Probabilistic Analysis of Asteroid Impact Risk Mitigation Programs

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Abstract: Encounters with near-Earth asteroids (NEAs) are rare, but can have significant consequences for humanity. Probabilistic analysis of asteroid impact risks is important to fully understand the danger that they pose. This work builds on the prior development of a method and model to simulate the distribution of asteroid impact magnitudes on the Earth's surface over a 100-year period. This approach enables analysis of the full distribution of impact events, including those that are large and infrequent. Results of this approach have shown some of the greatest risks to life and property over the next century are posed by objects in the 300-to-1000-meter diameter range, which impact the Earth more frequently than those greater than 1 kilometer in diameter, and can still produce impact events with global effects. This paper extends previous work to assess NEA risk mitigation efforts. We compare three types of possible space missions to alter the orbits of hazardous asteroids: kinetic impactors, standoff nuclear explosions, and gravity tractors. Each type of mission is assessed in terms of its reduction of impact risks. The analytic framework and results of this work can serve as input to a wide set of decisions including technology investments in potential countermeasures.

Keywords: Asteroids, NEAs, Asteroid Detection, Asteroid Risk Mitigation, Probabilistic Risk Assessment

1. INTRODUCTION

A globally cataclysmic asteroid impact is believed to be a low probability event. It is sufficiently consequential, however, that mitigation options have been proposed and are being studied. These range from "civil defense" measures to space missions that alter the trajectory of asteroids on a collision course with Earth. In this paper, we compare the effectiveness of three asteroid deflection options based on their risk reduction potential. Those options are kinetic impactors, standoff nuclear explosions, and gravity tractors.*

In previous work, a method was proposed to assess the risk of NEA impacts given no risk mitigation measures, and that method has been used to perform some preliminary risk assessments [3]. This paper builds upon those results to assess the effectiveness of NEA impact countermeasures. Our results, along with further development, can help to inform decision makers in government, research centers, and industry about risk mitigation priorities.

2. ASSESSING THE RISK OF ASTEROID IMPACTS

A significant amount of work has been done in recent decades to examine the risk of NEA impacts on the Earth [4-7]. These studies, however, assumed average values for many relevant NEA properties such as density, velocity, and angle of impact, each of which influences the magnitude of the impact effects. Effects calculations are typically nonlinear, so using mean values as input does not necessarily produce the mean output. Therefore, many of these approaches do not account for dense, fast, high-angle strikes, and the correspondingly more intense effects.

* The use of nuclear devices in space could violate the terms of the 1967 Outer Space Treaty. It could, however "be possible to negotiate exceptions to the treaties so as to make a planetary defense system legal under international law" [1]. It has been argued that "asteroids, comets, and meteors that would be targeted are non-living, completely natural objects with no aspects of human input or control in their genesis and direction," and therefore, that the use of nuclear devices to protect mankind would be peaceful, non-aggressive actions "for the benefit and in the interests of all countries" [2].

Many risk metrics for asteroid impacts have been developed. Most focus on either the risks associated with specific objects or estimates of average annual death rates [8,9]. While object-specific data are valuable, the probability of impact for specific NEAs does not provide a sufficient measure of total risk, even when likely consequences are considered. This is because these risk estimates only consider NEAs that have been observed, and do not account for those that have not been observed yet but are believed to exist. Mean annual death rate estimates are based on the frequencies of large past events and their potential effects on the current global population. Like all low-probability high-consequence event risk measures, these average estimates are problematic. The loss distributions themselves are far more informative.

Finally, recent studies have suggested that NEAs in 10-meter to 1.5-kilometer range pose a greater risk to human life than previously thought [10]. These objects are large enough to cause damage and fatalities, and impact more frequently than very large asteroids. In light of the incomplete detection of asteroids in this range, key questions persist: what are the risks posed by these NEAs? How effective are different risk mitigation measures?

2.1 Overview of the Project Fox Method

This study is built on a simulation tool known as Project Fox [3]. The objective of Project Fox was to design and construct an analysis method and computation tool to assess the aggregate risk of NEA impacts over the next 100 years. The Project Fox approach uses probability distributions for key NEA encounter properties: diameter (we assume that they are spherical), relative velocity with the Earth at time of impact, angle of impact, density of NEA material, NEA type (stony or metallic), location of impact, and ground density at point of impact. Distributions for each of these parameters were assessed from relevant literature in the field, or through interviews with experts.

The Project Fox method differentiates two NEA impact effect regimes. First, it considers *primary effects*, which result directly from the impact of the NEA itself and include blast waves, thermal radiation, cratering, fireballs, and seismic waves. Primary effects are estimated using the computations of Collins, Melosh, and Marcus [11]. In contrast to primary effects, a *cataclysm* is the regime in which global effects are feasible (in this case, sub-micron dust loading of the upper atmosphere). This is assessed through calculations of the resulting mass ejecta and total energy release. The key thresholds for testing whether or not a cataclysm may occur are based on studies of catastrophic climate events [12]. The population that can be affected by a particular NEA impact is estimated using geography-specific population data from the LandScan database [13].

