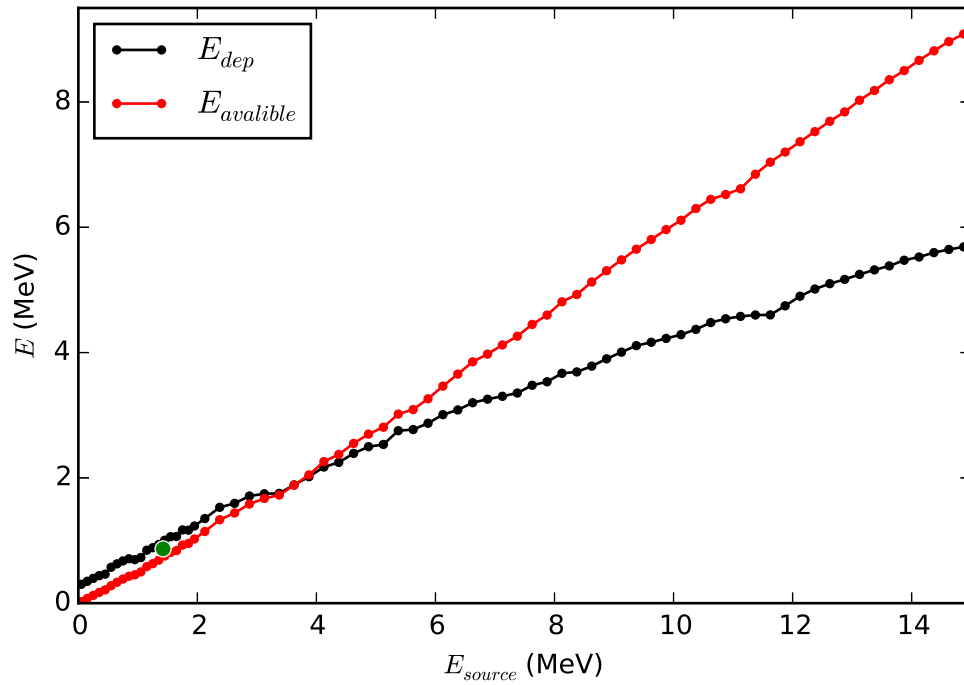


Figure C.4. Available neutron energy and energy deposited per neutron for wet tuff.

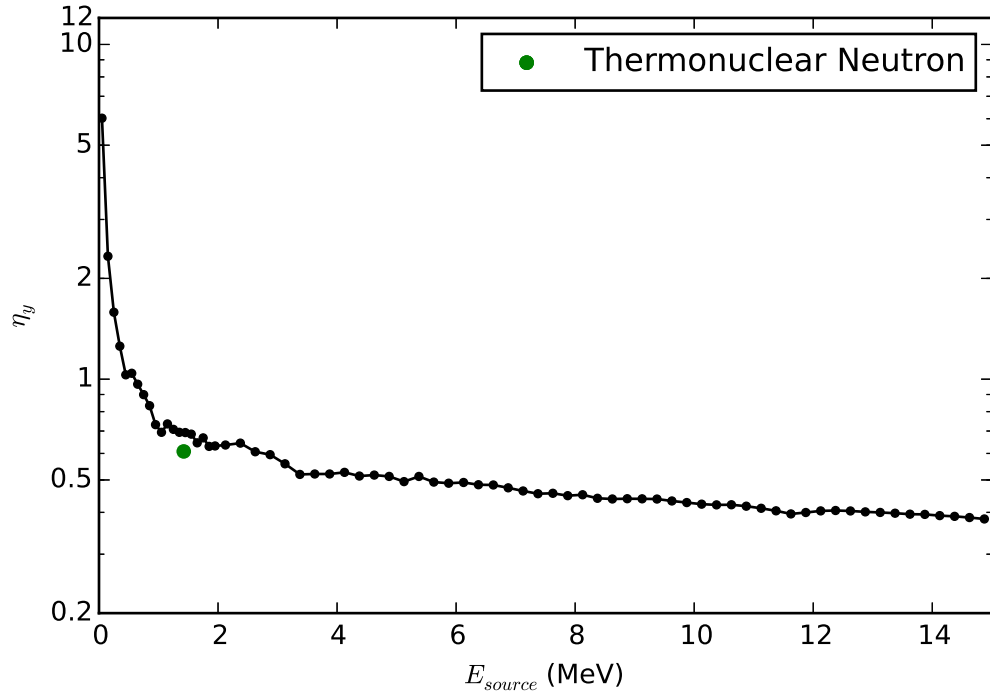


Figure C.5. Neutron yield coupling efficiency for wet tuff.

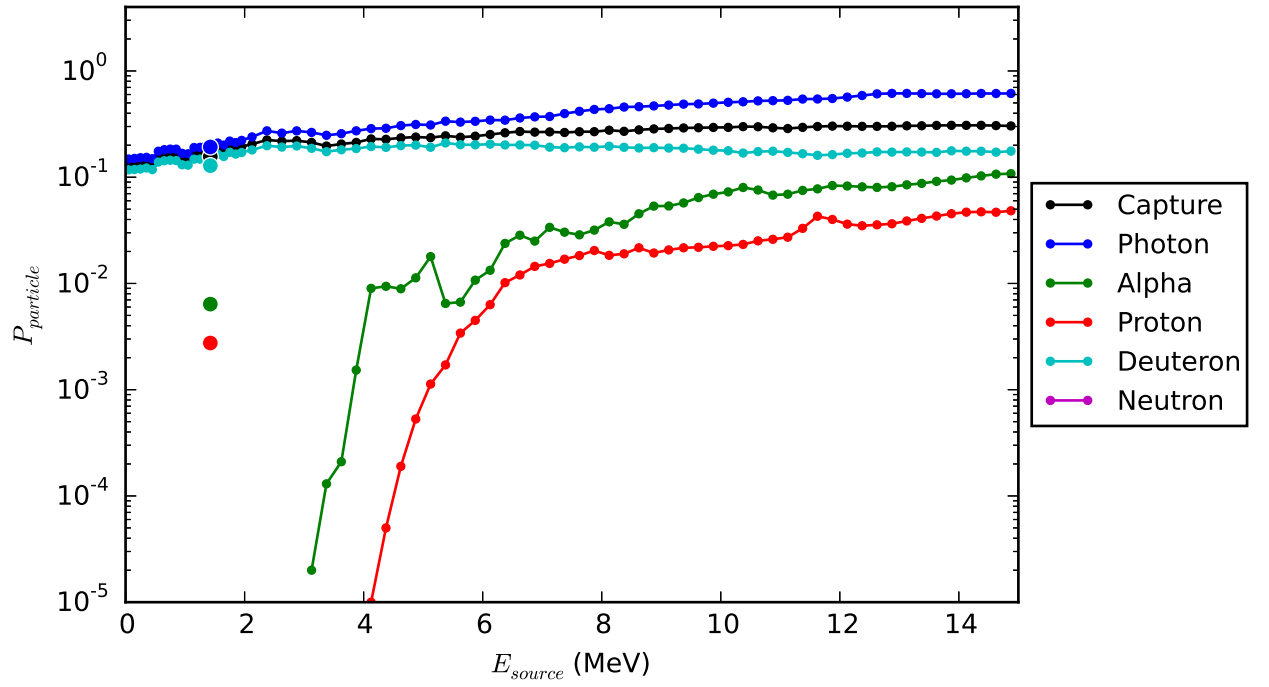


Figure C.6. Secondary particle creation and neutron capture probability for wet tuff.

Table C.2. Reaction Q values (+) or threshold energies (-) for wet tuff.

Isotope	Reaction						First Nuclear Exited State (MeV)	Mass Fraction
	(n, γ)	(n,p)	(n,d)	(n,t)	(n, α)	(n,2n)		
^1H	2.225	-	-	-	-	-	-	.0258
^{16}O	4.143	-9.669	-10.527	-15.391	-2.355	-16.651	6.0494	.6146
^{28}Si	8.474	-3.466	-9.698	-16.743	-2.749	-17.799	1.7790	.3595

C.3 Quartz

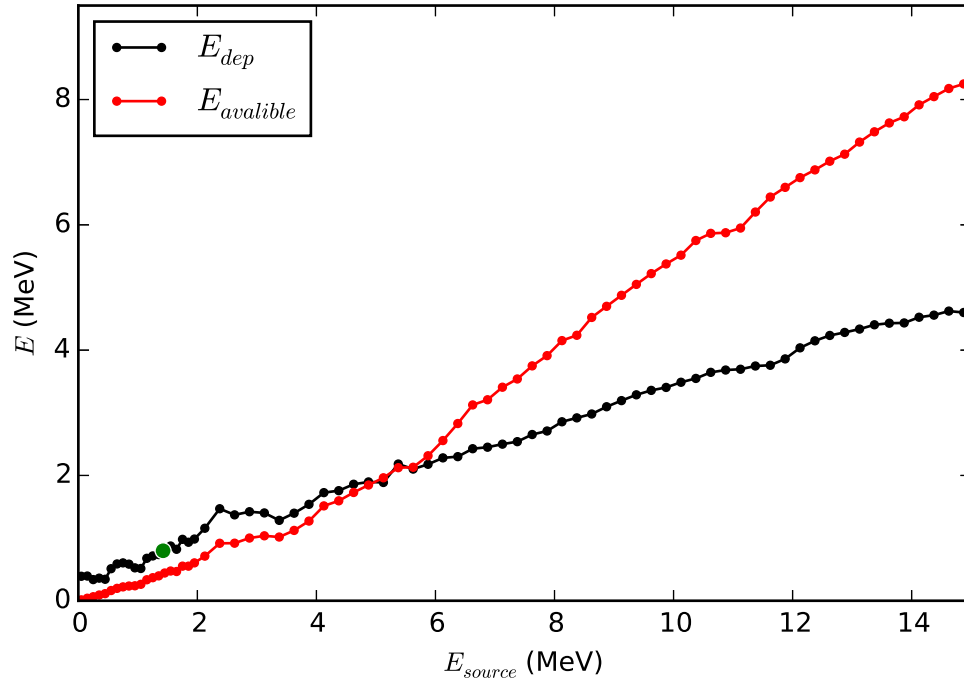


Figure C.7. Available neutron energy and energy deposited per neutron for quartz.

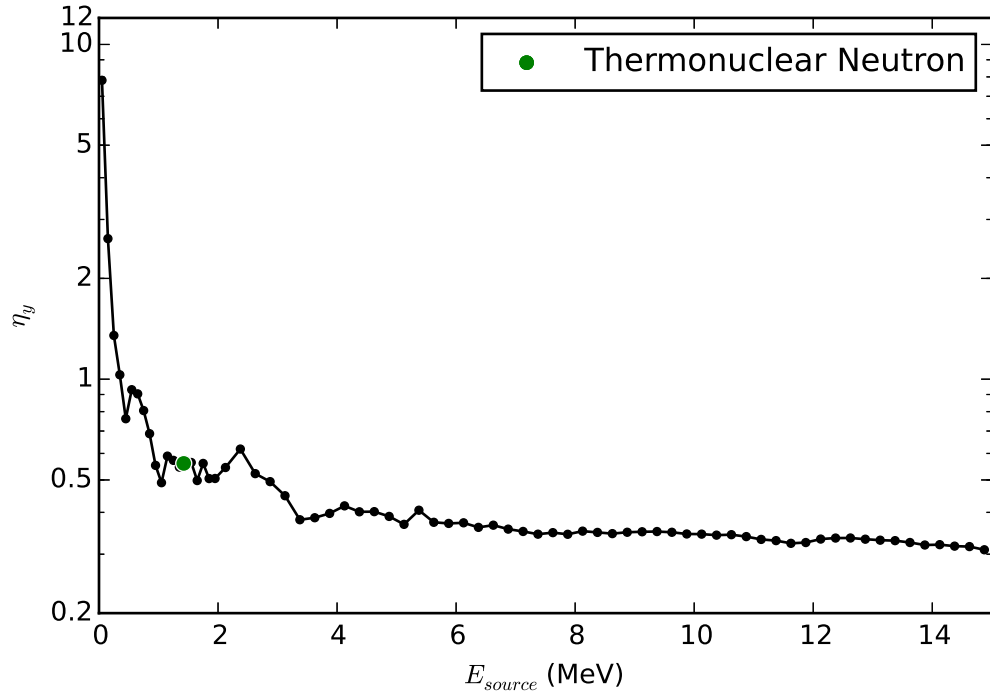


Figure C.8. Neutron yield coupling efficiency for quartz.

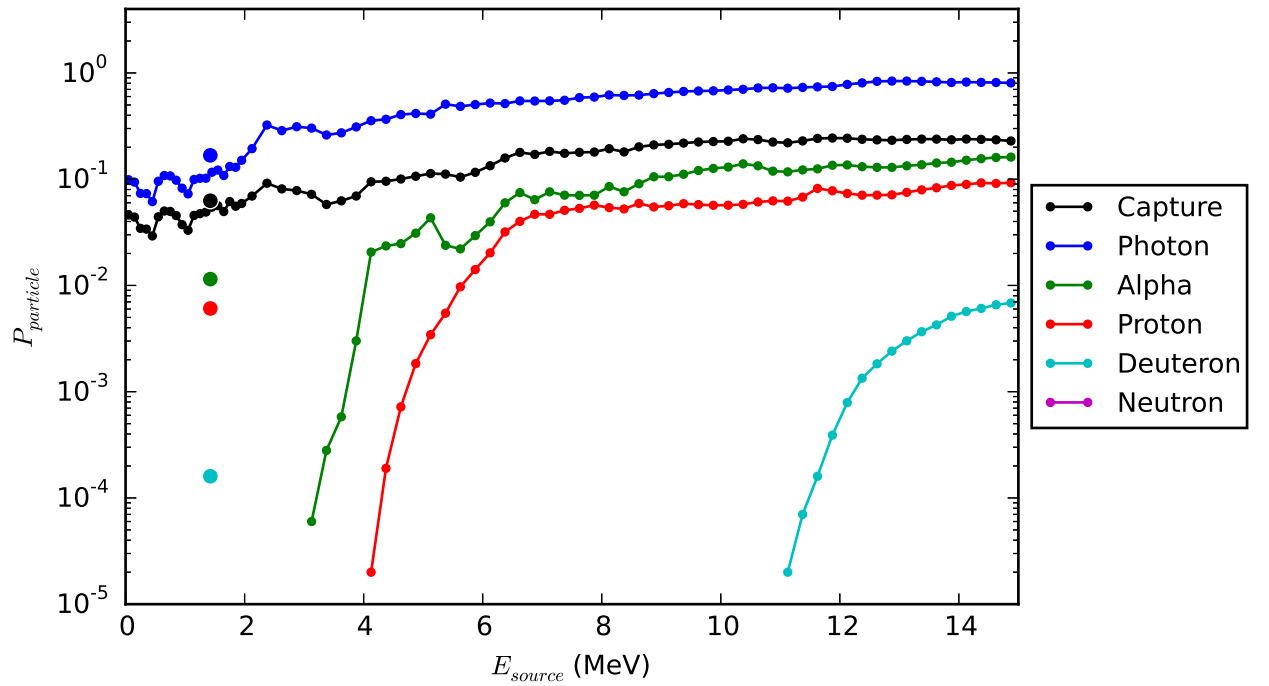


Figure C.9. Secondary particle creation and neutron capture probability for quartz.

Table C.3. Q values (+) or threshold energies (-) for neutron reactions in quartz (MeV).

Isotope	Reaction						First Nuclear Exited State (MeV)	Mass Fraction
	(n, γ)	(n,p)	(n,d)	(n,t)	(n, α)	(n,2n)		
^{16}O	4.143	-9.669	-10.527	-15.391	-2.355	-16.651	6.0494	.5326
^{28}Si	8.474	-3.466	-9.698	-16.743	-2.749	-17.799	1.7790	.4708

C.4 Granite

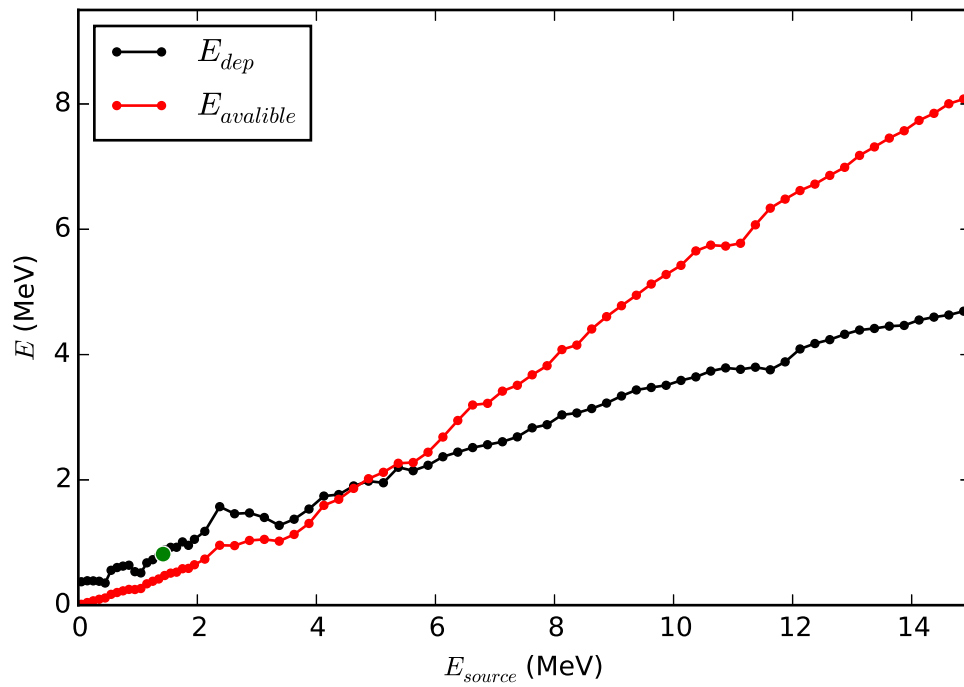


Figure C.10. Available neutron energy and energy deposited per neutron for granite.

