Risk-Risk Tradeoff Analysis of Nuclear Explosives for Asteroid Deflection

Seth D. Baum
Global Catastrophic Risk Institute
http://sethbaum.com * http://gcrinstitute.org

Published in *Risk Analysis*, vol. 39, no. 11 (November 2019), p.2427-2442.
DOI 10.1111/risa.13339. This version 11 November 2019.

Abstract

To prevent catastrophic asteroid-Earth collisions, it has been proposed to use nuclear explosives to deflect away Earthbound asteroids. However, this policy of nuclear deflection could inadvertently increase the risk of nuclear war and other violent conflict. This article conducts risk-risk tradeoff analysis to assess whether nuclear deflection results in a net increase or decrease in risk. Assuming nonnuclear deflection options are also used, nuclear deflection may only be needed for the largest and most imminent asteroid collisions. These are low-frequency, high-severity events. The effect of nuclear deflection on violent conflict risk is more ambiguous due to the complex and dynamic social factors at play. Indeed, it is not clear whether nuclear deflection would cause a net increase or decrease in violent conflict risk. Similarly, this article cannot reach a precise conclusion on the overall risk-risk tradeoff. The value of this article comes less from specific quantitative conclusions and more from providing an analytical framework and a better overall understanding of the policy decision. The article demonstrates the importance of integrated analysis of global risks and the policies to address them, as well as the challenge of quantitative evaluation of complex social processes such as violent conflict.

Keywords: nuclear weapons, asteroids, risk-risk tradeoff

1. INTRODUCTION

Earthbound asteroids and comets can pose a significant risk to humanity and the environment. The risk is illustrated by the 2013 collision at Chelyabinsk, Russia, which injured approximately 1,500 people and damaged thousands of buildings (Popova, 2013). More rarely, large collisions can be globally catastrophic, such as the Chicxulub collision implicated in the Cretaceous-Paleogene extinction event 66 million years ago (Alvarez, Alvarez, Asaro, & Michel, 1980).

The response to this risk has primarily been twofold. First, for several decades, there have been programs to detect near-Earth objects (NEOs)[1] and assess whether they are on trajectory to collide with Earth. These include the Spaceguard Survey (Harris, 2008) and NEOWISE project (Mainzer et al., 2011; 2014). Thus far, all detected NEOs are not Earthbound. The search is not yet complete, though there has been detection of over 90% of the largest NEOs (Mainzer et al., 2014). Second, there have been studies of techniques for deflecting away Earthbound NEOs.[2] These techniques may be used in the event that an Earthbound NEO is detected.[3]

---

[1] NEOs are defined by convention as asteroids and comets that approach within 1.3 astronomical units of the Sun.

[2] NEO deflection is defined as changing the orbit of the NEO; the terms *disruption* and *fragmentation* are used for breaking the NEO into smaller pieces (Ahrens & Harris, 1992; National Aeronautics and Space Administration [NASA], 2007); National Research Council [NRC], 2010).

[3] A third policy response, which has received less attention, is for post-collision disaster response (Garshnek, Morrison, & Burkle, 2000).

A promising but controversial deflection technique uses nuclear explosives, henceforth referred to as *nuclear deflection*. Nuclear deflection is promising because of the high energy density of nuclear explosives, enabling a stronger deflection than other techniques. Deflection studies find nuclear deflection to be the most effective technique, especially for large NEOs and imminent collisions (Ahrens & Harris, 1992; NASA, 2007; NRC, 2010). Governments have likewise indicated interest in nuclear deflection, including China (Tyler, 1996) and reportedly also Russia (Gerrard & Barber, 1997) in the 1990s and the United States in the 2010s.[4] The US has taken at least one initial step toward a nuclear deflection program, with its National Nuclear Security Administration retaining an important nuclear explosives component for "potential use in planetary defense against earthbound asteroids" (GAO, 2014).