The Project Fox simulation tool estimates the complementary cumulative distribution of primary effect fatalities over 100 years without impact risk mitigation actions. The simulation also estimates the probability of a potentially cataclysmic event (as defined above) over 100 years. The original Project Fox results are shown in Figures 4 and 5 (solid and dotted black curves) as a comparison to the results of this study. The first figure shows a plot indicating that the probability that in the next 100 years at least 1 person is killed from a NEA encounter is about 3×10^{-4} and that more than 1 million people are killed is about 2×10^{-6}. The initial estimation of the probability of an impact that could produce a cataclysm is $q = 8\times10^{-4}$, a value that is greater than, but consistent with findings from Chapman and Morrison [5]. Finally, as shown in Figure 5, Project Fox found that the majority of cataclysm risk over the next 100 years comes from NEAs in the 300-to-1000-meter diameter range.

3. NEA DEFLECTION: MODELS OF ORBIT MODIFICATION

We study three methods for deflecting an asteroid: kinetic impactors, standoff nuclear explosions, and gravity tractors. These are summarized in Table 1. All three approaches are well known and were discussed as plausible countermeasures by the National Academies [14]. Each approach is based on causing a change of velocity (ΔV) of the asteroid, either slowing it down or speeding it up on its trajectory. This causes a change in position (Δs) at a future time. We use the convention that an asteroid must be deflected by at least one Earth-diameter by the time of its encounter with Earth.

Several time parameters are used as part of the analysis for this paper. These are illustrated in Figure 1. For an asteroid that might impact the Earth, the total warning time (t_W) is the time from discovery of the asteroid to the time of possible impact. For any asteroid deflection option, there is a preparation time for a mission (t_P), which may include development, build, assembly, and test activities; a transit time (t_T) for the spacecraft to reach the asteroid after launch from Earth; and an effect lead time (t_E), the time elapsed between the initial effect on the asteroid and its original impact time. For a gravity tractor, there is also a "dwell time" (t_G), during which the spacecraft maintains proximity to the asteroid (we assume 100 meters for this analysis).

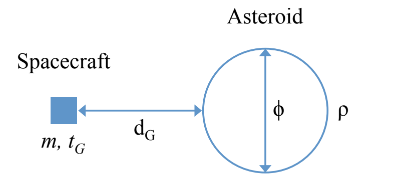
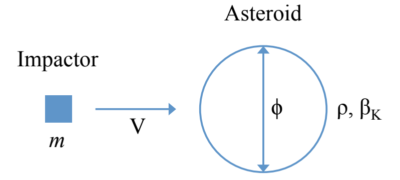
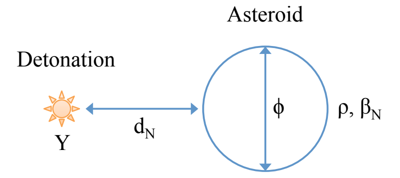
	Insensitive to NEA material properties?	**Potentially feasible for 50m–1.5km objects in less than 10 years?**	**Relevant technology demonstrations?**	**Diagram** *Notation defined in sections 3.1–3.3*
Gravity Tractor	Yes	No	NASA's NEAR-Shoemaker mission rendezvoused, orbited, and landed on the near Earth asteroid 433 Eros in 2000–2001.	
Kinetic Impactors	No	Yes	NASA's Deep Impact Mission impacted comet Temple 1 in 2005. (The spacecraft went on to a flyby of Comet Hartly 2 in 2010).	
Stand-Off Nuclear Detonation	No	Yes	The Fishbowl nuclear test series by the U.S. in 1962 demonstrated effects of nuclear detonations in space.	