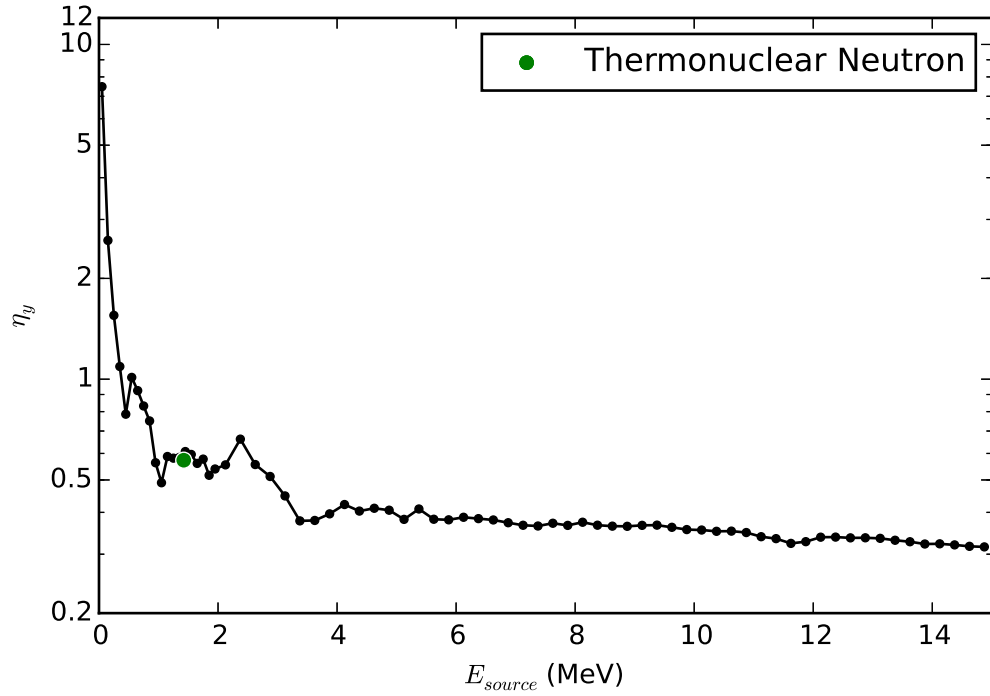


Figure C.11. Neutron yield coupling efficiency for granite.

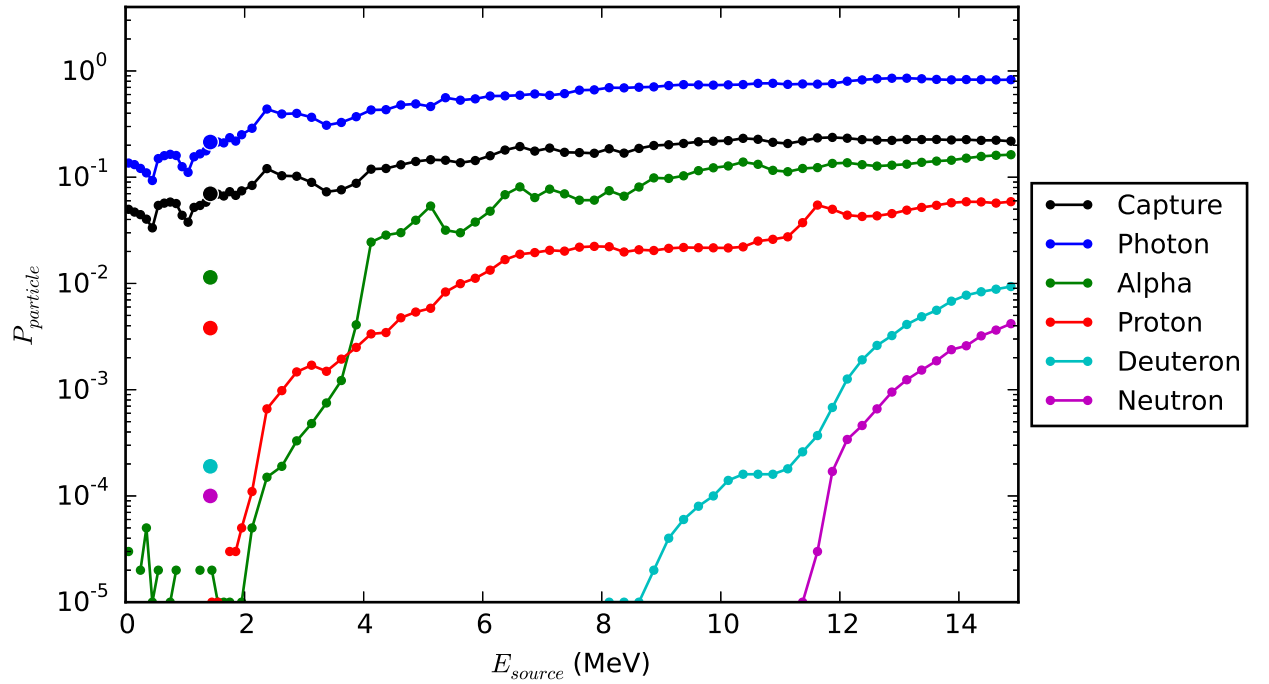


Figure C.12. Secondary particle creation and neutron capture probability for granite.

Table C.4. Reaction Q values (+) or threshold energies (-) for granite.

Isotope	Reaction						First Nuclear Exited State (MeV)	Mass Fraction
	(n, γ)	(n,p)	(n,d)	(n,t)	(n, α)	(n,2n)		
¹⁶ O	4.143	-9.669	-10.527	-15.391	-2.355	-16.651	6.0494	.4835
²³ Na	6.959	-3.212	-6.858	-11.145	-4.036	-12.964	0.4399	.0274
²⁴ Mg	7.331	-4.393	-9.866	-16.287	-2.663	-17.226	1.3687	.0043
²⁷ Al	7.725	-1.364	-6.273	-11.289	-3.249	-13.546	0.8438	.0763
²⁸ Si	8.474	-3.466	-9.698	-16.743	-2.749	-17.799	1.7790	.3392
³⁹ K	7.800	0.728	-4.264	-9.99	1.361	-13.416	2.5225	.0319
⁴¹ K	7.534	-1.228	-5.722	-9.422	-0.118	-10.344	0.9805	.0023
⁴⁰ Ca	8.363	-0.018	-6.258	-13.25	1.748	-16.029	3.3526	.0130
⁵⁶ Fe	7.646	-2.445	-8.103	-12.143	0.326	-11.399	0.8468	.0216

C.5 Allende Meteorite

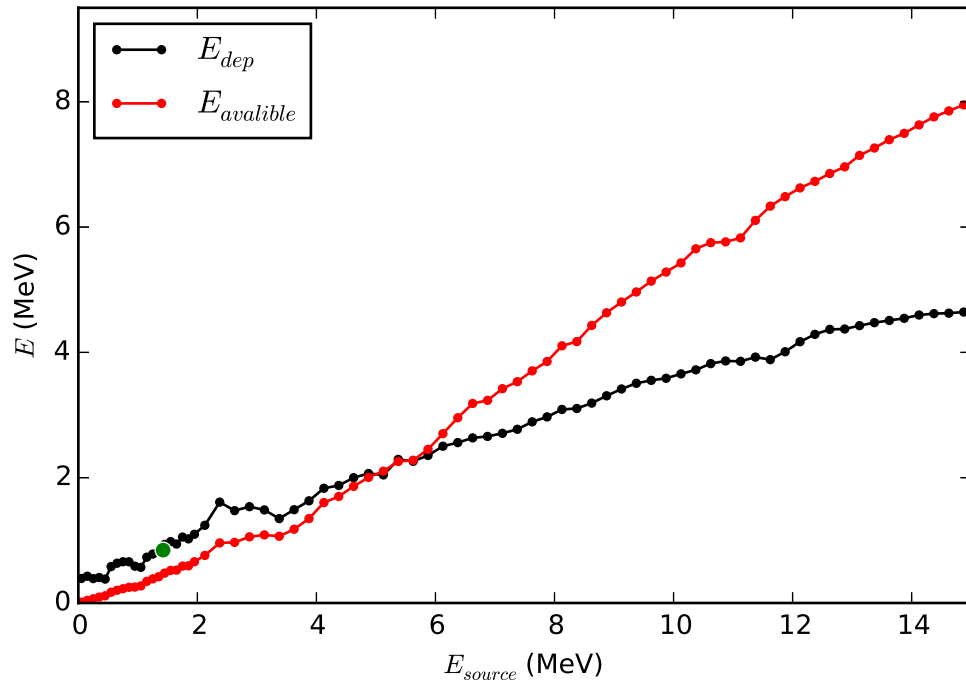


Figure C.13. Available neutron energy and energy deposited per neutron for Allende Meteorite.

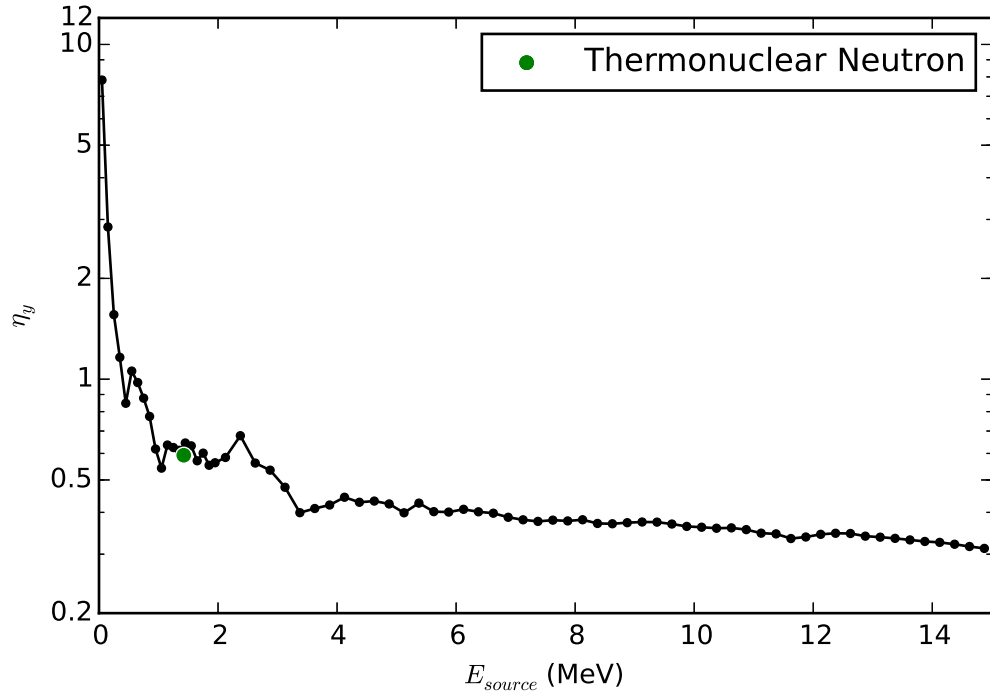


Figure C.14. Neutron yield coupling efficiency for Allende Meteorite.

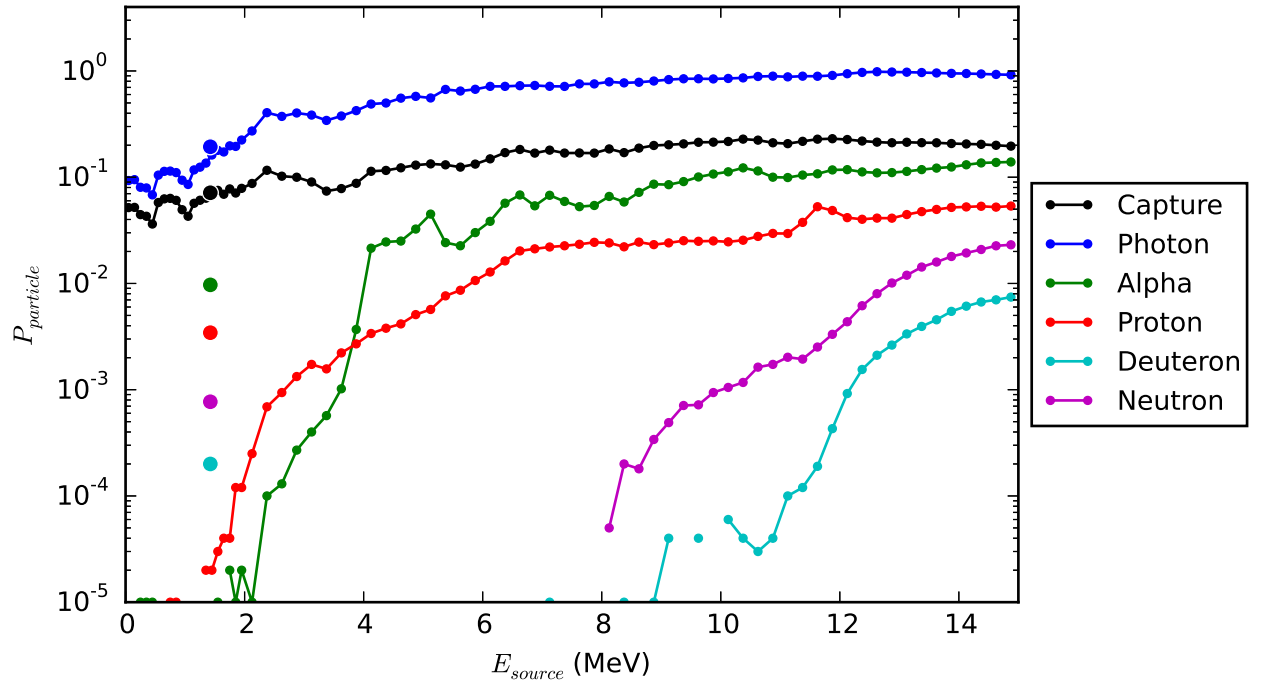


Figure C.15. Secondary particle creation and neutron capture probability for Allende Meteorite.

Table C.5. Reaction Q values (+) or threshold energies (-) for Allende Meteorite.

Isotope	Reaction						First Nuclear Exited State (MeV)	Mass Fraction
	(n, γ)	(n,p)	(n,d)	(n,t)	(n, α)	(n,2n)		
¹⁶ O	4.143	-9.669	-10.527	-15.391	-2.355	-16.651	6.0494	.6663
²⁴ Mg	7.331	-4.393	-9.866	-16.287	-2.663	-17.226	1.3687	.1167
²⁵ Mg	11.093	-2.64	-10.236	-10.967	0.478	-7.626	0.5850	.0148
²⁶ Mg	6.443	-8.362	-12.384	-15.244	-5.624	-11.524	1.8087	.0162
²⁷ Al	7.725	-1.364	-6.273	-11.289	-3.249	-13.546	0.8438	.0170
²⁸ Si	8.474	-3.466	-9.698	-16.743	-2.749	-17.799	1.7790	.1605
⁴⁰ Ca	8.363	-0.018	-6.258	-13.25	1.748	-16.029	3.3526	.0184
⁵⁶ Fe	7.646	-2.445	-8.103	-12.143	0.326	-11.399	0.8468	.2351
⁵⁸ Ni	8.999	0.912	-6.051	-11.259	2.899	-12.429	2.4592	.0095
⁶⁰ Ni	7.820	-1.555	-7.431	-11.698	1.355	-11.579	1.3325	.0032

C.6 Olivine (Mg)

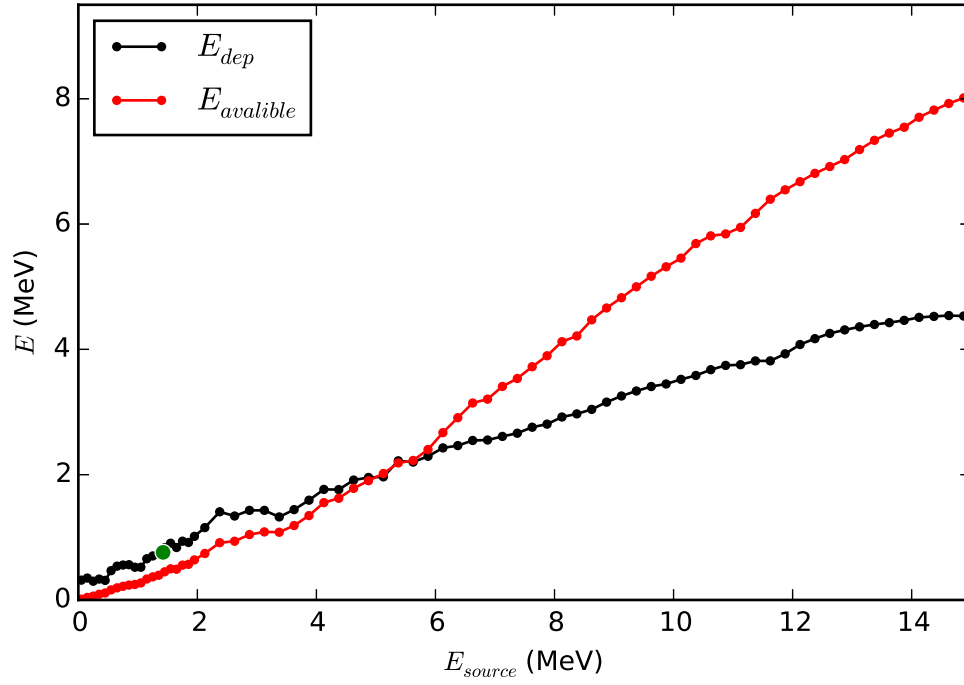


Figure C.16. Available neutron energy and energy deposited per neutron for olivine (Mg).

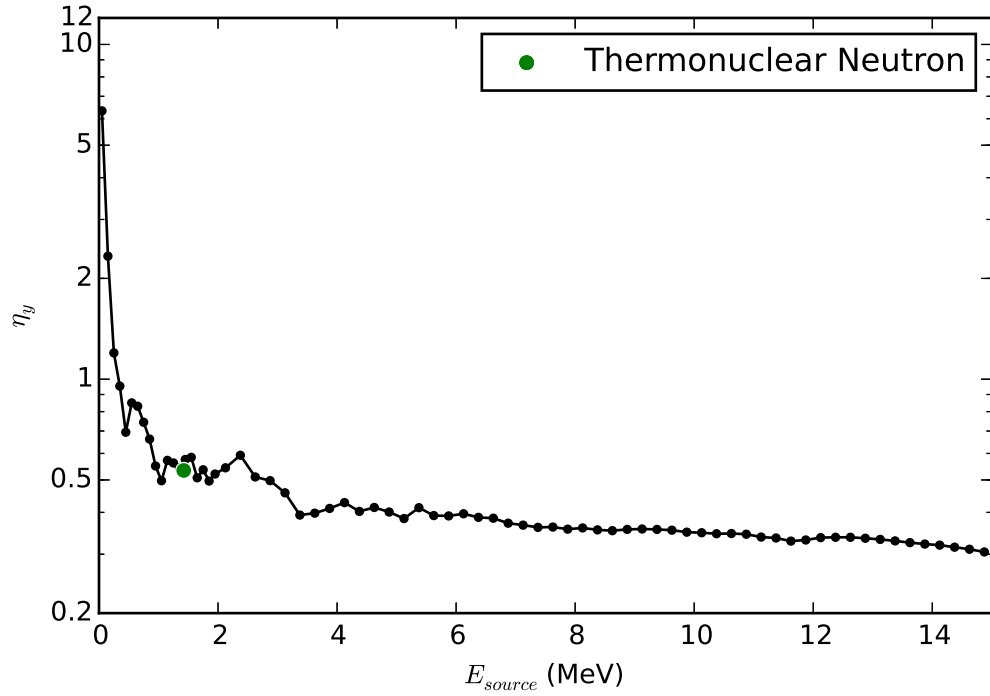


Figure C.17. Neutron yield coupling efficiency for olivine (Mg).