Nuclear deflection is controversial because it intersects with nuclear weapons issues and related issues of violent conflict. The most commonly expressed concern is that nuclear deflection may violate certain international treaties on nuclear weapons, including the Partial Test Ban Treaty, the Comprehensive Nuclear-Test-Ban Treaty (CTBT), and the Outer Space Treaty.[5] (Nuclear deflection could also violate the new—as of July 2017—Treaty on the Prohibition of Nuclear Weapons.) Other concerns expressed about nuclear deflection include that it is politically difficult and contentious (Bucknam & Gold, 2008; Koenig & Chyba, 2007; Packer et al., 2013), that it could be geopolitically destabilizing (Chapman, 1999), and that it could impede nuclear disarmament (Graham & Schweickart, 2008). On the other hand, some have expressed the view that nuclear deflection would be good because it diverts nuclear explosives away from military purposes, thereby "beating swords into ploughshares" (Mellor, 2007).

This article evaluates the merits of nuclear deflection of Earthbound asteroids in consideration of its potential effects on both asteroid and violent conflict risks.[6] The primary goal of nuclear deflection is to keep Earth safe from potential harm. Any increase in violent conflict risk caused by nuclear deflection programs would go against this goal. The question is whether the decrease in asteroid risk from nuclear deflection programs is large enough to offset any increase in violent conflict risk. To make progress on this question, the article conducts risk-risk tradeoff analysis (Graham & Wiener, 1995; Lave, 1981; Lofstedt & Schlag, 2017) of asteroid and nuclear weapons risks to inform policy decisions about whether and how nuclear deflection programs should proceed.

This article is framed in terms of violent conflict risk more generally, and not violent nuclear conflict risk more specifically, in deference to the possibility that nuclear deflection can also affect the risk of non-nuclear violent conflict. For example, nuclear deflection programs could impede nuclear disarmament. If nuclear weapons are fully disarmed, then there may be greater risk of non-nuclear war (more on this below). Thus, this article might be more precisely described as a risk-risk-risk tradeoff analysis, with the three risks being asteroid collision, violent nuclear conflict, and violent nonnuclear conflict.

---

[4] Government Accountability Office [GAO] (2014); Interagency Working Group for Detecting and Mitigating the Impact of Earth-Bound Near-Earth Objects (2018).

[5] Bucknam & Gold (2008); Chapman (1999); Gerrard & Barber (1997); Kunich (1997); Mayer (2015); Packer, Kurr, & Abelkop (2013); Remo (1996); Schweickart, Jones, von der Dunk, Camacho-Lara, Association of Space Explorers International Panel on Asteroid Threat Mitigation Association of Space Explorers International Panel on Asteroid Threat Mitigation (2008); Su (2015); Sweet (1999).

[6] Comets are rarer, harder to detect, and harder to deflect, and thus are excluded from this study, as has been done for other studies, e.g. Stokes et al. (2003).

This article makes several original contributions. First, it contributes risk and policy analysis to a broader literature on the intersection of nuclear deflection and nuclear weapons issues.[7] As elaborated below, prior studies in this literature have not considered the risk-risk tradeoff in substantial detail. Second, it provides an example of risk-risk tradeoff analysis in the context of global catastrophic risk. Global catastrophic risk is an important class of risk and an emerging field of study.[8] However, these risks can be difficult to study due to their complex global nature and their inherent data problem—modern global human civilization has never previously been destroyed. This article shows that some policy decisions involve global catastrophic risk-risk tradeoffs, which require quantification to resolve, though rigorous quantification may be difficult to achieve. Evaluation of these decisions requires an integrated analysis of multiple global catastrophic risks (Baum & Barrett, 2017).

The article is organized as follows. Section 2 surveys prior literature on the nuclear deflection risk-risk tradeoff. Section 3 presents theory and assumptions concerning the underlying evaluative framework and the nuclear deflection decision. Section 4 assesses asteroid and violent conflict risks. Sections 5 and 6 assess the effects of nuclear deflection on asteroid and violent conflict risks. Section 7 analyzes policy implications. Section 8 concludes.

2. PRIOR LITERATURE

Several studies have noted the existence of a nuclear deflection risk-risk tradeoff. Remo (1996) worries that nuclear deflection could "inadvertently trigger another nuclear arms race which could create a short-term peril far greater than the NEOs themselves". Sweet (1999) postulates that "the mere existence of such a nuclear arsenal could constitute a danger to human life that may be much greater than the threat it is intended to mitigate". Gerrard and Barber (1997) state that "It seems obvious that the deployment of a nuclear weapons system in China, Russia, or anywhere else poses a threat of accidental or malevolent mass destruction that dwarfs the odds that such a system will be suddenly needed to beat back a long-period comet or another atypical threat that arises with too little warning for us to develop a defensive system from scratch". However, the studies do not provide any analysis in support of these assertions.