Table 1: Summary of NEA Deflection Alternatives

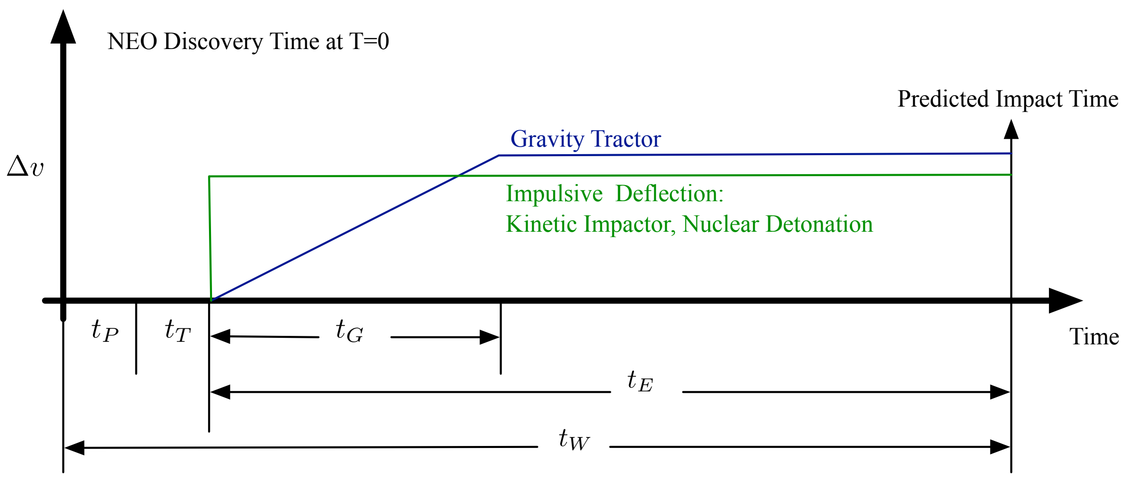


Figure 1: Time Parameters Associated with Asteroid Deflection Alternatives

For all three deflection methods, we assume a simple relationship between ΔV and Δs for velocity changes of an asteroid parallel to its direction of motion, based on the work of Ahrens and Harris [15]:

$$\Delta s \approx 3 \cdot t_E \cdot \Delta V \qquad \textbf{Eqn. 1}$$

where t_E is the lead time in seconds, ΔV is the change in velocity in meters per second, and Δs is the change in position in meters.†

3.1. Gravity Tractors

A gravity tractor is based on simple physics: a relatively large spacecraft maintains position close to an asteroid, and gravitational attraction between the two objects gradually alters the asteroid's velocity. The acceleration applied per second by a gravity tractor spacecraft on an asteroid is:

$$a = \frac{Gm}{r^2} \qquad \textbf{Eqn. 2}$$

where $G = 6.67\times10^{-11}$ m^3 kg^{-1} s^{-2} is the gravitational constant, m is the mass of the spacecraft in kilograms, and r is the distance in meters between the center-of-mass of the spacecraft and the asteroid.

The gravity tractor approach requires a timescale of decades for most objects. One of its significant benefits is that it generally does not depend on the properties of the asteroid material.

The technical challenges associated with gravity tractors center on the operation of a propulsion system for maintaining proximity to the asteroid over a few decades. This may be within the technical capabilities of proposed nuclear-electric propulsion systems (e.g., see [18]). Generally, the effectiveness of this approach increases with the mass of the spacecraft and the amount of time it can stay near the asteroid. This analysis assumes that the spacecraft continues to act on the NEA body until the end of its lifetime, t_G, or the end of the effect lead time, t_E, whichever is shorter.

The change in position for the NEA resulting from a gravity tractor (Δs_G) can be approximated with the formula (see Appendix 1 for a derivation, which is consistent with [14]):

$$\Delta s_G = (2t_E t_G - t_G^2)\frac{6Gm}{(\phi + 2d_G)^2} \quad where\ \ t_G \le t_E \qquad \textbf{Eqn. 3}$$

where t_G is the dwell time of the spacecraft near the NEA body, expressed in seconds. The parameter G is the gravitational constant in cubic meters per kilogram per second squared, m is the mass of the spacecraft in kilograms, ϕ is the radius of the NEA body in meters, ρ is the density of the asteroid, and d is the distance in meters maintained between the spacecraft and the NEA surface.

3.2. Kinetic Impactors

A kinetic impactor changes the momentum of an asteroid by impacting its surface. This method is effective on a much shorter timescale than a gravity tractor, but the change in velocity depends on properties of the asteroid material. Generally, these properties are difficult to determine until a spacecraft arrives at the object, making the exact effectiveness of a kinetic impactor uncertain until that time.

An asteroid's change in velocity after an impact is a simple physics problem, and we use the convention of the 2010 National Academies Committee Report [14]:

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†Chelsey and Spahr [16] use a different approach, solving for the ΔV required to deflect an object by one Earth-radius, using a geometric mean of equations from Carusi et al. [17]. Chelsey and Spahr note that their approach corresponds within a factor of two to the Ahrens and Harris approach. Therefore, for simplicity, we adopt the Ahrens and Harris equation:

$$\Delta V = \beta_K \frac{mU}{M} \quad \textbf{Eqn. 4}$$

where m is the mass of the spacecraft in kilograms, U is the relative velocity of the spacecraft and the NEA in meters per second, M is the mass of the NEA (also in kilograms), and β_K is a parameter that represents the amplification effects of impact-ejecta on the asteroid's momentum (β_K has a lower bound of 1 and we assume an upper bound of 5 to be consistent with the literature [14]). We assume that the relative velocity of the NEA and the spacecraft is $U = 10$ kilometers per second in all analyses presented in this paper.

With Equations 1 and 4, we can approximate the position change of the NEA resulting from a kinetic impactor (Δs_K) by the formula:

$$\Delta s_K = 3t_E\beta_K \frac{6mV}{\pi\phi^3\rho} \quad \textbf{Eqn. 5}$$

Where t_E is the effect lead time in seconds, ϕ is the NEA diameter in meters and ρ is the density of the NEA in kilograms per cubic meter.