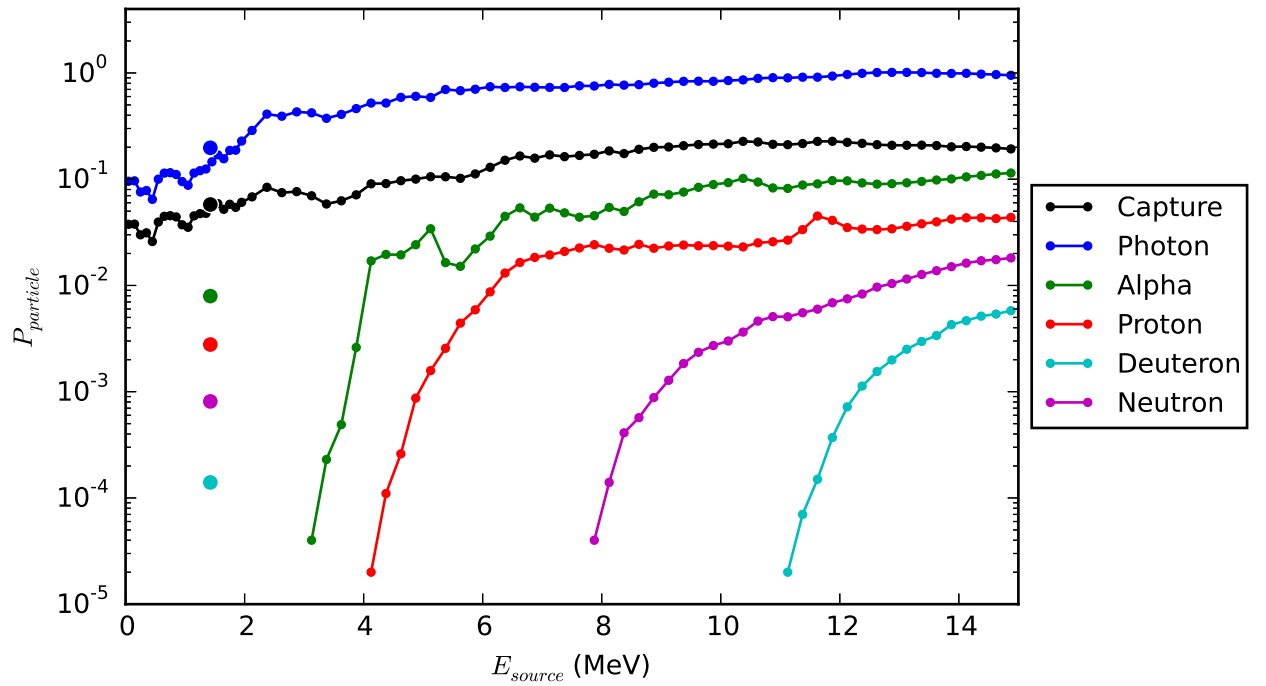


Figure C.18. Secondary particle creation and neutron capture probability for olivine (Mg).

Table C.6. Reaction Q values (+) or threshold energies (-) for olivine (Mg).

Isotope	Reaction						First Nuclear Exited State (MeV)	Mass Fraction
	(n, γ)	(n,p)	(n,d)	(n,t)	(n, α)	(n,2n)		
^{16}O	4.143	-9.669	-10.527	-15.391	-2.355	-16.651	6.0494	.4549
^{24}Mg	7.331	-4.393	-9.866	-16.287	-2.663	-17.226	1.3687	.2729
^{25}Mg	11.093	-2.64	-10.236	-10.967	0.478	-7.626	0.5850	.0346
^{26}Mg	6.443	-8.362	-12.384	-15.244	-5.624	-11.524	1.8087	.0380
^{28}Si	8.474	-3.466	-9.698	-16.743	-2.749	-17.799	1.7790	.1666

C.7 Olivine (Fe)

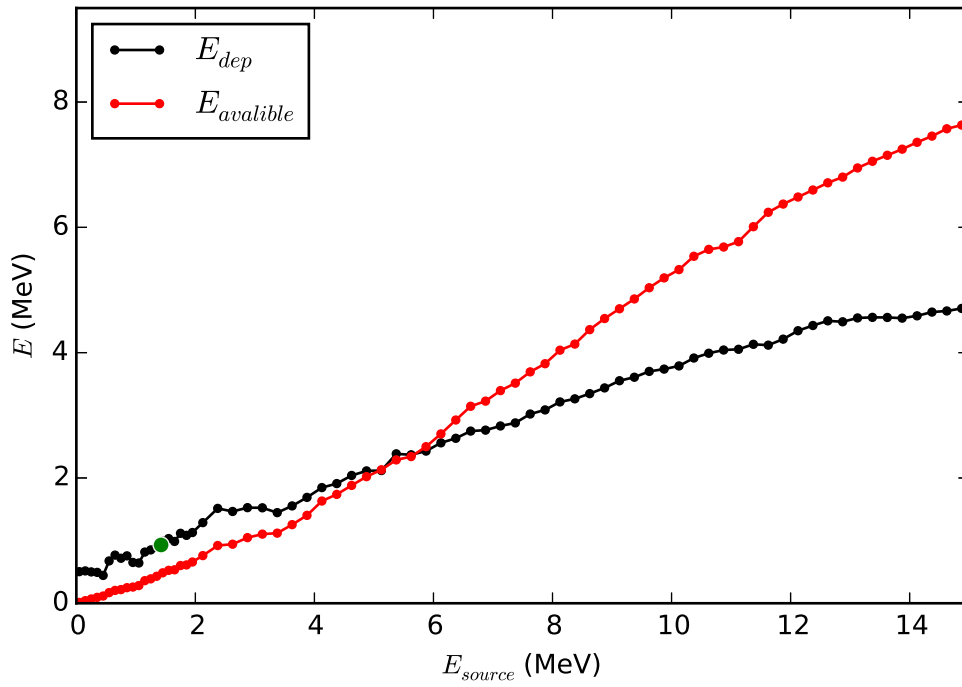


Figure C.19. Available neutron energy and energy deposited per neutron for olivine (Fe).

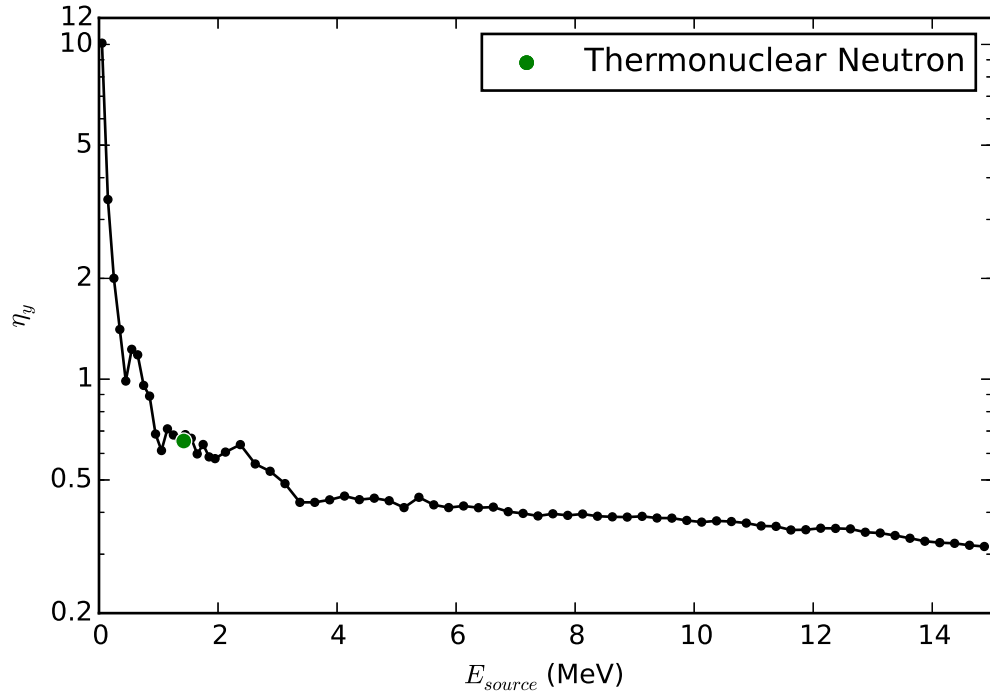


Figure C.20. Neutron yield coupling efficiency for olivine (Fe).

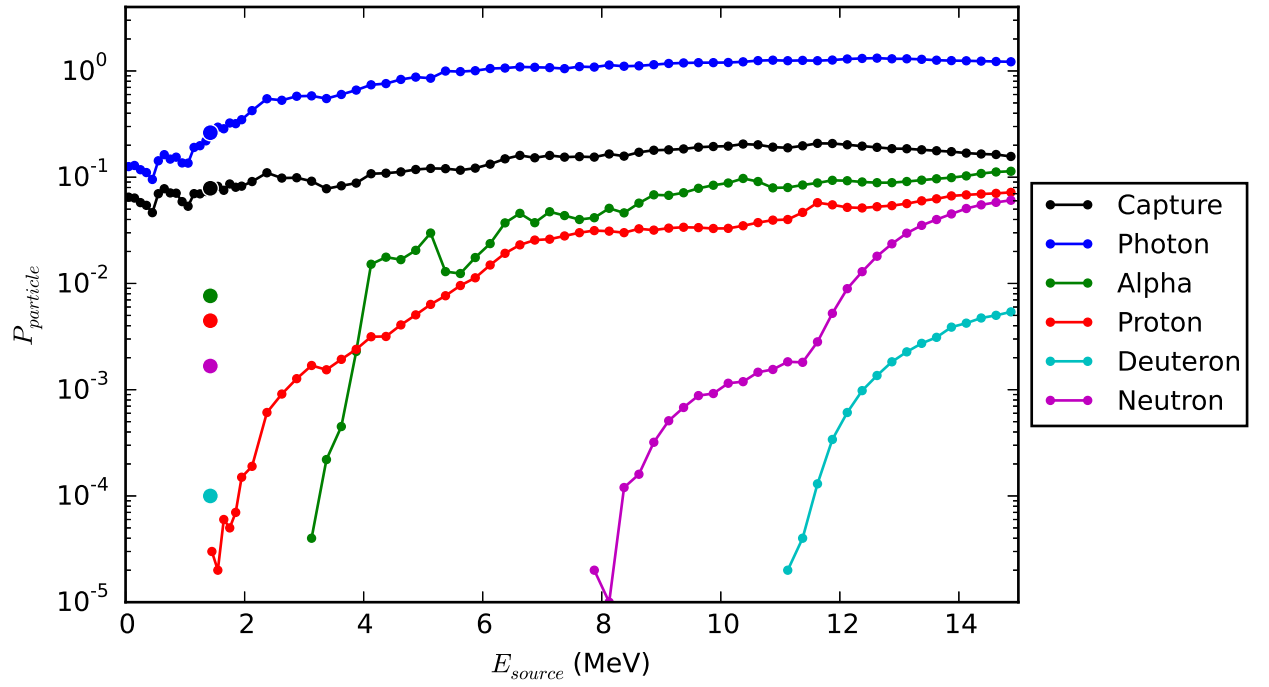


Figure C.21. Secondary particle creation and neutron capture probability for olivine (Fe).

Table C.7. Reaction Q values (+) or threshold energies (-) for olivine (Fe).

Isotope	Reaction						First Nuclear Exited State (MeV)	Mass Fraction
	(n, γ)	(n,p)	(n,d)	(n,t)	(n, α)	(n,2n)		
¹⁶ O	4.143	-9.669	-10.527	-15.391	-2.355	-16.651	6.0494	.3141
²⁸ Si	8.474	-3.466	-9.698	-16.743	-2.749	-17.799	1.7790	.1378
⁵⁴ Fe	9.298	0.596	-6.753	-12.658	0.844	-13.629	1.4082	0.318
⁵⁶ Fe	7.646	-2.445	-8.103	-12.143	0.326	-11.399	0.8468	.5027
⁵⁷ Fe	10.045	-1.426	-8.482	-9.514	2.399	-7.782	0.0144	.0121

C.8 Meteoric Iron

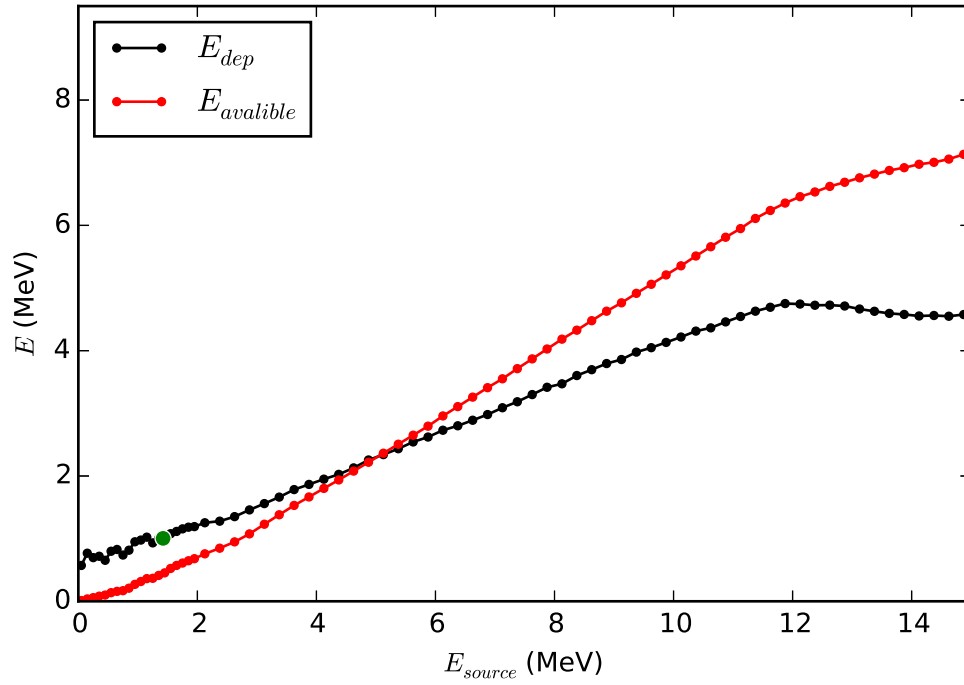


Figure C.22. Available neutron energy and energy deposited per neutron for meteoric iron.

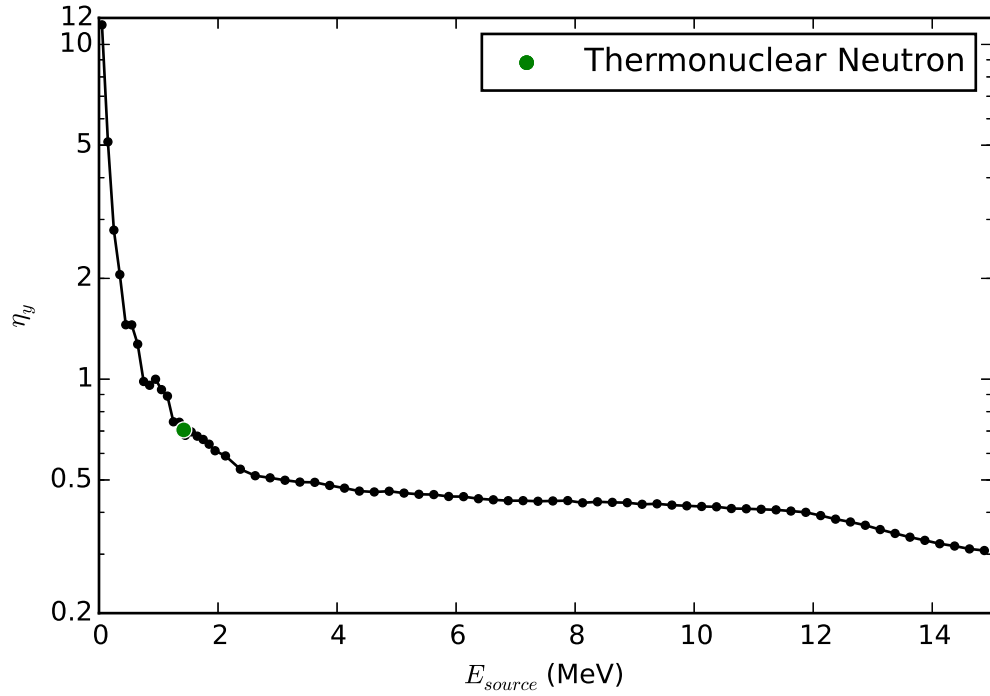


Figure C.23. Neutron yield coupling efficiency for meteoric iron.