Graham and Schweickart (2008) argue that nuclear deflection is not important enough to factor into nuclear weapons policy decisions. They emphasize the low probability of the large NEO collisions that require nuclear deflection, claiming that this probability is too low to be counted. However, this analysis neglects the large severity of large collisions and does not attempt to compare the effect of NEO deflection on NEO collision risk to its effect on risks posed by nuclear weapons.

Remo (2015) argues that nuclear deflection reduces long-term risks to human civilization, accounting for both NEO collision and nuclear war risks. Remo emphasizes the point that over long time scales, large NEO collisions are highly probable, perhaps inevitable, and thus human survival requires a mechanism for deflecting large NEOs. In contrast, Remo argues that nuclear war is not inevitable, and can be avoided by eliminating humanity's "aggressive, self-destructive tendencies". However, this analysis overlooks the possibility that over such long time scales, humanity will have developed other, nonnuclear means for deflecting large NEOs, or will become more able to survive NEO collisions. Future policymakers can consider such matters;

---

[7] Baum (2015); Bucknam & Gold (2008); Chapman (1999); Gerrard & Barber (1997); Graham & Schweickart (2008); Koenig & Chyba (2007); Kunich (1997); Mayer (2015); Mellor (2007); Packer et al. (2013); Remo (1996; 2015); Schweickart et al. (2008); Su (2015); Sweet 1999).

[8] Baum & Tonn (2015); Bostrom & Ćirković (2008); Garrick (2008); Häggström (2016).

today's policymakers arguably should focus on the potential benefits and risks of nuclear deflection over the shorter time horizons of near-term nuclear deflection programs.

Finally, Baum (2015) argues that the benefits of nuclear deflection for NEO risk reduction do not outweigh the downsides for the risk of nuclear war, except perhaps if the nuclear deflection is governed by the international community. This analysis is based on the notion that nuclear war is a larger risk than NEO collision. However, the analysis does not provide support for the claim that nuclear war is the larger risk. It also errs in comparing the size of two risks instead of comparing the size of the effect of nuclear deflection on the two risks. Even if nuclear war is the larger risk, nuclear deflection may still provide a net risk reduction if it has relatively little effect on nuclear war risk.

This article improves on this prior literature by providing a more detailed and theoretically sound analysis of the nuclear deflection risk-risk (or risk-risk-risk) tradeoff.

3. THEORY AND ASSUMPTIONS

This article only considers the potential human consequences of nuclear deflection. All other factors are excluded. In the context of nuclear deflection, other factors could include impacts on natural environments, legal and political considerations, scientific insights from deflection missions, and mission cost. Other factors are excluded strictly to focus the analysis. The article does not claim that other factors are irrelevant to nuclear deflection policy. The sole claim is that human consequences are one important factor.

To assess the potential human consequences, the article uses an undiscounted expected utility decision parameter, in which decision makers base their decision at least in part on the effect that decision option(s) have on the expected value of human welfare integrated across space and time, with all units of welfare counted equally:

$$D_u(x) = E\left[\int_{t=1}^{T} u(x,t)\,\partial t\right] \tag{1}$$

In Equation (1), D_u is the decision parameter for utility, x is the decision option being evaluated, E is the expected value operator, T is the time horizon, and u(x,t) is the total welfare (utility) of the population alive at time t if decision option x is pursued. Each element of {x} is a specific potential nuclear deflection program; {x} includes having no nuclear deflection at all. The decision parameter D_u is taken as one factor in decision making; other factors are not evaluated in this article. A decision option x_1 is taken to be better *in terms of expected utility* than another decision option x_2 if $D_u(x_1) > D_u(x_2)$, though x_1 is not necessarily better *overall* than x_2 once any other factors besides expected utility are accounted for. In Equation (1), utility can be interpreted as either the satisfaction of human preferences or the quality of life experienced by humans (Broome, 1991; Kahneman & Sugden, 2005; Ng, 2003). Additionally, Equation (1) can be interpreted as being risk-neutral in the sense that possible changes in utility are weighted according to their probability. Although it is possible that utility definitions and probability weighting could have some effect on the analysis, that is beyond the scope of this article. As with any decision parameter, expected utility is subject to normative critique, but it also has substantial philosophical support and is transparent and easy to interpret.