3.3 Stand-Off Nuclear Detonations

The third alternative considered in this paper is the use of nuclear explosions near the surface of an asteroid to change its trajectory (we do *not* consider methods to break up an asteroid by using nuclear explosives). Neutron radiation from the detonation heats the surface of the NEA body, ejecting material and changing the asteroid's momentum.

Scientists at the Lawrence Livermore National Laboratory (LLNL) have conducted preliminary studies of nuclear detonations for asteroid deflection by using detailed numerical simulations (e.g., see [19]). LLNL researchers have provided an approximation formula to estimate an asteroid's velocity change resulting from a standoff nuclear explosion [20]. Using the relationship between ΔV and Δs from Equation 1, we approximate the change in position for an NEA resulting from a standoff nuclear explosion (Δs_N) in meters, by using the following formula:‡

$$\Delta s_N = 3t_E\beta_N \frac{8A}{\phi^3}\sqrt{\left(\frac{Y\phi d_N^2}{\phi + 2d_N}\right)\left(1 - \frac{\sqrt{\left(1+\frac{2d_N}{\phi}\right)^2 - 1}}{1+\frac{2d_N}{\phi}}\right)\left(\frac{\phi}{d_N}\left(1+\ln\left(\frac{Y}{Bd_N^2}\right)\right) - \left(1+\frac{\phi}{d_N}\right)\ln\left(1+\frac{\phi}{d_N}\right)\right)} \quad \textbf{Eqn. 6}$$

where t_E is the effect lead time is seconds, A and B are constant terms (that fit the results of the LLNL numeric simulations) with $A = 57.5\frac{m^3}{s\cdot\sqrt{kT}}$ and $B = 3.16\times10^{-4}\frac{kT}{m^2}$. Yield from the nuclear device, Y, is expressed in kilotons of TNT equivalent (kT) and the NEA body diameter, ϕ, is expressed in meters. Finally, as in Equation 5, the parameter β_N represents an amplification factor resulting from the force of ejecta, similar to the effect described in the case of the kinetic impactor. Typical values of β_N are assumed to be in the range of 1 to 3. This study assumes that the standoff distance, d_N, in meters is chosen for each mission to maximize Δs_N and that a 1-megaton-yield device is used for all deflection missions.

‡ Equation 6 is a reasonable estimation under the specific circumstances of this analysis: range and stand-off distances, yield of the device, and the asteroid diameters that we consider. We also assume solid asteroids. However, it should not be used without careful consideration of these assumptions and of the approximations made in its derivation, and cannot be generalized to other cases or uses.

4. SIMULATION AND ANALYSIS

We make several assumptions, beyond those already discussed, for the purpose of simplifying the modeling and analysis. These simplifications allow us to develop a high-level method to estimate the risk mitigation performance of the options examined:

Perfect Observation – It is assumed that all asteroids that will impact the Earth in a 100-year period have been discovered at the start of that timeframe.

Instant Mitigation – For all three deflection options, it is assumed that the preparation time for a mission (t_P) and transit time (t_T) for the spacecraft to reach the asteroid after a launch from Earth are both zero.

Perfect Launch, Transit, and Rendezvous Reliability – It is assumed that the mission will launch, transit to the NEA, and initiate its actions successfully.

NEA Cohesion – It is assumed that the size of an asteroid relative to either a kinetic impactor or standoff nuclear detonation is such that the asteroid will not break up after deflection.

Spacecraft Mass – For kinetic impactors and gravity tractors, we are assuming a spacecraft mass of 10,000 kg. This mass is consistent with the recent National Academies' assumptions to approximate current launch capabilities [14].

Spacecraft Lifetime – For gravity tractors, we model the lifetime of the spacecraft (t_G) as an uncertain factor that is characterized by an exponential distribution with a mean of 50 years.

Many of these assumptions can be relaxed in future studies. Under the current assumptions, the results of this analysis should be interpreted as an estimate of the upper bound of risk mitigation performance (given the parameters used). The purpose here is to demonstrate the method developed and provide a coarse understanding of the effectiveness of deflection methods.

4.1 Modeling the Effectiveness of Mitigation Measures

Each deflection option is examined in terms of the estimated change in position, Δs, at the time when the asteroid would have struck the Earth. The position shift is approximated using one of the formulations shown in Equations 3, 5, and 6. Each of these formulas can be written as:

$\Delta s = 3 \cdot g(t_E, \beta) \cdot h(\phi, \rho, \ldots)$ for stand-off nuclear explosions or kinetic impactors, and

$\Delta s = 3 \cdot g(t_E, t_G) \cdot h(\phi, \rho, \ldots)$ for gravity tractors.

The function g takes two random variables as its arguments. For standoff nuclear explosions or kinetic impactors, they are the effect lead time, t_E, and the β amplification factor. For gravity tractors, they are the effect lead time and the spacecraft lifetime, t_G. In all cases, the g function variables are assumed to be independent. The joint distribution is calculated and discretized for selected values, resulting in a joint probability mass function (PMF) over the range of outputs of the g function.