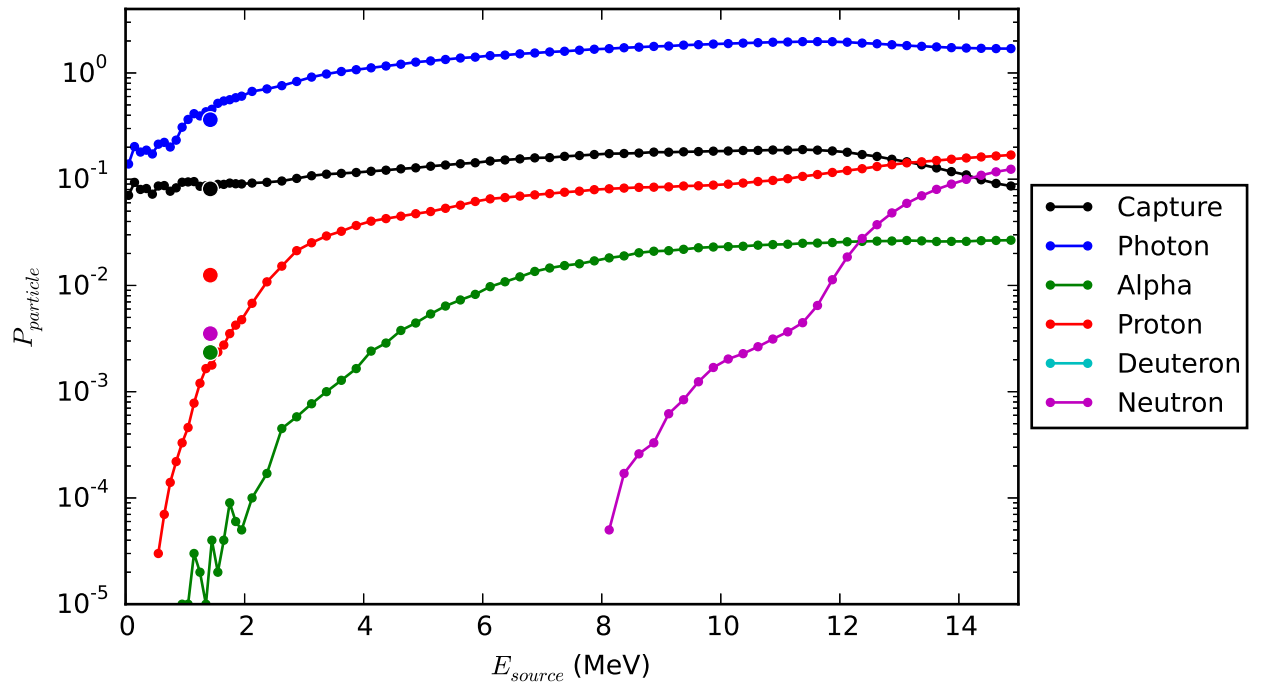


Figure C.24. Secondary particle creation and neutron capture probability for meteoric iron.

Table C.8. Reaction Q values (+) or threshold energies (-) for meteoric iron.

Isotope	Reaction						First Nuclear Exited State (MeV)	Mass Fraction
	(n, γ)	(n,p)	(n,d)	(n,t)	(n, α)	(n,2n)		
⁵⁴ Fe	9.298	0.596	-6.753	-12.658	0.844	-13.629	1.4082	.0348
⁵⁶ Fe	7.646	-2.445	-8.103	-12.143	0.326	-11.399	0.8468	.5503
⁵⁷ Fe	10.045	-1.426	-8.482	-9.514	2.399	-7.782	0.0144	.0132
⁵⁸ Ni	8.999	0.912	-6.051	-11.259	2.899	-12.429	2.4592	.2723
⁶⁰ Ni	7.820	-1.555	-7.431	-11.698	1.355	-11.579	1.3325	.1049
⁶¹ Ni	10.596	-0.031	-7.762	-9.018	3.580	-7.95	0.0674	.0046
⁶² Ni	6.838	-4.093	-9.058	-12.17	-0.442	-10.768	1.1730	.0145

Appendix D. Center Line Energy Deposition

The following two figures are centerline energy profiles for four initial simulations.

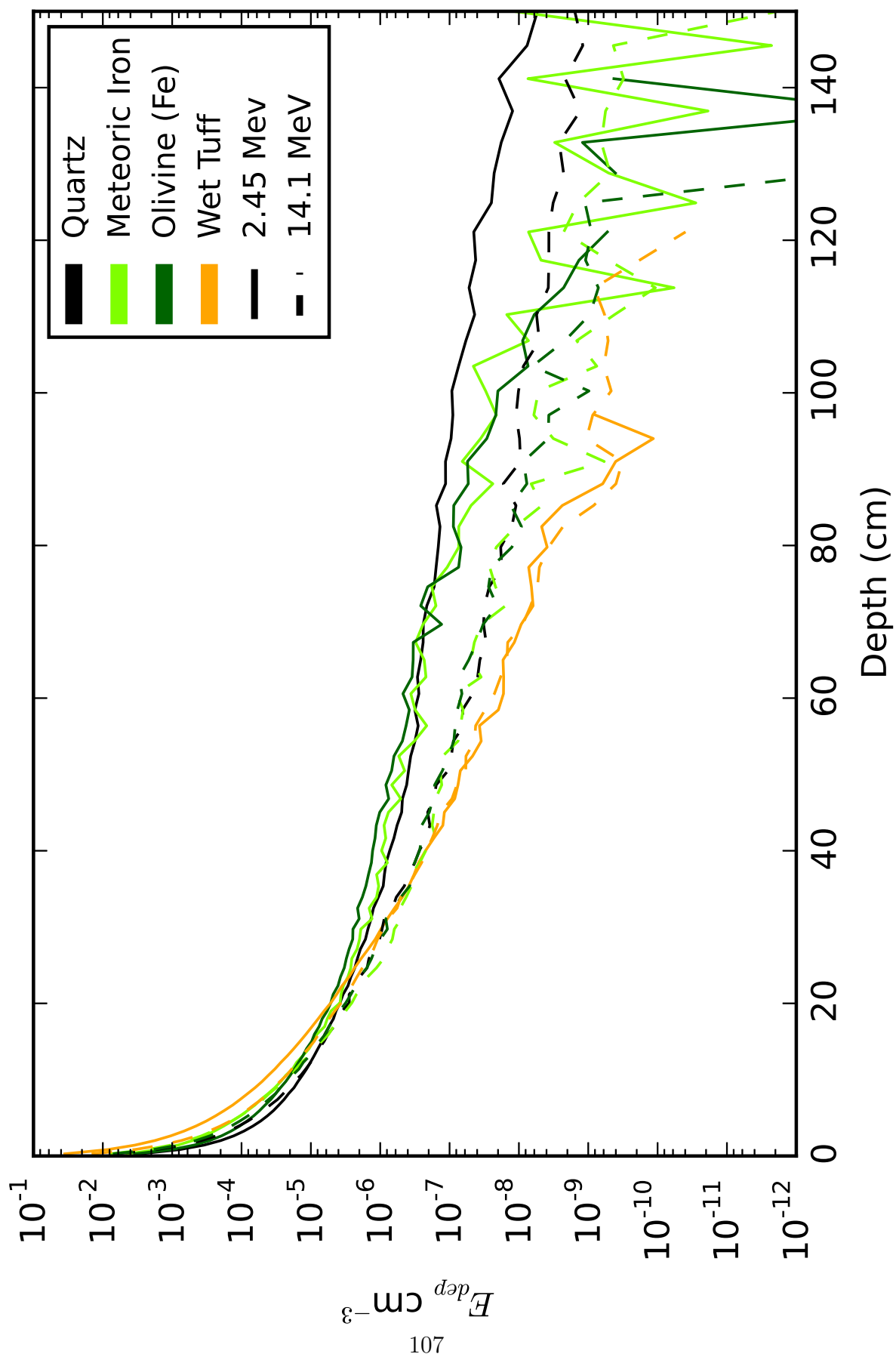


Figure D.1. Energy deposition contour centerline profile.

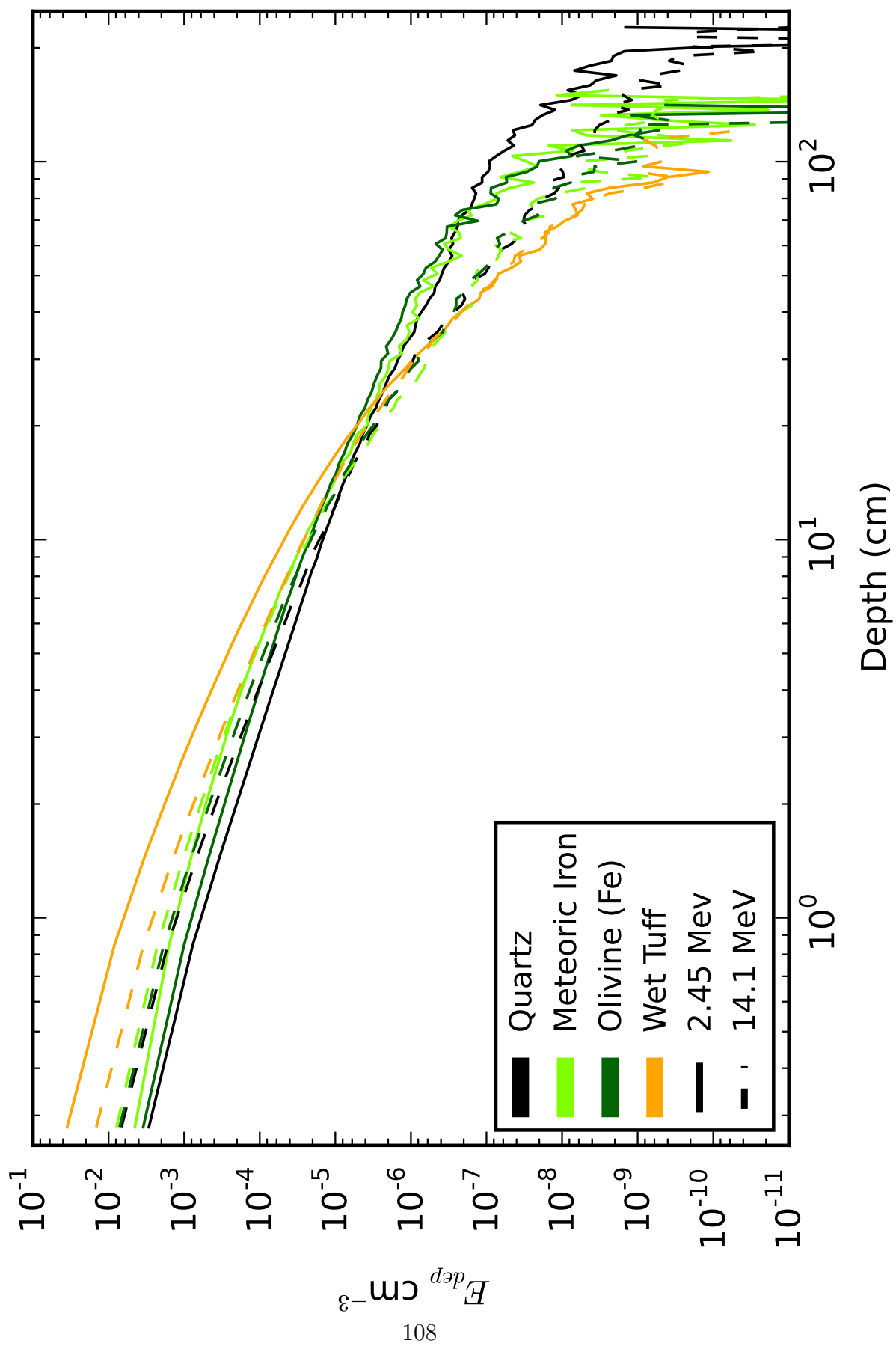


Figure D.2. Energy deposition contour centerline profile.

Appendix E. MCNP 2D Energy Deposition Profiles

Figures E.1 to E.24 are a series of energy deposition profiles in four materials for three neutron energies. For each material-neutron energy combination, the first figure is the energy deposition contour extending 31 cm from the surface and 31 cm from the z-axis. The second figure is the energy deposition contour extending 5 meters from the surface and 5 meters from the z-axis. The units are energy deposited per cm^3 of the total neutron yield.

E.1 Ice

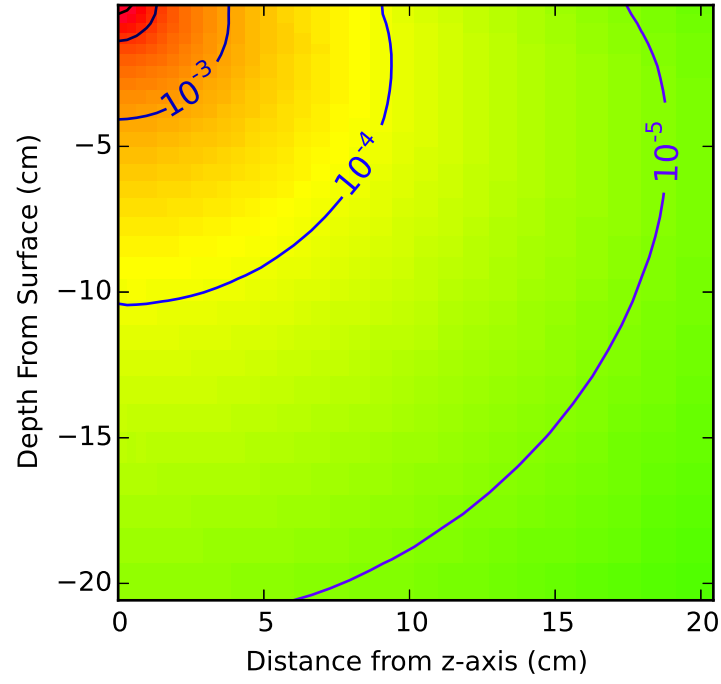


Figure E.1. Near surface energy contour in ice for a 2.45 MeV neutron source ($E_{dep}\text{cm}^{-3}Y_n^{-1}$).

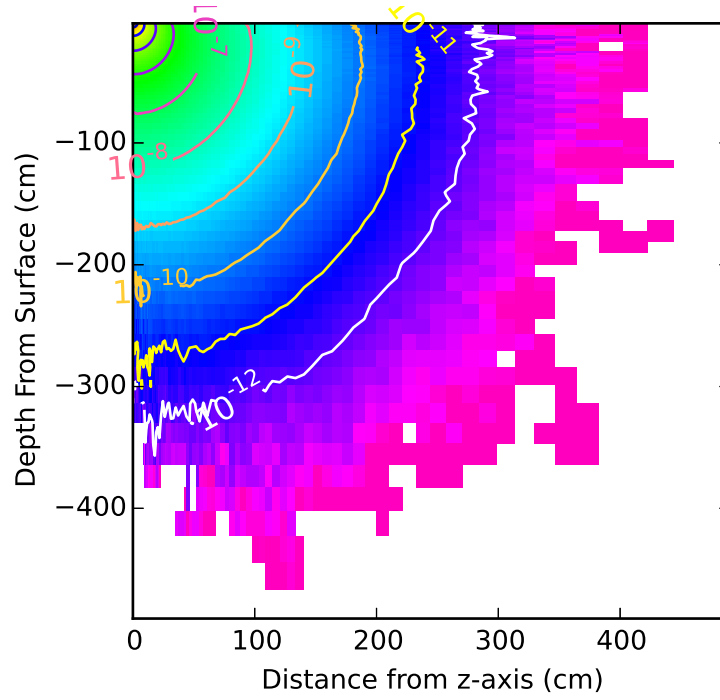


Figure E.2. Full energy contour in ice for a 2.45 MeV neutron source ($E_{dep}\text{cm}^{-3}Y_n^{-1}$).

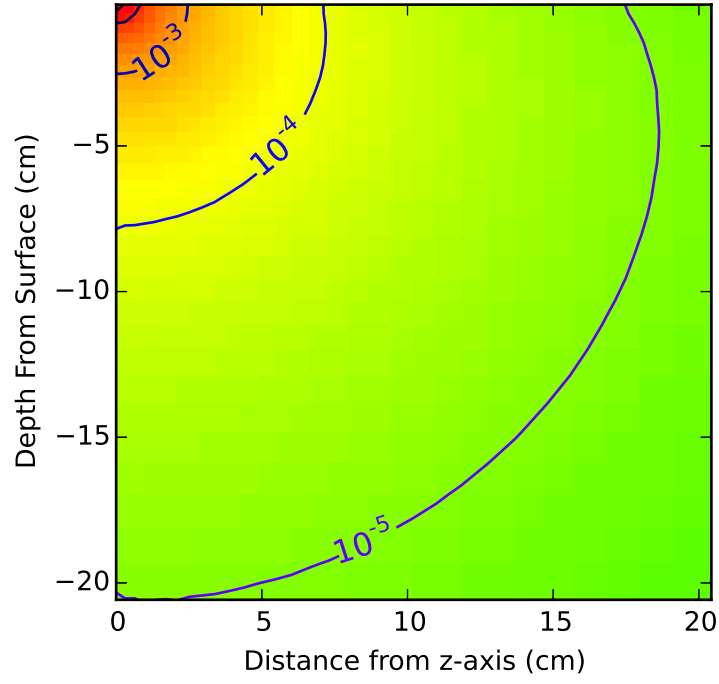


Figure E.3. Near surface energy contour in ice for a 14.1 MeV neutron source ($E_{dep}\text{cm}^{-3}Y_n^{-1}$).

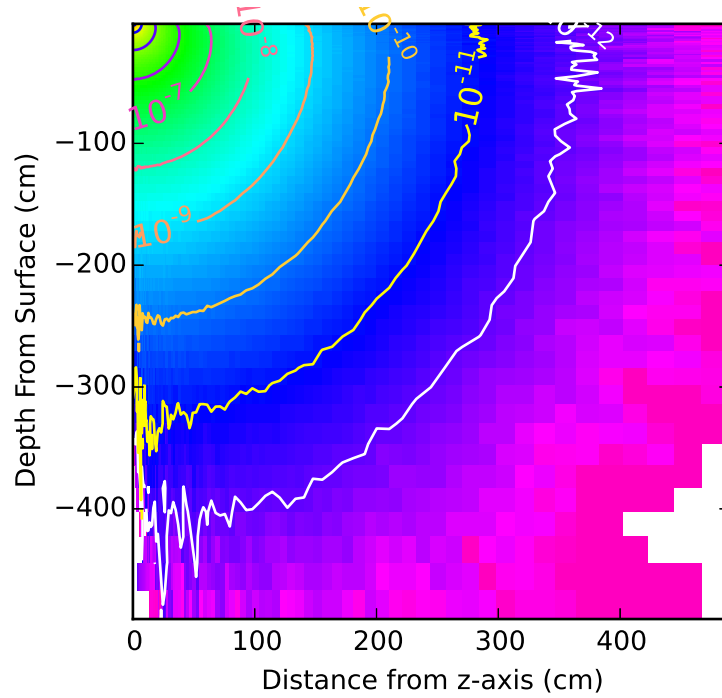


Figure E.4. Full energy contour in ice for a 14.1 MeV source ($E_{dep}\text{cm}^{-3}Y_n^{-1}$).