To simplify the analysis, the article assumes that expected utility is only affected by the risk of asteroid collision and the risk of violent (nuclear or non-nuclear) conflict. Thus, the decision parameter can be rewritten as:

$$D_u(x) = -\sum_{a=1}^{A} p(x,a)s(x,a) - \sum_{c=1}^{C} p(x,c)s(x,c) \tag{2}$$

In Equation (2), A and C are the sets of potential asteroid collisions and violent conflicts, while p and s are their probabilities and severities, with severity defined as loss of utility. Thus, decision options with larger asteroid collision risk and larger violent conflict risk yield lower values of D_u.

The article further assumes that non-nuclear deflection is used to the extent that it reduces asteroid collision risk. Prior studies have found that non-nuclear deflection can succeed for sufficiently small and non-imminent asteroid collisions (Ahrens & Harris, 1992; NASA, 2007; NRC, 2010). Non-nuclear deflection technologies pose much weaker risk-risk tradeoffs and also have legal and political advantages (Koenig & Chyba, 2007). Given this assumption, the effect of nuclear deflection on expected utility is evaluated in terms of (1) the additional reduction in asteroid collision risk it brings beyond what is already achieved from non-nuclear deflection and (2) any change in violent conflict risk it causes:

$$D_u(x) = -\Delta_{nd} \sum_{a=1}^{A} p(x,a)s(x,a) - \Delta_{nd} \sum_{c=1}^{C} p(x,c)s(x,c) \tag{3}$$

In Equation (3), Δ_{nd} is the change in expected utility due to nuclear deflection. If a nuclear deflection program causes a net decrease in risk to human utility, then D_u will be positive and the nuclear deflection program will be a good decision option *in terms of expected utility*, though, as elaborated above, whether it is a good decision option *overall* may also depend on other factors.

Finally, the article assumes that all deflection technologies will be used strictly to deflect Earthbound asteroids away from Earth. Harris et al. (1994) propose that asteroid deflection technology could be used to intentionally redirect non-Earthbound asteroids into Earthbound trajectories. However, it is unlikely that such a feat would be attempted. Globally catastrophic asteroid collisions are broadly undesirable. There are extremely few people who wish to cause global catastrophe—the rare exceptions include, for example, select apocalyptic cults. These people are unlikely to have asteroid deflection capabilities, and are more likely to pursue other options, such as the engineering of dangerous pathogens (Torres, 2016). Meanwhile, collisions that cause regional damage are much more difficult to orchestrate than traditional means of violence. Thus it is assumed that nuclear deflection does not intentionally increase asteroid collision risk. Nuclear deflection could inadvertently increase the risk in some mission failure scenarios, such as if the asteroid is deflected from an unpopulated to a populated location on Earth, or if the asteroid is fragmented and the fragments remain on an Earthbound trajectory (NRC, 2010).

4. RISK ANALYSIS

4.1 Probability of Asteroid Collision

As of 22 June 2018, NASA lists 18,438 known NEOs, including 18,331 asteroids and 107 comets (NASA Jet Propulsion Laboratory 2018). Mainzer et al. (2011) estimate approximately 1,000 NEOs of diameter 1km or larger and approximately 20,000 NEOs of diameter 100m or larger; Harris and D'Abramo (2015) report similar results.[9] Additional NEOs are identified on an ongoing basis, indicating that the total number is larger than this. Larger NEOs are easier to identify, so the unidentified NEOs will tend to be of smaller size (Mainzer et al., 2014).

The long-term rate of asteroid-Earth collisions is commonly taken to follow an approximately power-law distribution as a function of asteroid diameter. 10m asteroids collide approximately once per 10 years, 100m once per 1,000 years, and 1km once per one million years (Harris et al., 2015). More precisely, Harris (2008) gives a 10^{-8} annual probability for collision with 10km diameter asteroids (as in the Cretaceous-Paleogene extinction event) and a 6.7×10^{-4} annual probability for 50m diameter asteroids (as in the 1908 Tunguska collision). Chapman and Morrison (1994) estimate a 10^{-6} annual probability for asteroids of diameter 2km or larger. Recent research proposes that asteroid collision probability estimates are significantly underestimated due to undercounting of hard-to-detect ocean collisions (Gusiakov, Abbott, Bryant, Masse, & Breger, 2010), but this proposal has been disputed on scientific grounds (Bourgeois & Weiss, 2009; Goff, Dominey-Howes, Chagué-Goff, & Courtney, 2010).