Once a PMF estimate of the g function is determined, assessing the probability that a NEA is deflected is a matter of calculating the probability that Δs is greater than a threshold that corresponds to the minimum position shift that would avoid a collision with the Earth. This probability is noted as p. We use the convention that an asteroid with an Earth-impact trajectory must be deflected by approximately one Earth-diameter, about $D = 12{,}800\,\text{km}$, at the time of its initially anticipated encounter with Earth. It is assumed that no impact occurs if $\Delta s \geq D$. This is equivalent to calculating the value of the complementary cumulative distribution function (CCDF) of g at the argument $\frac{D}{3 \cdot h(\cdot)}$, which is:

$$p = \Pr(NEA\ Deflected) = \Pr\left(g(\cdot) \geq \frac{D}{3 \cdot h(\cdot)}\right) \quad \textbf{Eqn. 7}$$

4.2 Preliminary Comparison of Mitigation Measures

The three mitigation measures examined in this paper have varying levels of effectiveness for different combinations of NEA diameter and effect lead time. Figure 2 shows the probability of deflection, p, given the asteroid diameter and the effect lead time for each method. These results also assume that the mission is successful in its rendezvous with the asteroid. At the longest lead times considered here, a kinetic impactor (left in Figure 2) is most effective against objects smaller than 500 meters in diameter and less effective at shorter lead times. By contrast, gravity tractor options (right in Figure 2) are somewhat effective for larger NEAs, but only at long lead times. Strikingly, however, standoff nuclear explosions (center in Figure 2) are the most effective option offering high probabilities of deflection for large objects at shorter effect lead times.

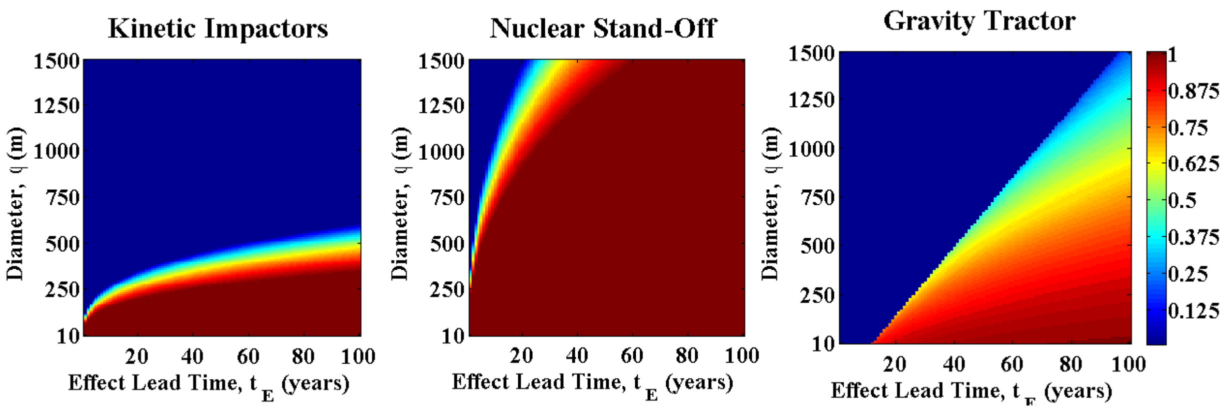

Figure 2: Probability of Deflection Using Alternative Mitigation Measures

Legend: The scale on the right shows the probabilities of successful deflection, and each part of the figure shows its variations for each deflection method, given the effect lead time and the asteroid diameter. NEO density is assumed to be $\rho = 3{,}000$ kilograms per cubic meters.

The kinetic impactor and nuclear stand-off explosion effectiveness depend on amplification factors, β_K and β_N. The gravity tractor's efficacy depends on the spacecraft lifetime, t_G. The β factors are assumed to be uniformly distributed over the ranges discussed previously (1 to 5 and 1 to 3 respectively), and t_G is assumed to be exponentially distributed with a mean of 50 years. Figure 3 illustrates the expected mitigation performance for each method as a function of the asteroid diameter. The expectation of the probability of a successful deflection, $E_{t_E}\{p(\phi, t_E)|\phi\}$, is taken over the effect lead time, t_E. Standoff nuclear detonations outperform kinetic impactors and gravity tractors at every considered diameter. Gravity tractors are superior to kinetic impactors for diameters larger than approximately 400 meters. For NEAs with diameters less than 400 meters, kinetic impactors are fairly effective.