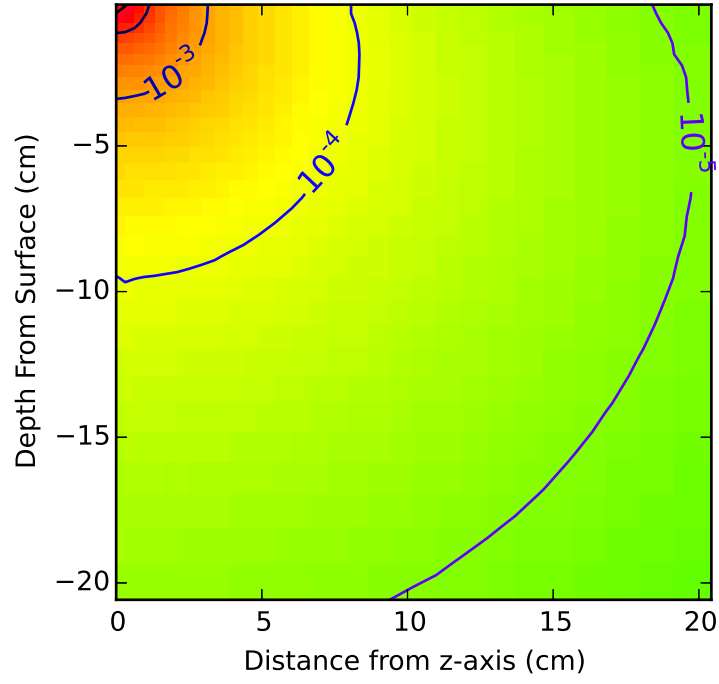


Figure E.5. Near surface energy contour in ice for a thermonuclear neutron spectrum ($E_{dep}\text{cm}^{-3}Y_n^{-1}$).

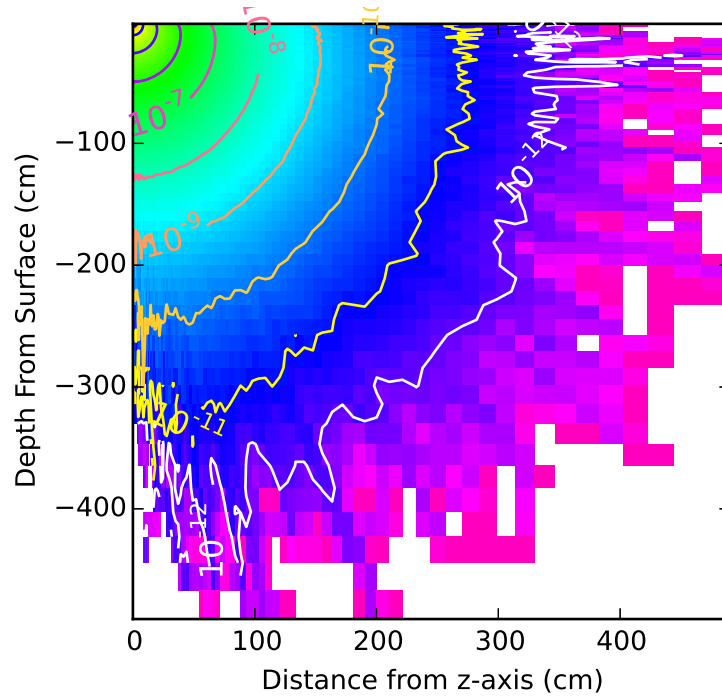


Figure E.6. Full energy contour in ice for a thermonuclear neutron spectrum ($E_{dep}\text{cm}^{-3}Y_n^{-1}$).

E.2 Quartz

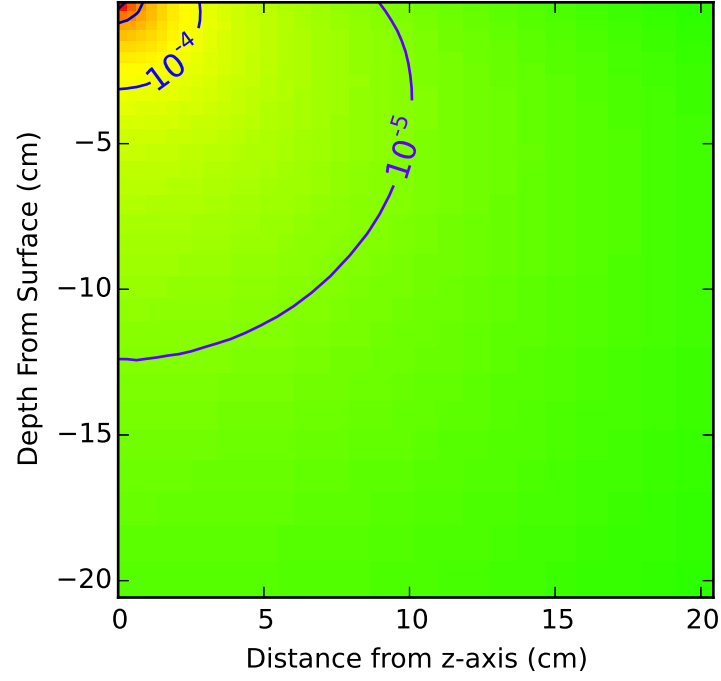


Figure E.7. Near surface energy contour in quartz for a 2.45 MeV neutron source ($E_{dep}\text{cm}^{-3}Y_n^{-1}$).

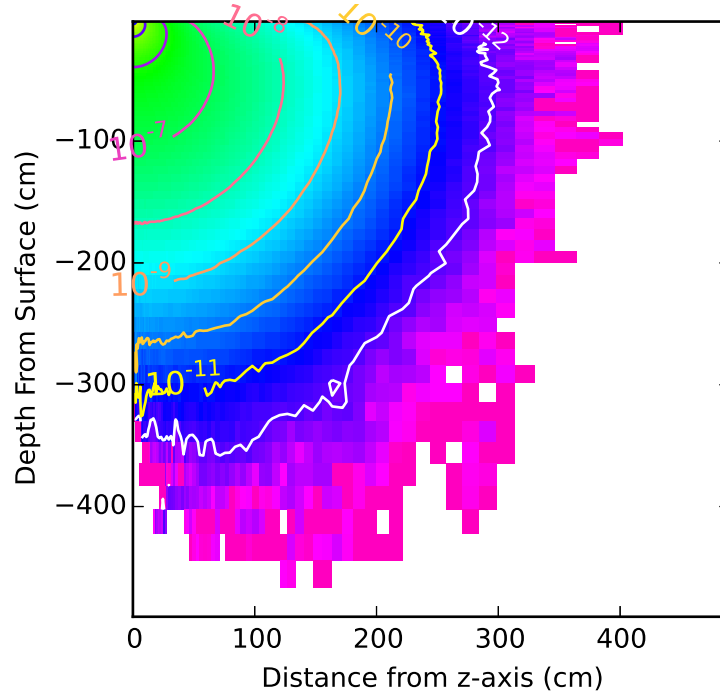


Figure E.8. Full energy contour in quartz for a 2.45 MeV neutron source ($E_{dep}\text{cm}^{-3}Y_n^{-1}$).

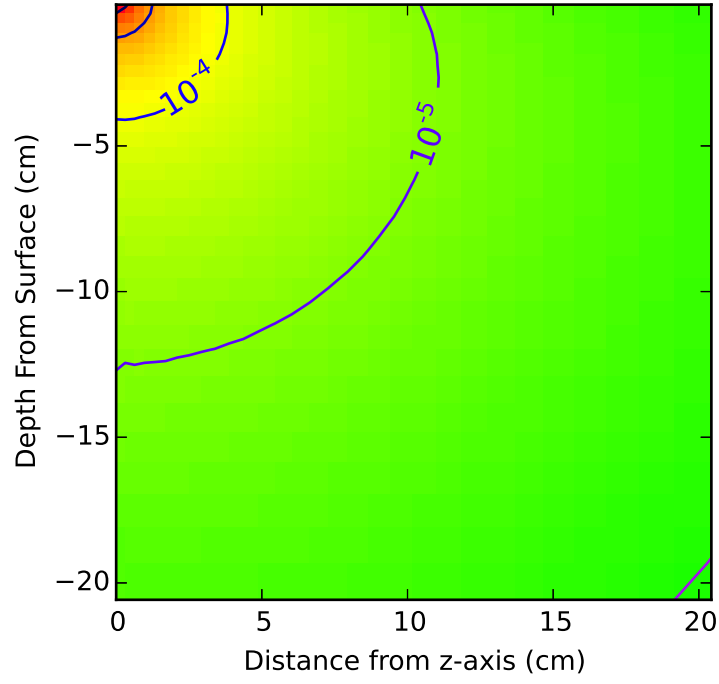


Figure E.9. Near surface energy contour in quartz for a 14.1 MeV neutron source ($E_{dep}\text{cm}^{-3}Y_n^{-1}$).

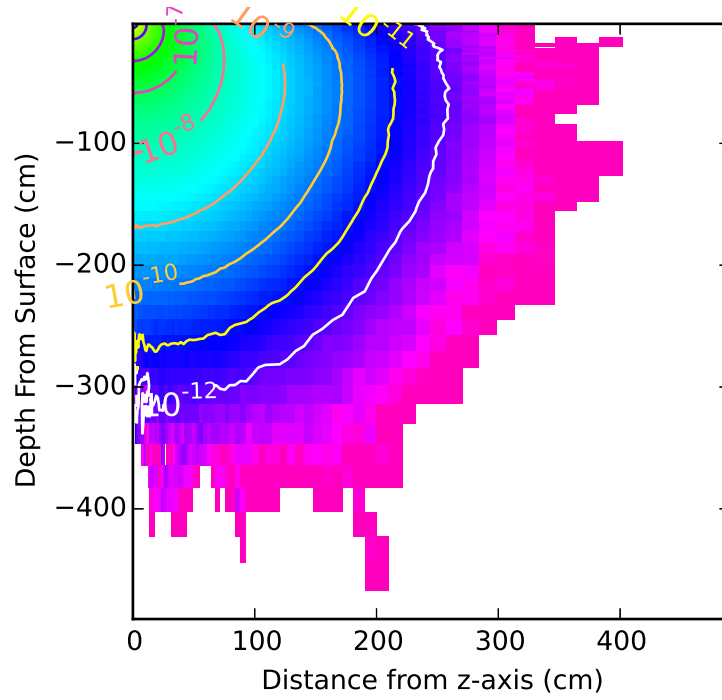


Figure E.10. Full energy contour in quartz for a 14.1 MeV source ($E_{dep}\text{cm}^{-3}Y_n^{-1}$).

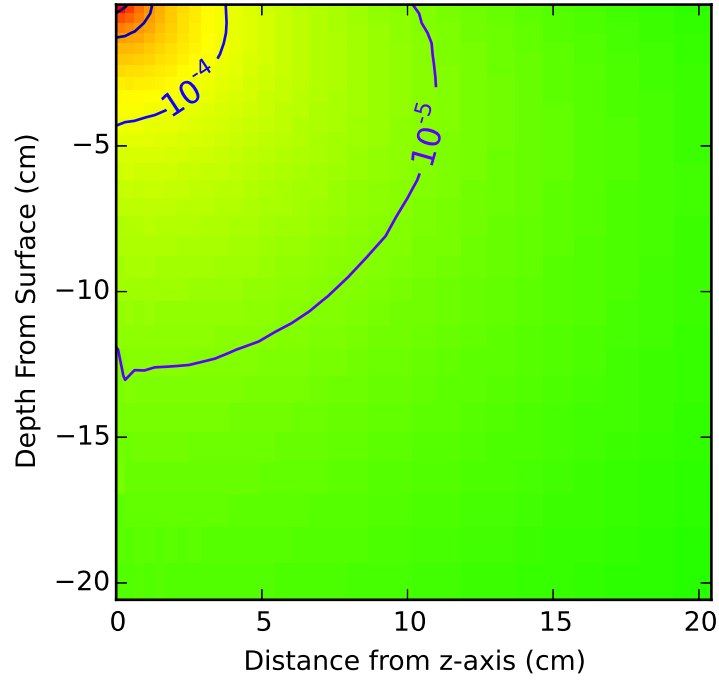


Figure E.11. Near surface energy contour in quartz for a thermonuclear neutron spectrum ($E_{dep}\text{cm}^{-3}Y_n^{-1}$).

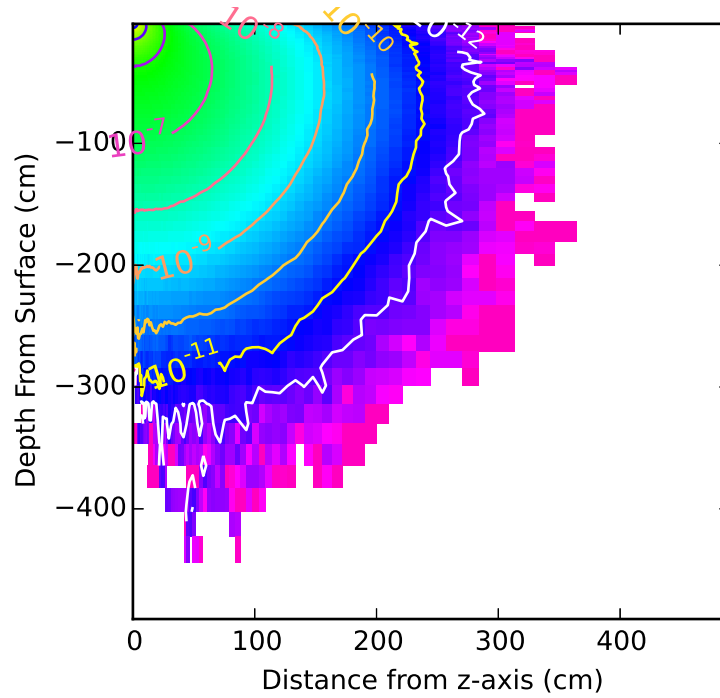


Figure E.12. Full energy contour in quartz for a thermonuclear neutron spectrum ($E_{dep}\text{cm}^{-3}Y_n^{-1}$).

E.3 Allende Meteorite

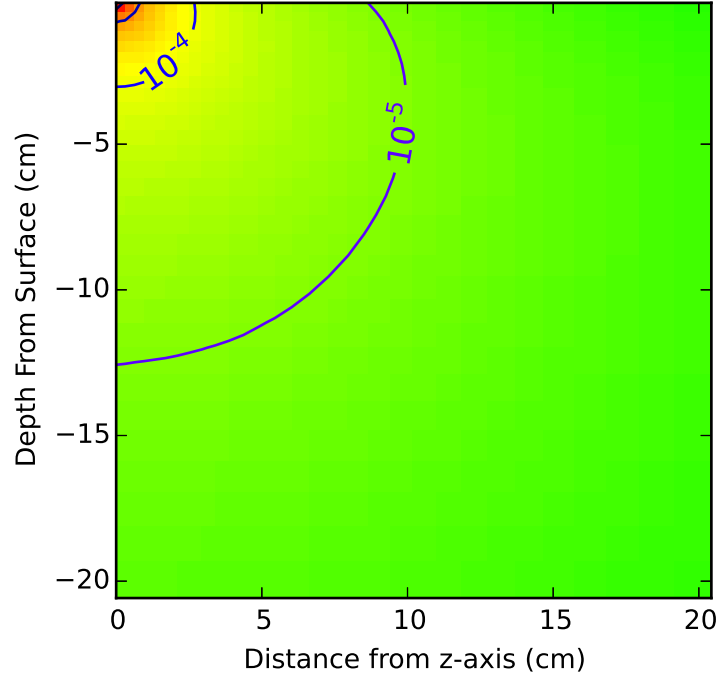


Figure E.13. Near surface energy contour in Allende Meteorite for a 2.45 MeV neutron source ($E_{dep}\text{cm}^{-3}Y_n^{-1}$).

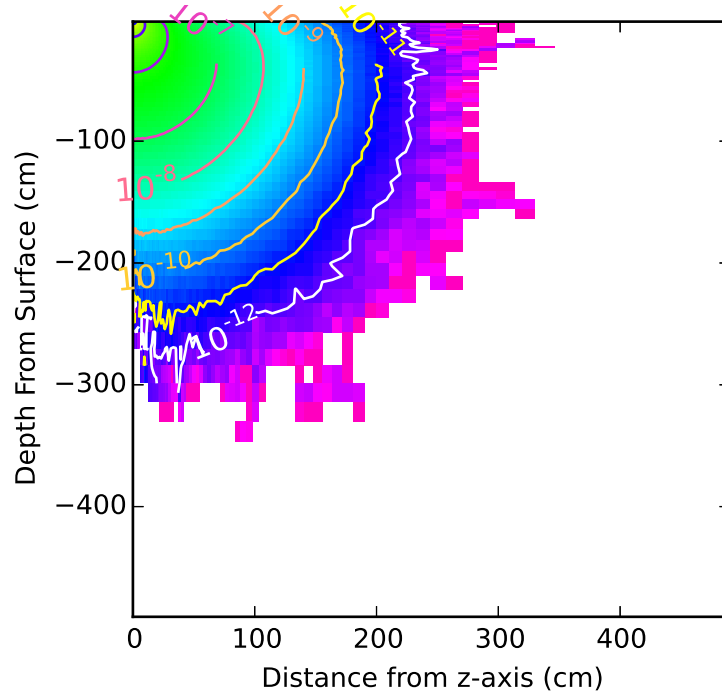


Figure E.14. Full energy contour in Allende Meteorite for a 2.45 MeV neutron source ($E_{dep}\text{cm}^{-3}Y_n^{-1}$).

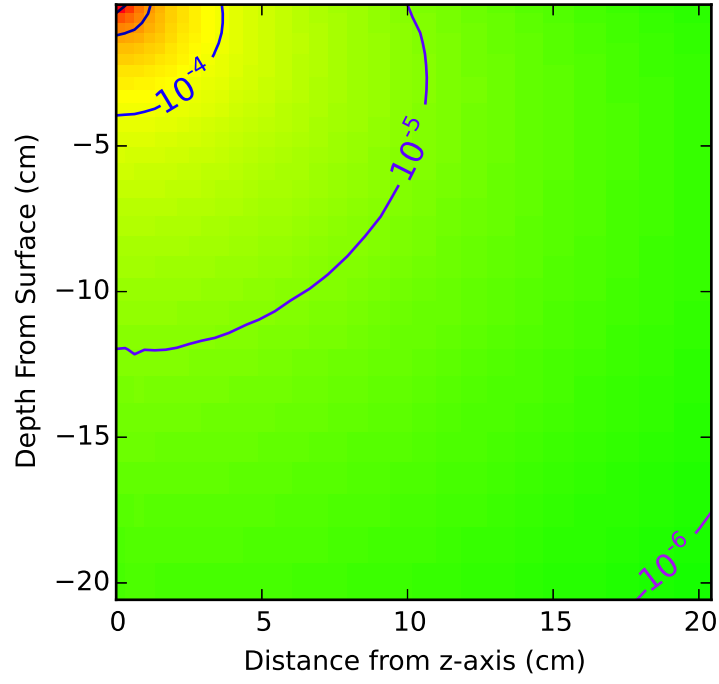


Figure E.15. Near surface energy contour in Allende Meteorite for a 14.1 MeV neutron source ($E_{dep}\text{cm}^{-3}Y_n^{-1}$).