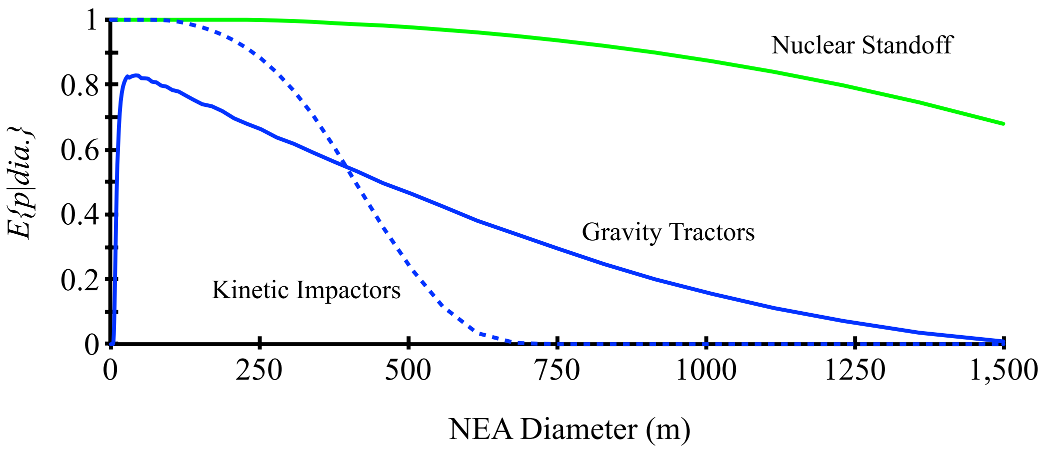

Figure 3: Mean Probability of Deflection Given Diameter

4.3 Simulation

In order to assess the different risk mitigation options, the Project Fox simulation was modified to include possible deflection of different types of NEAs. For each impact in the simulation, the set of asteroid characteristics (diameter, density, velocity, impact angle, and ground density) are drawn according to the joint distribution calculated from the probabilistic inputs of each parameter. Once an object is selected, the g and h functions are calculated for a particular mitigation option, and the probability p that the NEA is deflected is calculated using Equation 7. On the order of ten-million 100-year periods are used in the simulation for each mitigation option to get sufficient samples to assess the resulting cumulative complementary distribution function of the primary effect fatalities and cataclysm probability.

5. PERFORMANCE OF MITIGATION MEASURES

We use intermediate results discussed in Section 4 to evaluate several possible policies for asteroid responses described in Figures 2 and 3. These policies use the three deflection options examined and are (from most to least plausible):

Policy A: Use the most effective method against any NEA greater than 10 meters.
Policy B: Use the most effective non-nuclear method against any NEA greater than 10 meters.
Policy C: Use the most effective non-nuclear method for asteroids greater than 10m and less than 500 meters, and use whatever method provides the highest probability of effectiveness for asteroids greater than 500 meters.
Policy D: Use only kinetic impactors on any NEA larger than 10 meters.
Policy E: Use only standoff nuclear explosions on any NEA larger than 10 meters.
Policy F: Use only gravity tractors on any NEA larger than 10 meters.

Figure 4 illustrates the simulated risk reduction of these mitigation policies. The solid black curve corresponds to the case of no mitigation option. The dotted black curve illustrates a quantile-parameterized distribution (QPD) of the number of potential, primary-effect casualties that fit the empirical simulation results. This allows extrapolation of these results to estimate the probability of larger outcomes. Policy F (solid blue curve) uses only gravity tractors to mitigate the hazard of all asteroids, and does provide some risk reduction. However, because encounters with smaller NEAs happen more frequently, the mean effect lead time is short. It does not provide enough time for gravity tractors to change the course of the asteroid enough for effective deflection. Policy D (dotted blue curve) provides significantly more risk reduction because it enables much higher probabilities of deflection for NEA objects up to 500 meters. Policy B (solid red curve) allows for any non-nuclear option to be used for any asteroid size and provides slight more risk reduction than kinetic impactors alone. This is because Policy B selects the most effective of two options that perform differently for different size NEOs. Finally, Policy C (dotted red curve) allows for nuclear explosive devices to be used for any objects larger than 500 meters, and provides greater risk reduction than any of the non-nuclear options. This is because standoff nuclear explosions are very effective against NEAs in the diameter ranges considered, as shown in Figure 2. For potentially large fatality outcomes, the CCDFs of each of the non-nuclear policies tend to converge towards a limit of effectiveness because none of the non-nuclear mitigation options are very effective against large diameter NEAs.

The curves associated with policies A and E, which allow for the use of standoff nuclear explosions, are conspicuously absent from the results shown is Figure 4 because no casualty occurred across all simulation runs. This does not imply that nuclear explosive devices are a perfectly effective, especially if we do not have enough lead time. For example, for large NEAs that are going to impact the Earth imminently, even nuclear explosives (the 1 megaton explosive considered in this work) cannot prevent the impact. Therefore, according to these preliminary results, standoff nuclear explosions appear to be relatively more effective at reducing the likelihood of primary-effect deaths than the other mitigation options considered here. This is a promising result, as it implies that the world already possesses the basic technology to greatly reduce the risk of NEA impacts on the Earth.