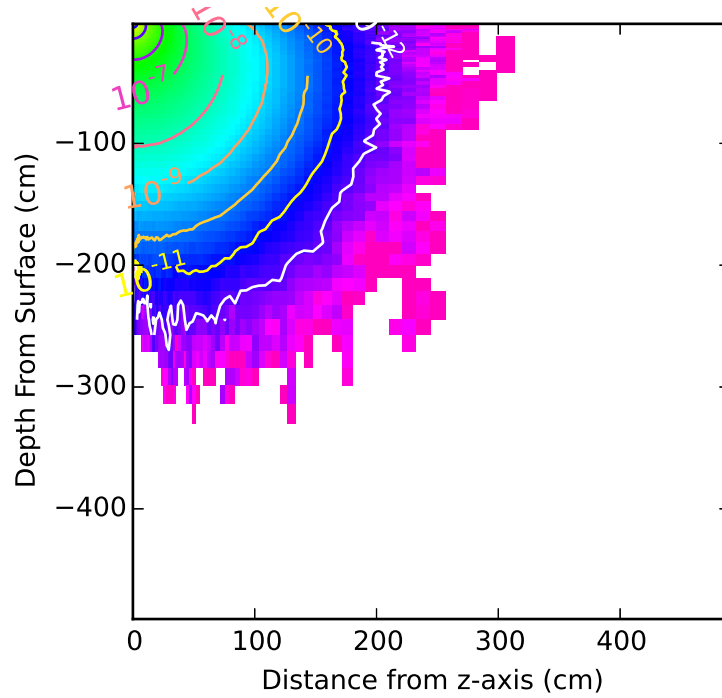


Figure E.16. Full energy contour in Allende Meteorite for a 14.1 MeV source ($E_{dep}\text{cm}^{-3}Y_n^{-1}$).

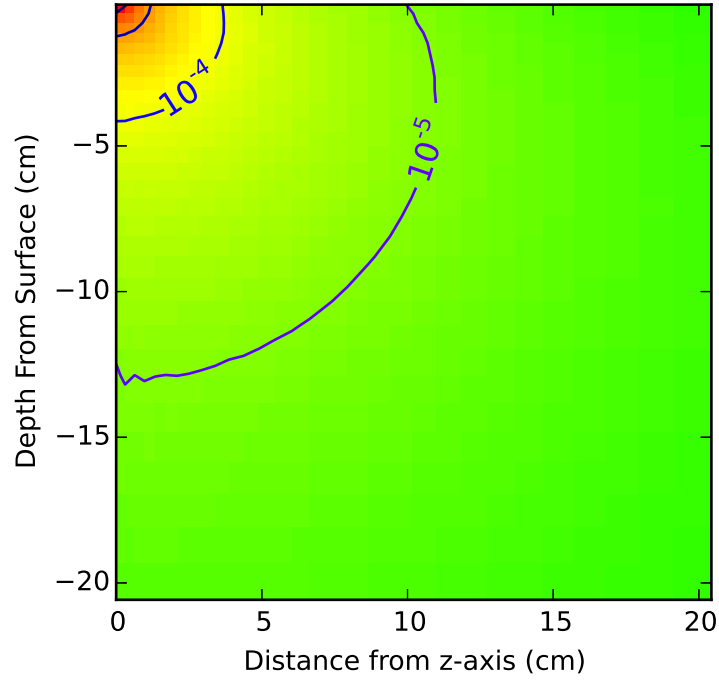


Figure E.17. Near surface energy contour in Allende Meteorite for a thermonuclear neutron spectrum ($E_{dep}\text{cm}^{-3}Y_n^{-1}$).

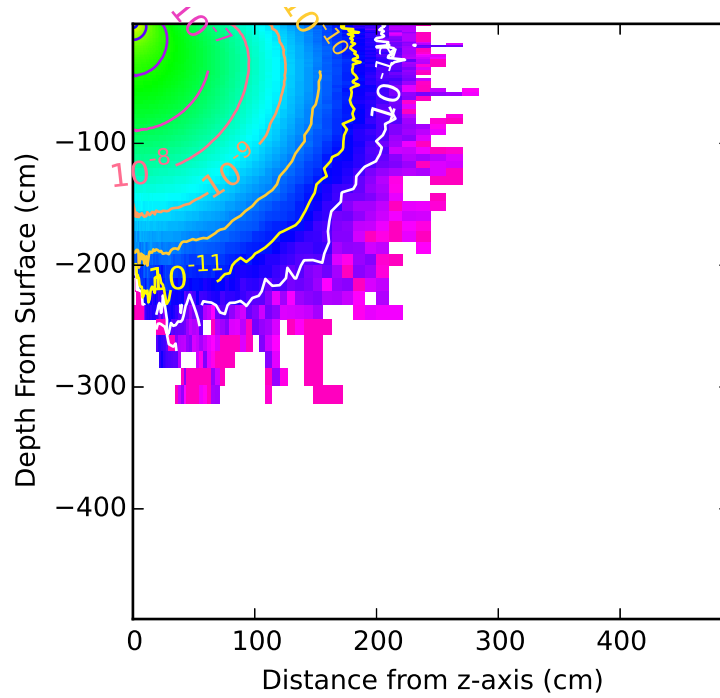


Figure E.18. Full energy contour in Allende Meteorite for a thermonuclear neutron spectrum ($E_{dep}\text{cm}^{-3}Y_n^{-1}$).

E.4 Meteoric Iron

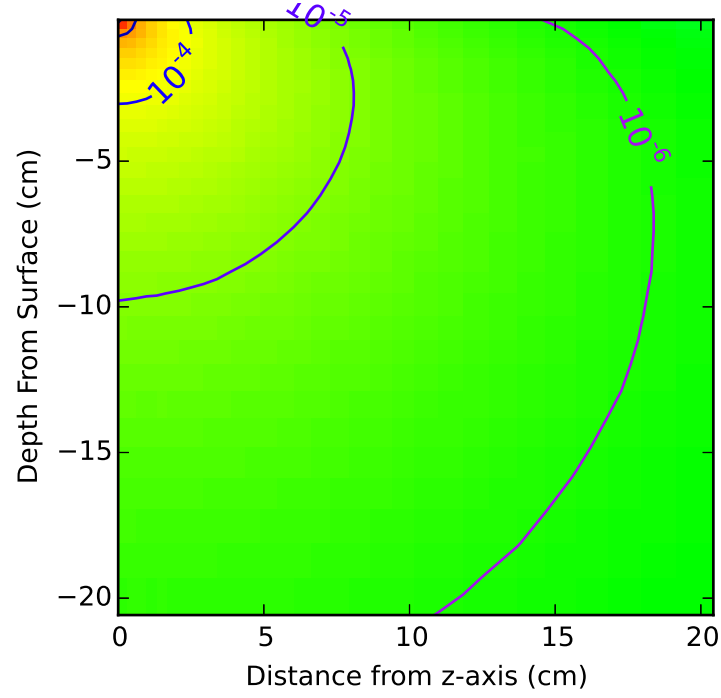


Figure E.19. Near surface energy contour in meteoric iron for a 2.45 MeV neutron source ($E_{dep}\text{cm}^{-3}Y_n^{-1}$).

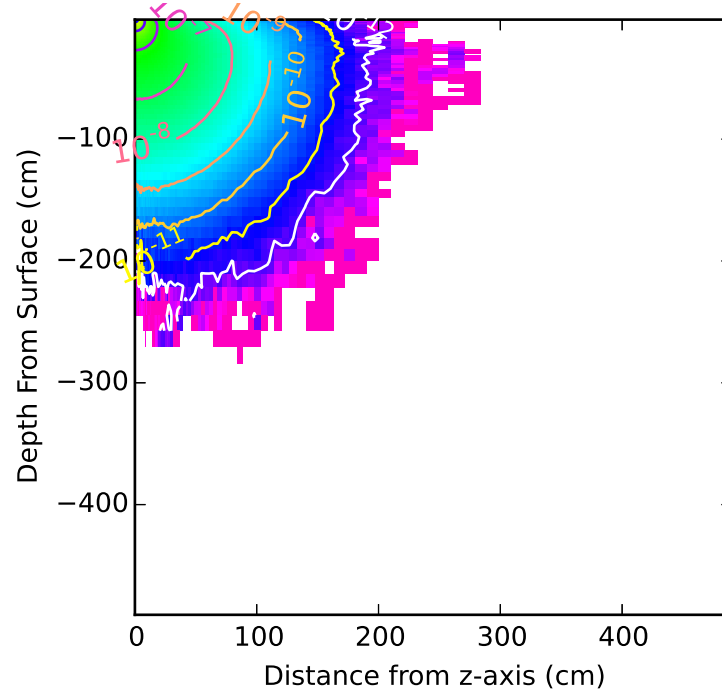


Figure E.20. Full energy contour in meteoric iron for a 2.45 MeV neutron source ($E_{dep}\text{cm}^{-3}Y_n^{-1}$).

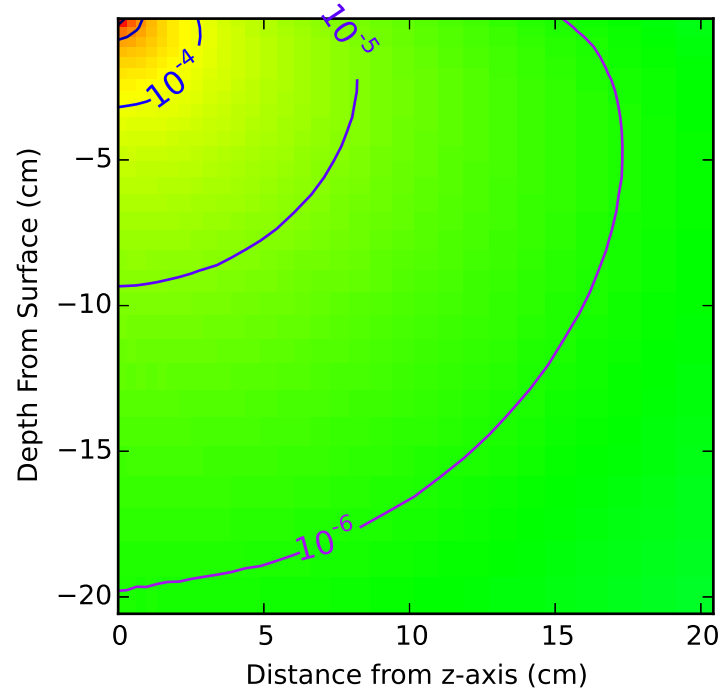


Figure E.21. Near surface energy contour in meteoric iron for a 14.1 MeV neutron source ($E_{dep}\text{cm}^{-3}Y_n^{-1}$).

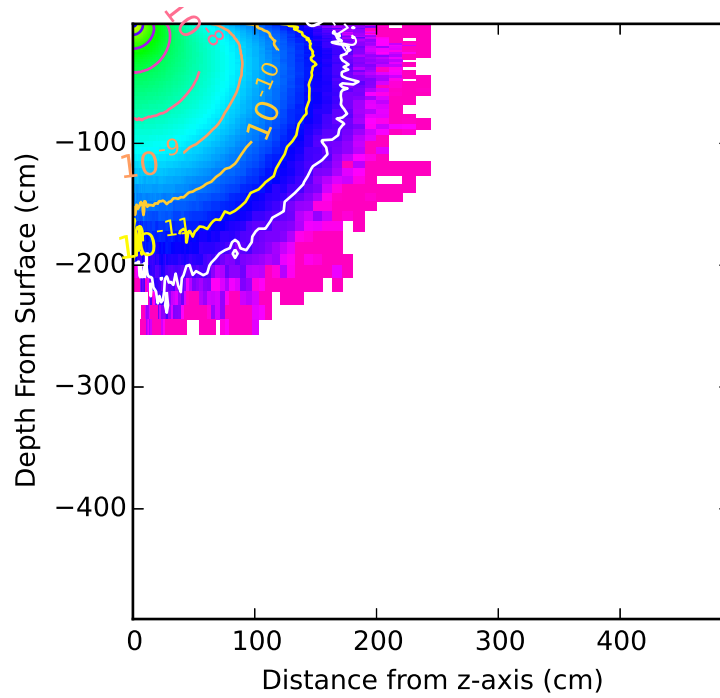


Figure E.22. Full energy contour in meteoric iron for a 14.1 MeV source ($E_{dep}\text{cm}^{-3}Y_n^{-1}$).

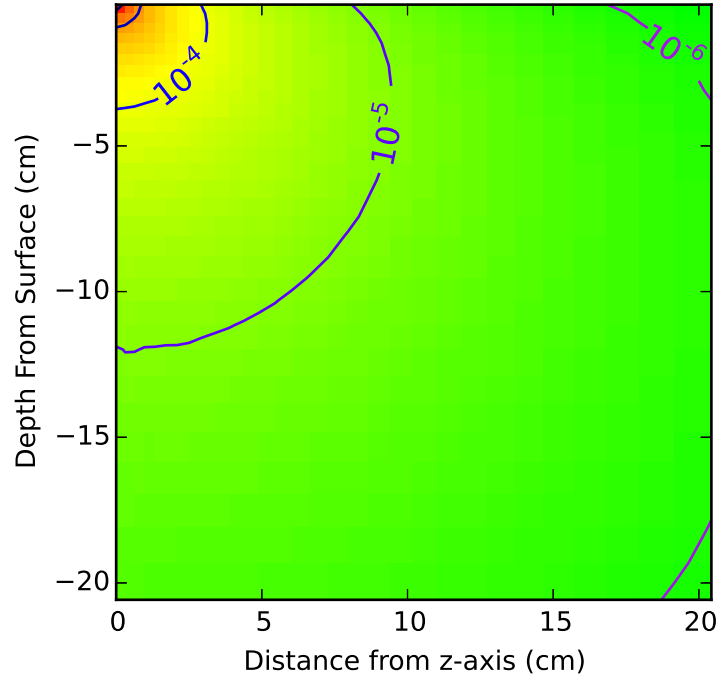


Figure E.23. Near surface energy contour in meteoric iron for a thermonuclear neutron spectrum ($E_{dep}\text{cm}^{-3}Y_n^{-1}$).

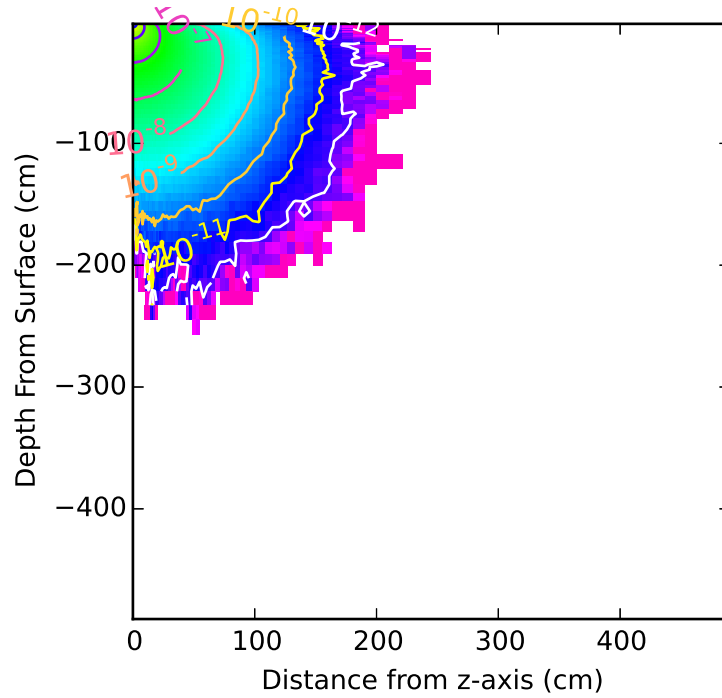


Figure E.24. Full energy contour in meteoric iron for a thermonuclear neutron spectrum ($E_{dep}\text{cm}^{-3}Y_n^{-1}$).

Appendix F. Height of Burst Variation

Figures F.1 to F.8 are a series of energy deposition profiles in quartz, where the neutron source varies from 0.01 cm to 800 cm above the surface of the asteroid. The units are energy per gram of the total neutron yield.

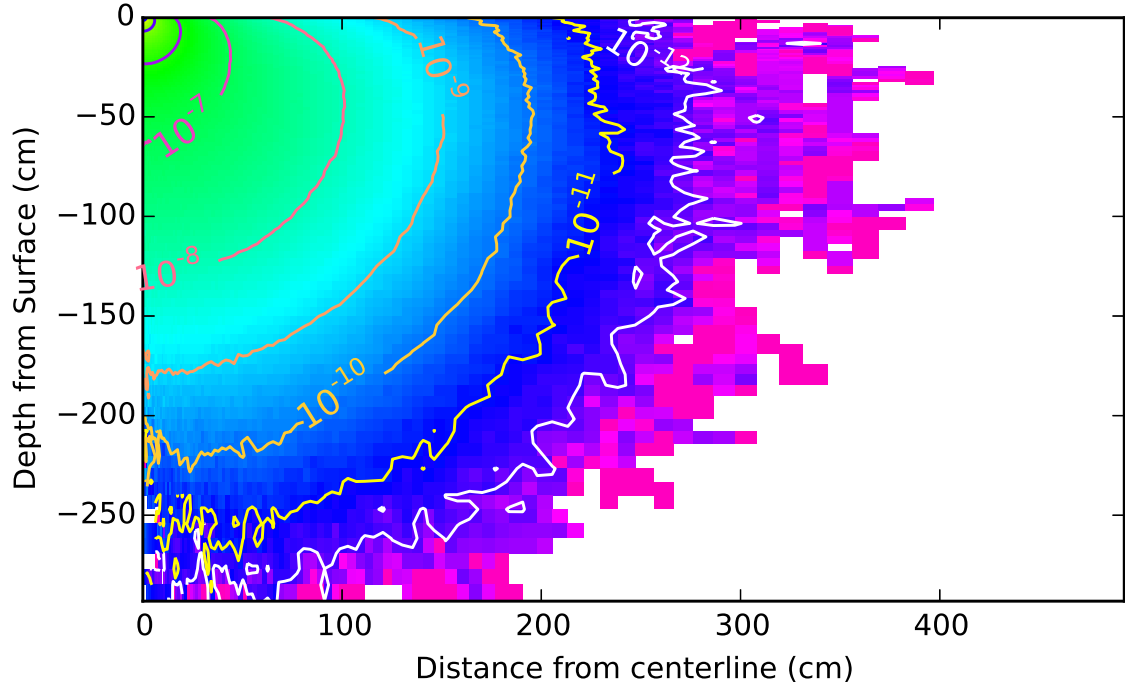


Figure F.1. Energy deposition profiles in quartz for a neutron source located 0.01 cm above the asteroid surface ($E_{dep}g^{-1}Y_n^{-1}$).