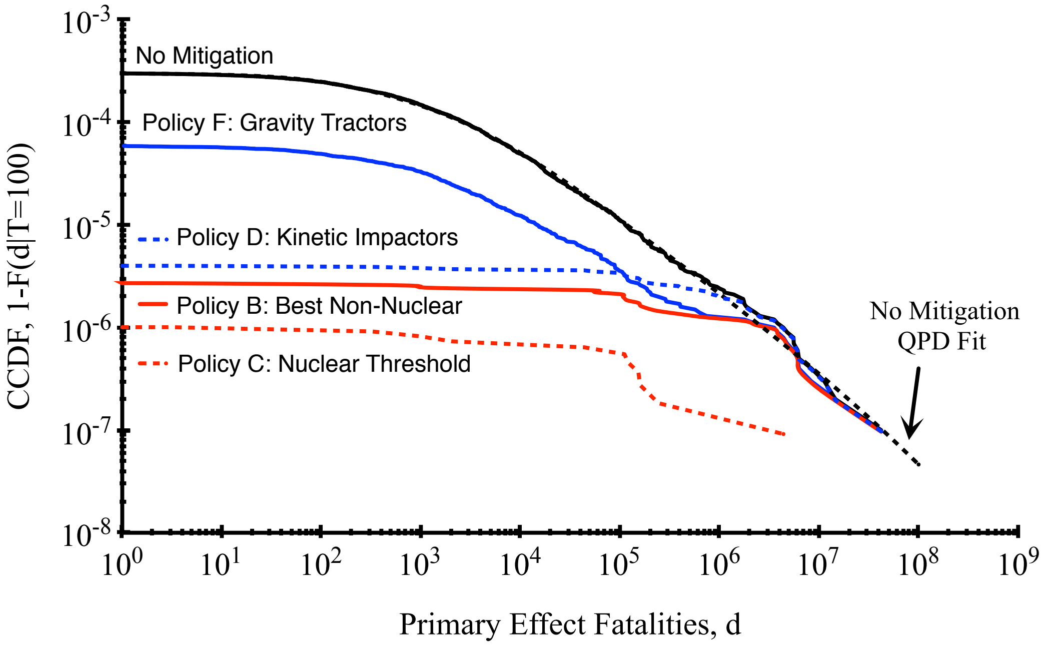

Figure 4: Reduction of Primary Effect Fatality Risk by Proposed Mitigation Policies

Consistent with the scope of Project Fox, this study defines a cataclysm as the regime in which global effects can occur. Specifically, this condition exists when the energy released in an impact is larger than 200MT and the mass ejecta exceeds 1.28×10^{11} metric tons. Figure 5 illustrates the cataclysm risk reduction effectiveness of the proposed policies.

Based on the initial Project Fox results (solid black curve), the probability of a cataclysm over a one hundred year period is significant for NEA diameters greater than 300 meters. The total probability q of a global-effect scenario over the next 100 years was found to be about 8×10^{-4} without risk mitigation measures.

Policy D (dotted blue curve) uses only kinetic impactors and reduces this risk by 7% to $q = 7.4\times10^{-4}$. This is because kinetic impactors are decreasingly effective for NEAs above 500 meters.

Policies B and F (solid red curve) provide a 29% risk reduction, resulting in $q = 5.7\times10^{-4}$. Policy B employs only non-nuclear options, while Policy F uses only gravity tractors. These policies have similar results given that gravity tractors are the most effective for NEAs larger than 400 meters, and the probability of cataclysms resulting from smaller NEAs is small.

Policy C (dotted red line) uses non-nuclear options for asteroids below 500 meters in diameter and all options—including nuclear devices—for asteroids above 500 meters. This policy is very effective, with a risk reduction of 82%, resulting in $q = 1.5\times10^{-4}$. Under Policy C, however, there is still a small residual risk of cataclysms for NEAs between 300 and 500 meters. If the threshold used for the use of nuclear explosive were lowered to 300 meters, this policy would likely have an effectiveness closer to those of the policies where nuclear use is permitted for all diameters.

Policies A and E (solid green curve) address the residual risk of Policy C, providing a total risk reduction of 84%, resulting in $q = 1.2\times10^{-4}$. Here again, standoff nuclear detonations are very effective, and become the dominant risk mitigation measure.