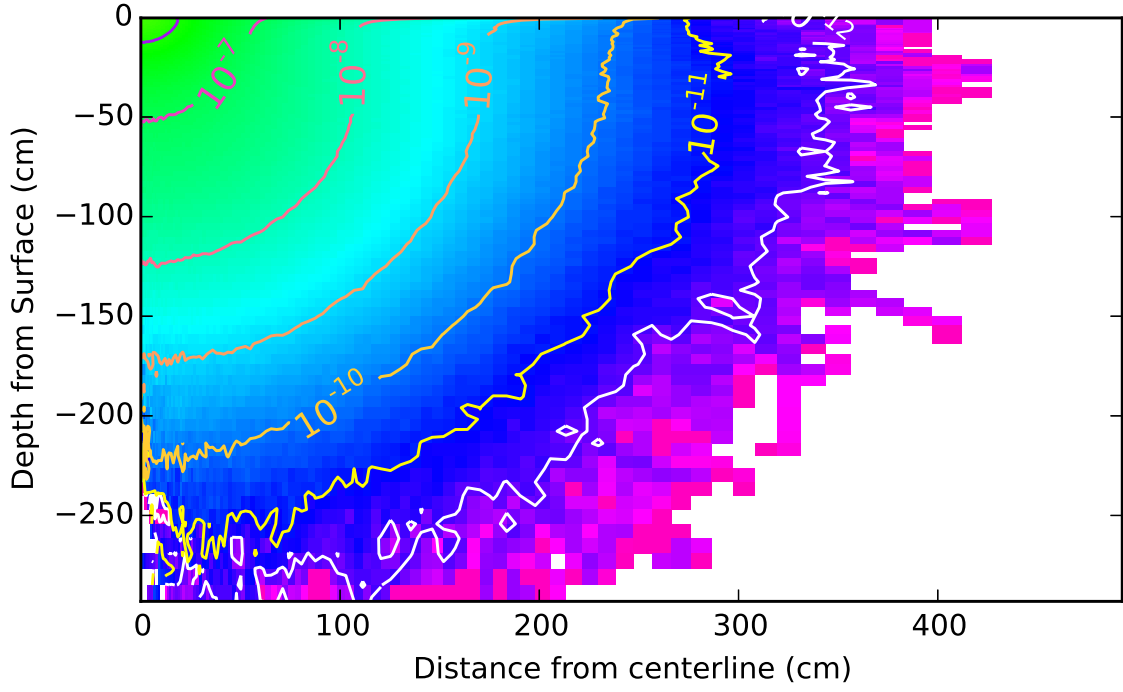


Figure F.2. Energy deposition profiles in quartz for a neutron source located 12.5 cm above the asteroid surface ($E_{dep}g^{-1}Y_n^{-1}$).

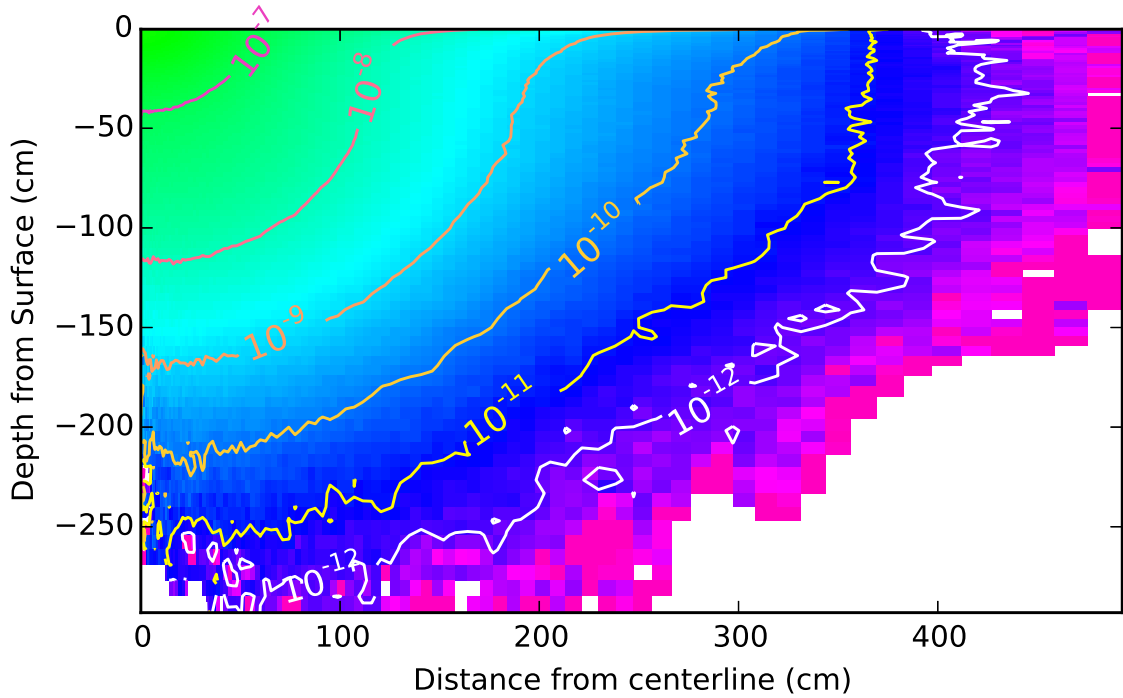


Figure F.3. Energy deposition profiles in quartz for a neutron source located 25 cm above the asteroid surface ($E_{dep}g^{-1}Y_n^{-1}$).

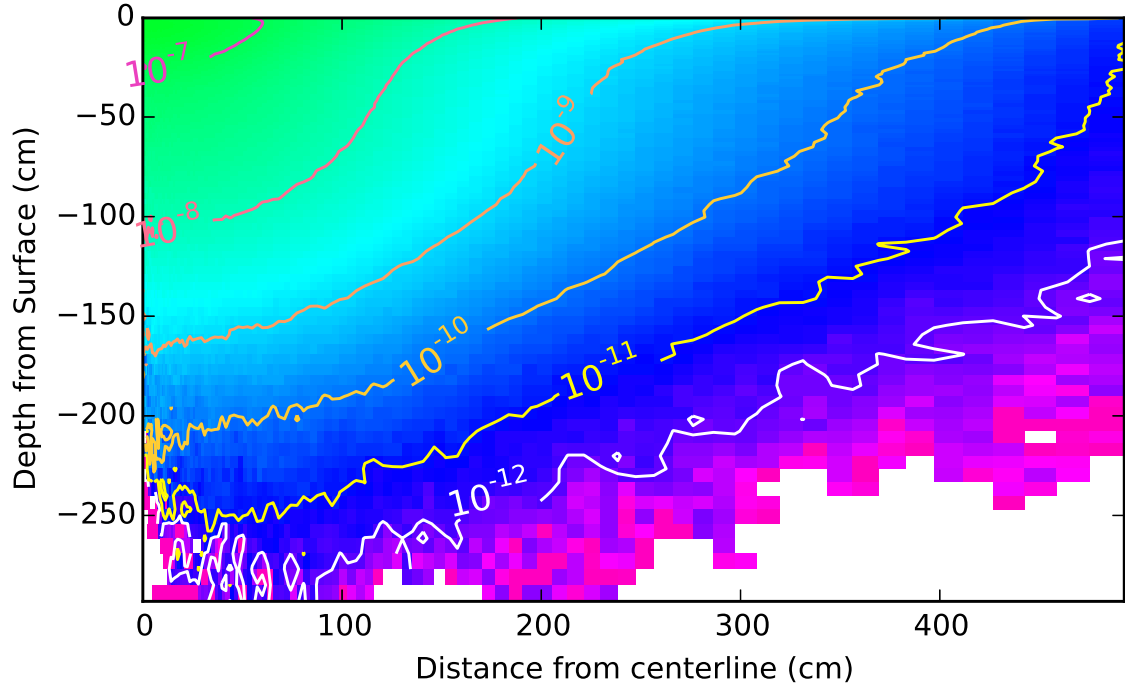


Figure F.4. Energy deposition profiles in quartz for a neutron source located 50 cm above the asteroid surface ($E_{dep}g^{-1}Y_n^{-1}$).

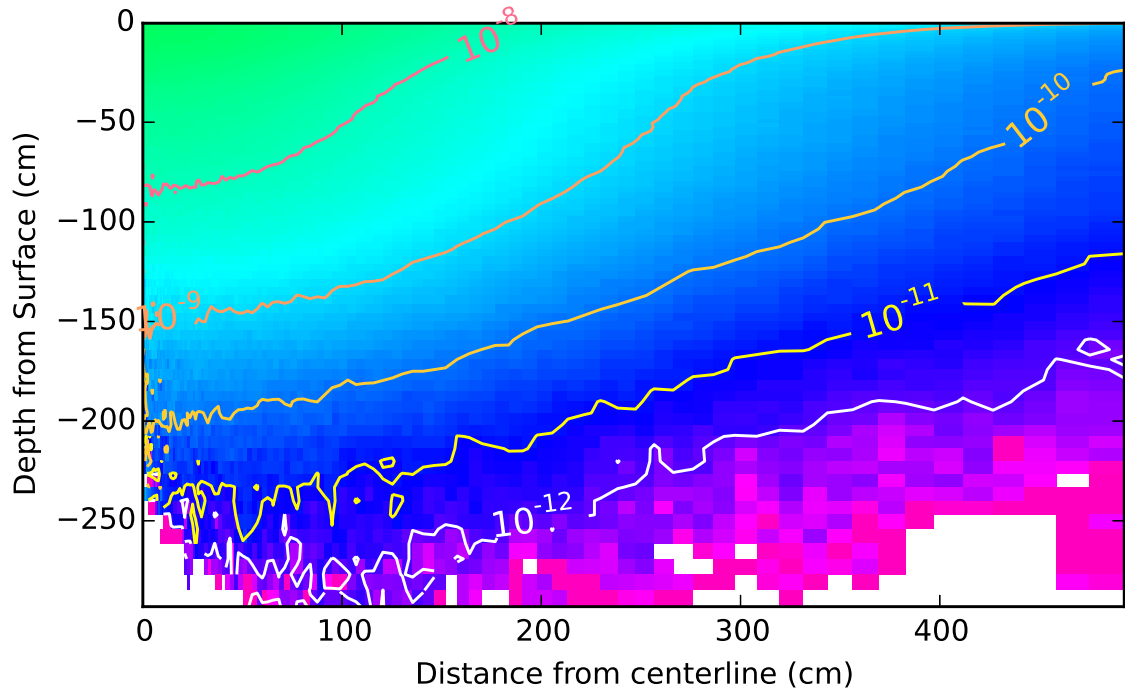


Figure F.5. Energy deposition profiles in quartz for a neutron source located 100 cm above the asteroid surface ($E_{dep}g^{-1}Y_n^{-1}$).

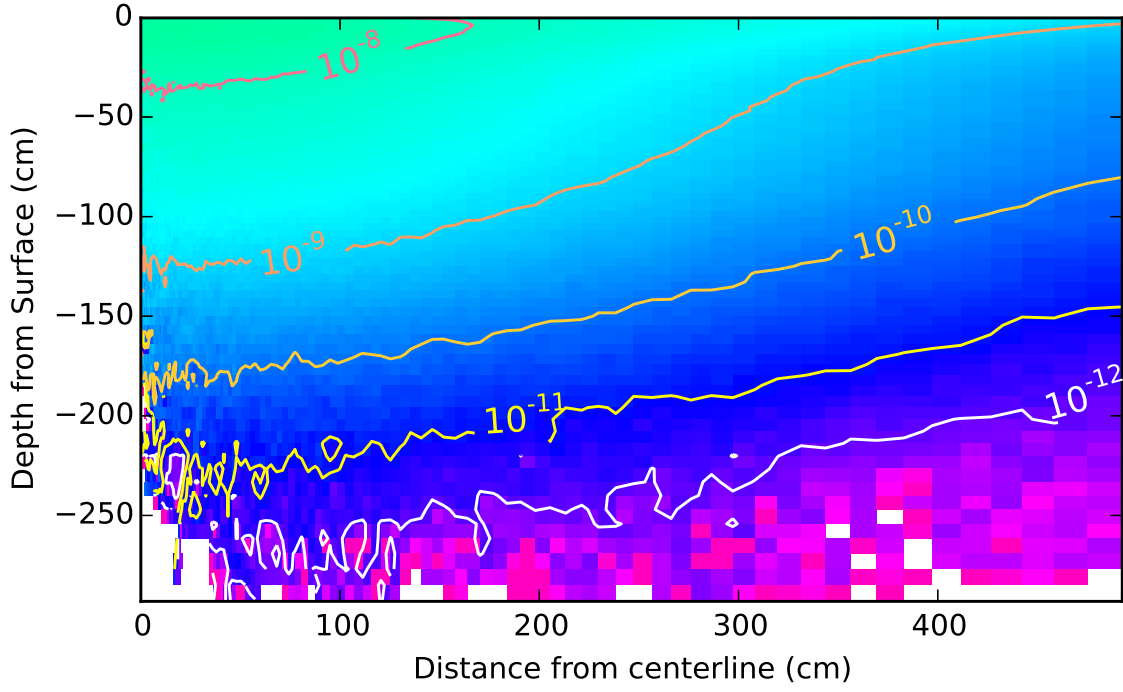


Figure F.6. Energy deposition profiles in quartz for a neutron source located 200 cm above the asteroid surface ($E_{dep}g^{-1}Y_n^{-1}$).

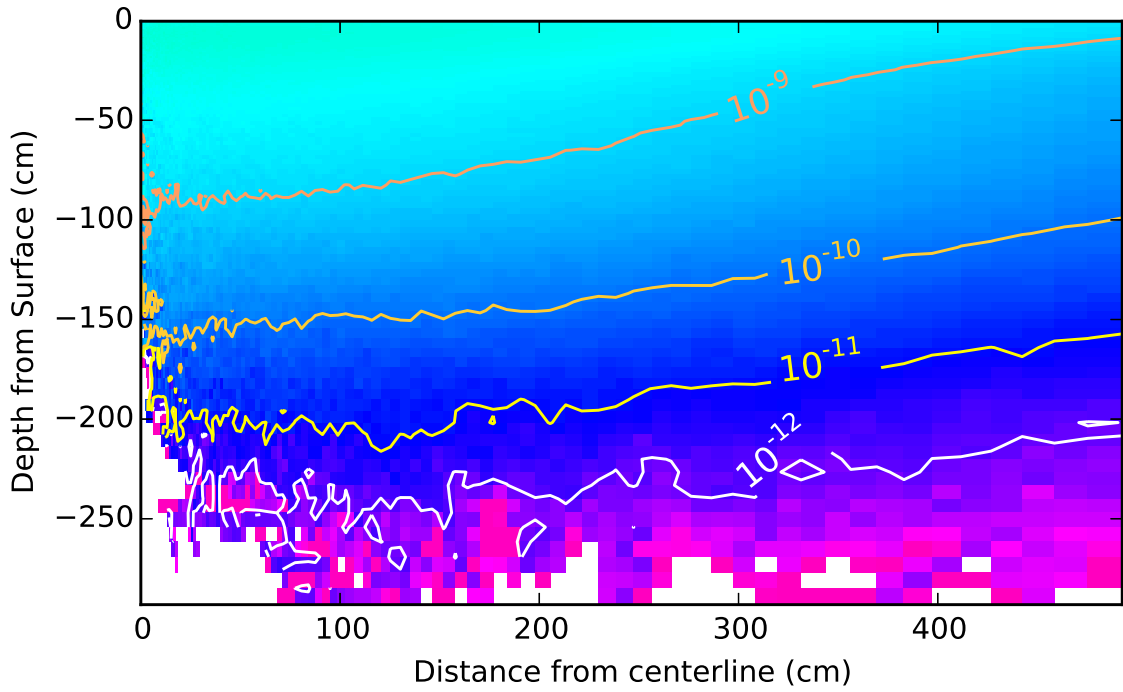


Figure F.7. Energy deposition profiles in quartz for a neutron source located 400 cm above the asteroid surface ($E_{dep}g^{-1}Y_n^{-1}$).

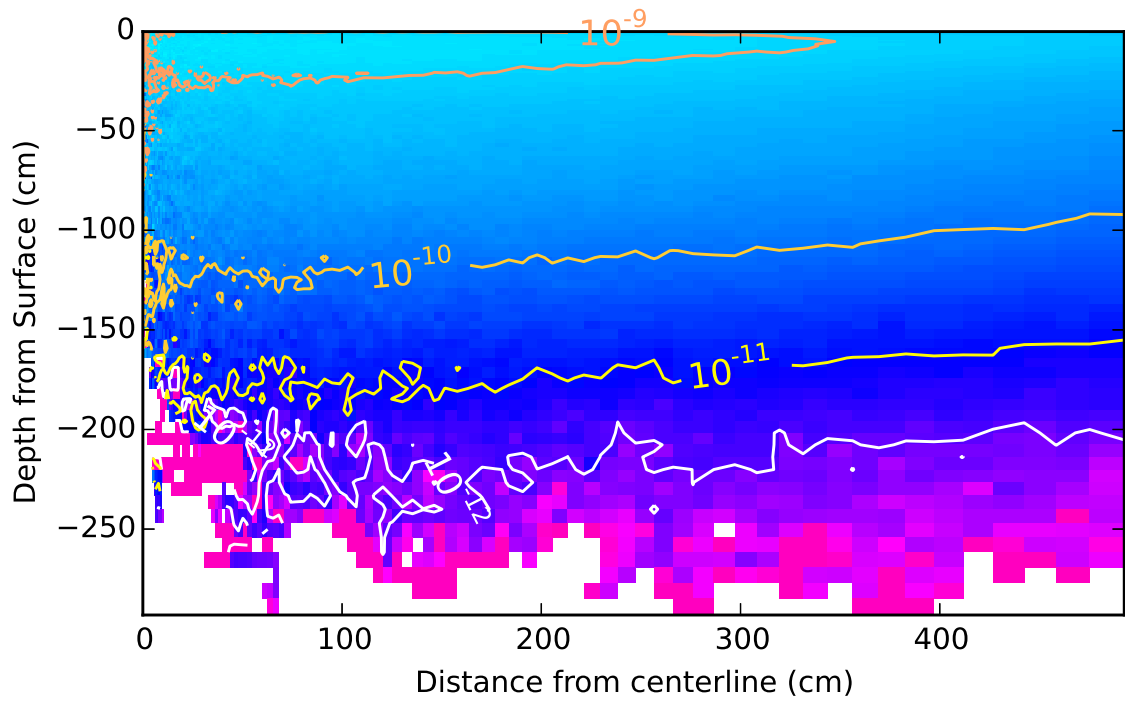


Figure F.8. Energy deposition profiles in quartz for a neutron source located 800 cm above the asteroid surface ($E_{dep}g^{-1}Y_n^{-1}$).

Appendix G. MCNP Physics Model Discrepancies

Initial MCNP simulations did not specify the isotopic composition of every material. The material cards used in these cases are shown in Figure G.1. Some of the simulation results seemed unusual, and as part of the investigation to explain the results, it was determined that without an isotopic composition specified, MCNP would use physics models instead of cross section tables to determine the material reaction cross sections. Simulations were then re-run with updated material cards where isotopic composition of every element were specified. These updated material cards are shown in Figure G.2. A comparison between the results using the physics models and cross section data are shown in Figures G.3-G.7.

```
c olivine
m10 8016.70c -0.4549 12000.70c -0.3455 14028.70c -0.1996

c ice
m10 8016.70c 1 1000.70c 2

c Allende Meteorite
m10 8016.70c -0.6663 12000.70c -0.1477 13027.70c -0.0170
    14028.70c -0.1605 20000.70c -0.0184 26056.70c -0.2351
    28058.70c -0.0095 28060.70c -0.0032

c granite
m10 8016.70c -0.4835 12000.70c -0.0043 13027.70c -0.0763
    14028.70c -0.0763 19000.70c -0.0342 11023.70c -0.0274
    20000.70c -0.0130 26056.70c -0.0216
mpn10 8016 12024 13027 14028 20040 11023 20040 26056
```

Figure G.1. Material cards containing unspecified isotopic compositions.

```

c olivine (Mg)
m10 8016.70c -0.4549 12024.70c -0.2729 12025.70c -0.0346
    12026.70c -0.0380 14028.70c -0.1996

c ice
m10 8016.70c 1 1001.70c 2

c Allende Meteorite
m10 8016.70c -0.6663 12024.70c -0.1167 12025.70c -0.0148
    12026.70c -0.0163 13027.70c -0.0170 14028.70c -0.1605
    20040.70c -0.0184 26056.70c -0.2351 28058.70c -0.0095
    28060.70c -0.0032

c granite
m10 8016.70c -0.4835 12024.70c -0.0043 13027.70c -0.0763
    14028.70c -0.0763 19039.70c -0.0319 19041.70c -0.0023
    11023.70c -0.0274 20040.70c -0.0130 26056.70c -0.0216
mpn10 8016 12024 13027 14028 20040 20040 11023 20040 26056

```

Figure G.2. Material cards with all isotopic compositions specified.

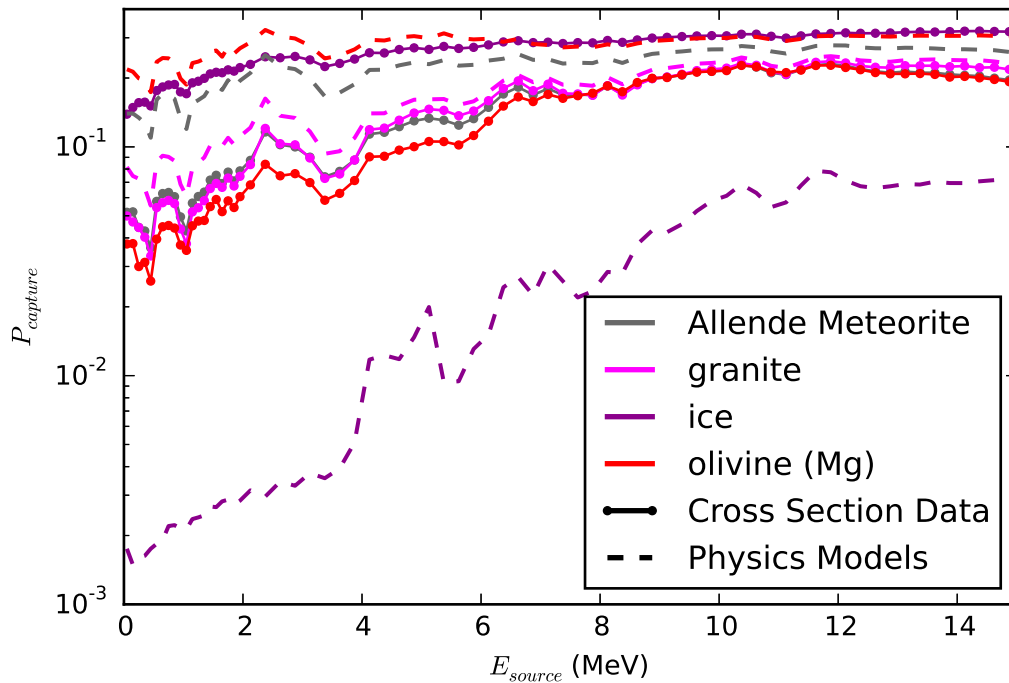


Figure G.3. Comparison of fraction of source neutrons captured using physics models and cross section tables for a surface burst.

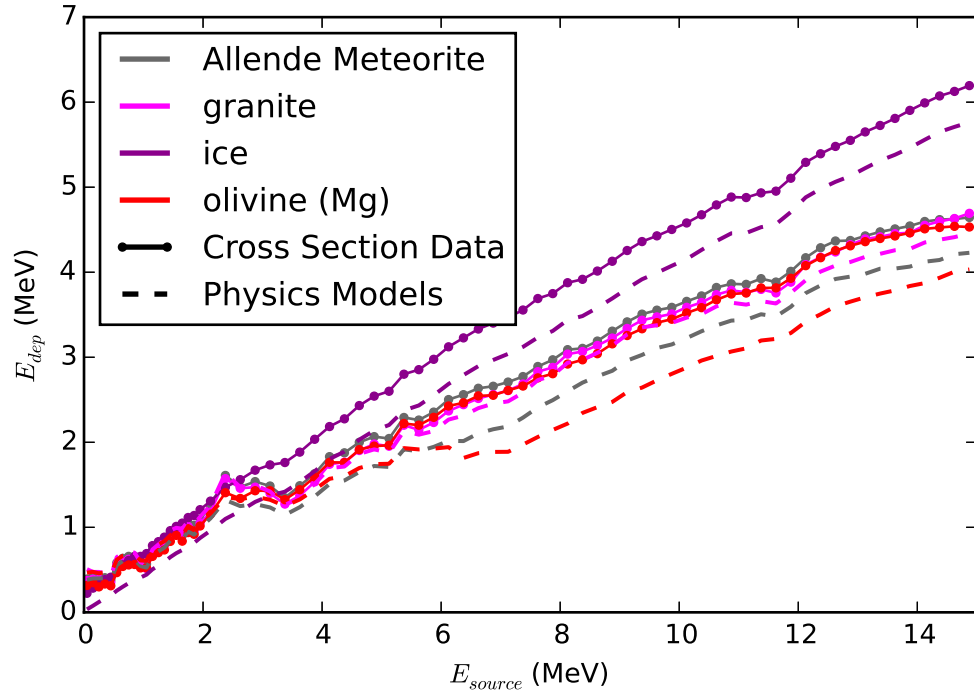


Figure G.4. Comparison of energy deposited per neutron using physics models and cross section tables for a surface burst.

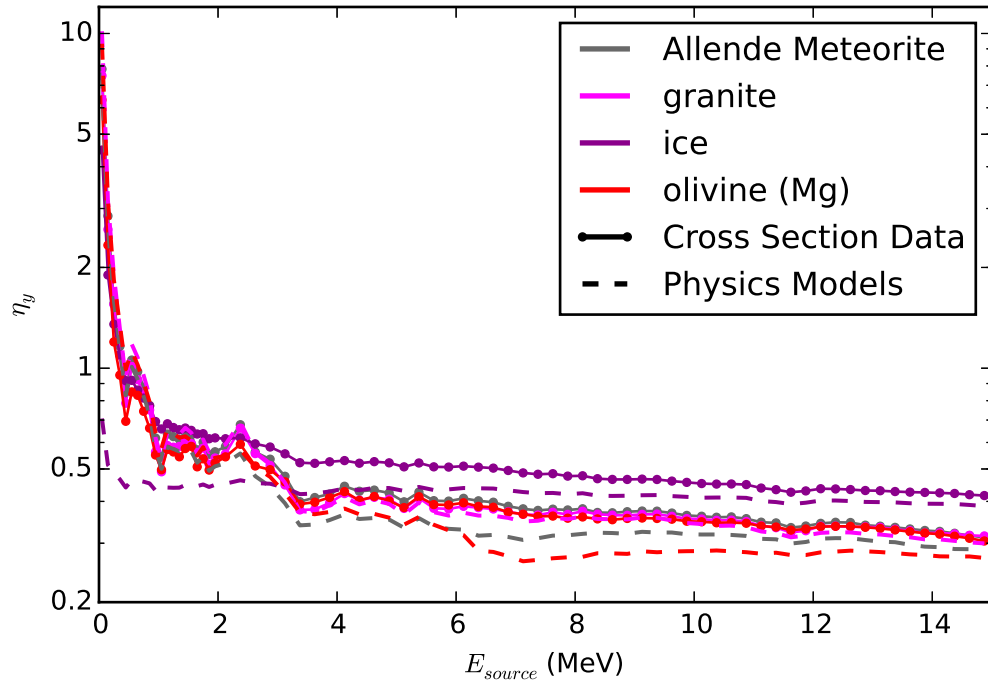


Figure G.5. Comparison of neutron yield coupling efficiency using physics models and cross section tables for a surface burst.

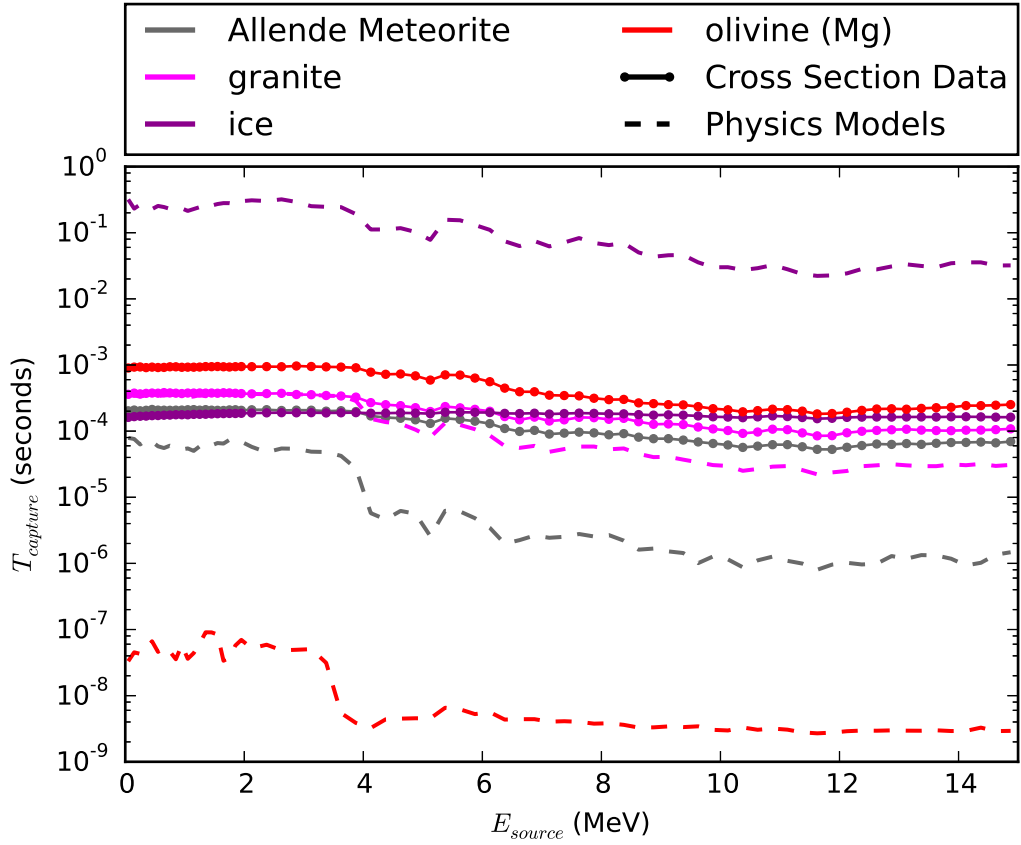


Figure G.6. Comparison of average neutron capture time using physics models and cross section tables for a surface burst.

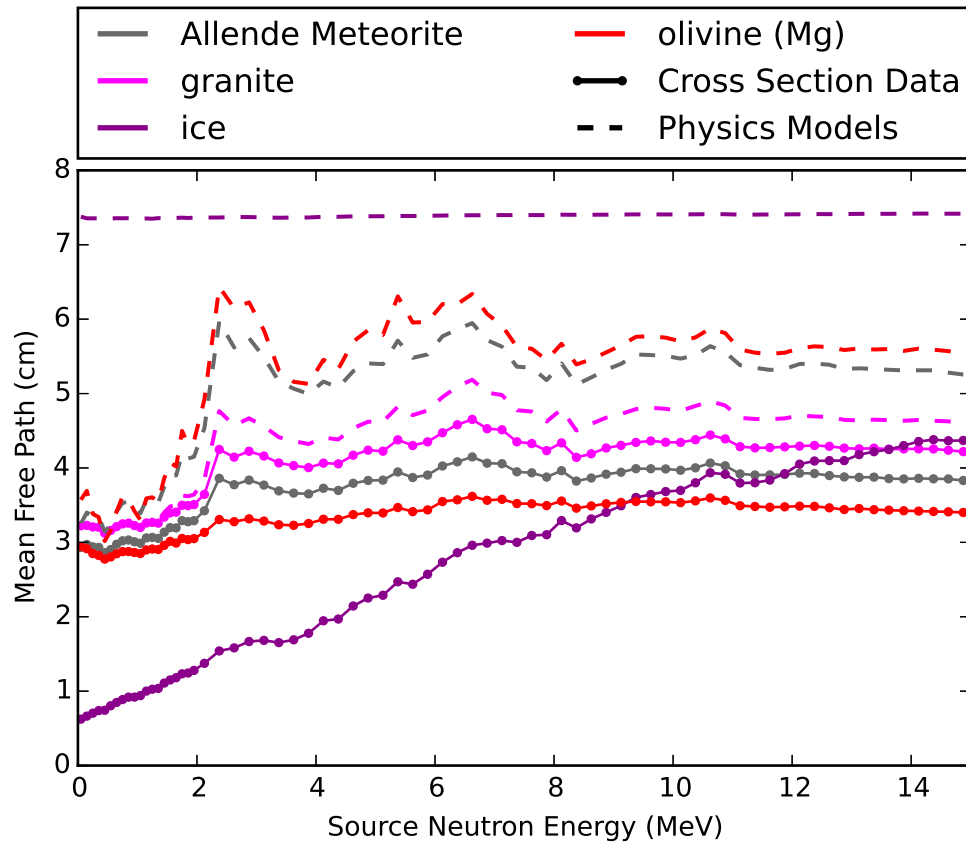


Figure G.7. Comparison of mean free path using physics models and cross section tables for a subsurface burst where no neutrons escape.

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Vita

Major Aaron Ferguson earned his commission as a second lieutenant in the Engineer Branch in 2004 from the Wheaton College Army ROTC program before attending the Engineer Officer's Basic Course at Ft. Leonard Wood, MO. He graduated from the Engineer Officer's Basic Course in March 2005. From 2005 to 2008, he served as an Assistant S4, Platoon Leader, and assistant S3 in the 30th Engineer Battalion (Topographic) (Airborne) at Ft. Bragg, NC. From 2007 to 2008 he served as the MNCI-C7 XO and Assistant Deputy Corps Engineer in the XVIII Airborne Corps in Baghdad Iraq, and Ft. Bragg, NC. Following completion of the Engineer Captains' Career Course at Ft. Leonard Wood, MO, in 2010, Major Ferguson commanded HHC, 94th Engineer Battalion, and served as assistant S3 of the 4th Maneuver Enhancement Brigade at Ft. Leonard Wood. In 2013, he transitioned to Functional Area 52 (Nuclear and Counterproliferation) and entered the Air Force Institute of Technology in pursuance of Master of Science degrees in Nuclear Engineering and Combating Weapons of Mass Destruction.

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14. ABSTRACT The use of nuclear weapons is one possible method for disrupting or deflecting an asteroid on a trajectory to impact the earth. A largely unexplored component of weapon yield in a disruption scenario is the impact of the neutron output. The results of MCNP-6 simulations are presented demonstrating the effect that incident neutron energy has on the total energy deposited in an asteroid, including that the efficiency of energy deposition in a material is inversely proportional to the incident neutron energy due to negative Q-value reactions. The effects of material composition on the total energy deposited as well as the spatial distribution are also explored. The neutron energy deposition profiles are further assessed using the hydrodynamics code Spheral, to evaluate the effect of varying energy deposition profiles on disruption effectiveness. In most materials, an increase in neutron energy results in an increase in per-neutron energy deposition. In meteoric iron, however, an increase in incident neutron energy above 12 MeV results in lower per-neutron energy deposition due to a sharp rise in the occurrence of the (n,2n) reaction in some of the isotopic constituents. This suggests that isotopic composition, and not just elemental composition, could influence the energy deposition due to the neutron yield of a nuclear weapon. Neutron yield coupling efficiency and disruption efficiency for 14.1 MeV neutrons is significantly lower than for 2.45 MeV neutrons or a thermonuclear neutron spectrum.					
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