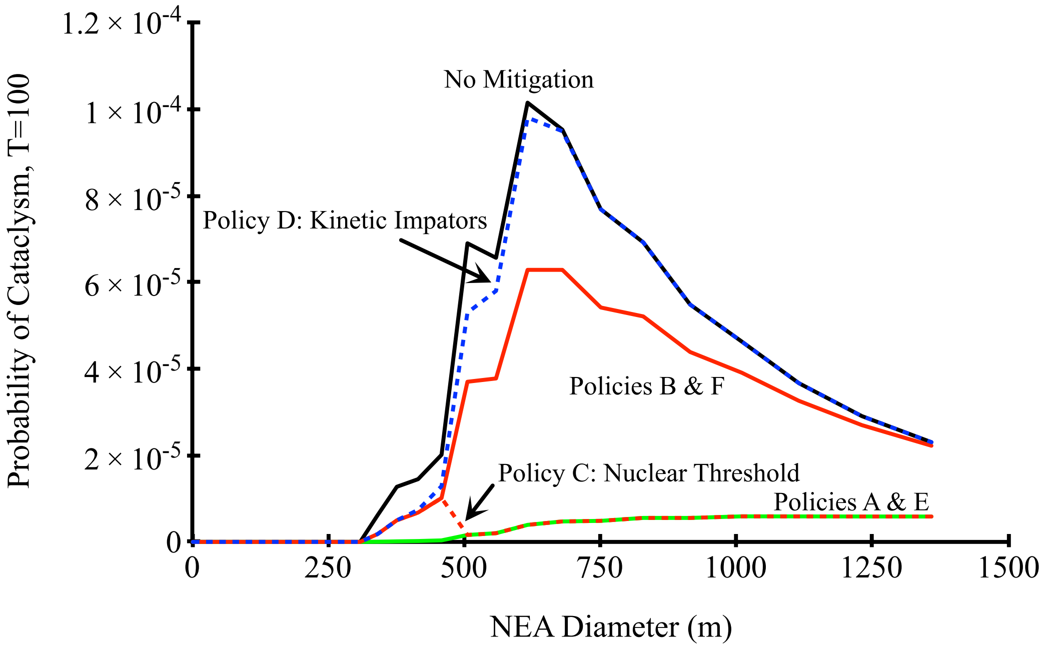

Figure 5: Reduction of Cataclysm Risk by Proposed Mitigation Policies

6. CONCLUSION

This study extends simulations of asteroid impact risks to include the effects of three risk mitigation options based on asteroid deflection. In order to keep the models simple and calculations feasible, reasonable approximation formulas are used to assess the performance of gravity tractors, kinetic impactors, and standoff nuclear detonations. Results indicate that kinetic impactors outperform gravity tractors in averting primary-effects fatalities, but gravity tractors outperform kinetic impactors for reducing global cataclysm risk. This is reasonable, as gravity tractors are more effective than kinetic impactors for large diameter NEAs. While all NEA deflection policies provide some risk reduction, deflection policies that include the use of nuclear explosive devices outperform all deflection policies that do not, because they can deflect larger asteroids with a shorter lead time.

Under the assumptions made in this paper, the results represent an upper bound of risk reduction for all the mitigation options examined. The delay for preparing technologies, the transit time from launch to the asteroid, the probability of failure during NEA rendezvous, the chances of spacecraft launch failures, equipment failures, and a host of other concerns would reduce the benefits of all mitigation options. Perhaps the most optimistic assumption in each simulation is that all NEAs that could impact the Earth over the next 100 years are already known. It is probably not the case at this time, especially for asteroids less than 1000 meters in diameter.

The results of this analysis suggest that we most likely have the technology to successfully mitigate most of the risk from asteroid impacts, given sufficient time between NEA discovery and a potential Earth impact. This suggests that an important next step is to improve and expand NEA discovery and observation missions, especially those that can provide data on objects in the 300-to-1000-meter range, and those that are difficult to observe, for example because they are aligned with the sun. Ideally, observation missions would be effective down to the low 10s of meters in diameter.

It is likely that the technology exists to deflect many moderate-sized asteroids given sufficient lead-time. The problem is that we may not be able to see them coming.

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Appendix 1: Derivation of Gravity Tractor Formula

The approximation for position shift for any deflection method is given by:

$$\Delta s = 3\,\Delta s'$$
$$\Delta s' = \Delta v \cdot t$$
$$\Delta v = a \cdot \Delta t$$

The acceleration induced by a massive spacecraft on a NEA body is given by:

$$\Delta a = \frac{Gm}{r^2}$$

The acceleration depends only on the mass of the spacecraft, and is constant for a given encounter. There are two cases that must be examined: 1) the lifetime of the spacecraft is less than the effect lead time, or $t_G \leq t_E$, and 2) the lifetime of the spacecraft lifetime is longer than the effect lead time, or $t_G > t_E$. In the first case, we have the following:

$$\Delta s' = \frac{Gm}{r^2} t_G \left(\frac{t_G}{2} + (t_E - t_G)\right)$$
$$\Delta s' = \frac{Gm}{r^2} \left(t_E t_G - \frac{t_G^2}{2}\right)$$
$$\Delta s' = \frac{Gm}{2r^2} (2t_E t_G - t_G^2)$$
$$\Delta s' = \frac{Gm}{2\left(\frac{\phi}{2} + d_G\right)^2} (2t_E t_G - t_G^2)$$
$$\Delta s' = \frac{2Gm}{(\phi + 2d_G)^2} (2t_E t_G - t_G^2)$$

Substituting back into position shift approximation, we have:

$$\Delta s = 3\,\Delta s'$$
$$\Delta s = \frac{6Gm}{(\phi + 2d_G)^2} (2t_E t_G - t_G^2)$$

In the case where $t_G > t_E$, the effect lead time, t_E, is essentially equal to t_G, and the result above holds.