The estimated rate of asteroid collision can change over time. On astronomical time scales, the collision rate has gradually lowered due to the stabilization of planetary orbits and the accretion of small asteroids and comets (NRC, 2010). On human time scales, the estimated rate is changing due to the findings of asteroid monitoring programs, especially for larger asteroids, which are easier to detect. Mainzer et al. (2011) report the detection of 90% of NEOs of diameter 1km or larger, 25% at 100m, and less than 1% at 20m, with none found to be on course for Earth collision. Harris et al. (2015) estimate ~100% of asteroids of diameter≥4km have been detected, with detection rates decreasing down to a minimum of ~10m.

4.2 Probability of Violent Nuclear Conflict

Nine states are believed to possess nuclear weapons, with a total of approximately 3,600 deployed and 14,450 total nuclear weapons worldwide (Federation of American Scientists [FAS], 2018). About 90% of the weapons are held by Russia and the United States. China, France, India, Israel, Pakistan, and the United Kingdom each possess nuclear arsenals in the range of 80 to 100 weapons. North Korea is believed to have no more than twenty nuclear weapons. These numbers are much lower than the Cold War peak of over 60,000 nuclear weapons, but current arsenals still pose significant risk.

The probability of violent nuclear conflict is more difficult to estimate than the probability of asteroid collision because violent nuclear conflict depends on complex and dynamic social factors. The historical record offers some data but requires subtle interpretation. There has been one nuclear war (World War II) in seventy-five years, but this does not imply a one-in-seventy-five annual probability because geopolitical conditions have changed. For example, unlike during WWII, today multiple countries have sizable nuclear arsenals. This creates more

---

[9] Although NEO diameter makes for a convenient metric, NEO collision energy (and thus severity) also depends on NEO density, NEO velocity relative to Earth, the angle of NEO trajectory relative to Earth, and the density of the ground on Earth if the collision occurs on land (Collins, Melosh, & Marcus, 2005; Reinhardt, Chen, Liu, Manchev, & Paté-Cornell 2016).

opportunity for nuclear war, but it also enables deterrence, which may reduce the probability. An important ongoing factor is the quality of relations between nuclear-armed countries. For example, the probability of nuclear war between Russia and the U.S. was presumably higher during the tensest moments of the Cold War than it was after the Cold War ended, though it arguably has increased again recently due to instability in Ukraine and related matters.

No nuclear war has occurred since the advent of nuclear deterrence, but there may have been several near misses. For example, during the Cuban Missile Crisis, a Soviet submarine may have nearly launched its nuclear weapons, restrained only by a single officer who refused to order launch. In 1995, after the Cold War, Russian radar operators mistakenly believed that a Norwegian-U.S. scientific weather rocket launch was a nuclear attack, allegedly prompting Russian President Yeltsin to contemplate launching in retaliation. These events suggest a higher ongoing probability, but how high is a matter of historical debate (Lewis, Williams, Pelopidas, & Aghlani, 2014; Tertrais, 2017).

Two recent studies estimate the ongoing probability of specific nuclear war scenarios by modeling the sequences of events in the scenarios. Hellman (2008) models Russia-U.S. nuclear war caused by crises similar to the Cuban missile crisis, finding an annual probability in the range of $2x10^{-4}$ to $5x10^{-3}$. Barrett, Baum, & Hostetler (2013) model Russia-U.S. nuclear war caused by false alarms like the 1995 Norwegian rocket incident, finding an annual probability in the range of approximately 10^{-5} to 0.07, with mean values around 0.01. These studies should be taken with a grain of salt, for example because they are based on historical event frequency data that may not match future event frequencies, but they nonetheless provide a starting point for thinking about nuclear war probabilities. Note that the total probability across all nuclear war scenarios will necessarily be larger than the probability for the two scenarios in these studies.

The probability of nuclear terrorism is modeled by Bunn (2006). Bunn models the total probability of nuclear terrorism across all scenarios and tentatively estimates an annual probability of nuclear terrorism of approximately 0.03, corresponding to an average of one nuclear terrorist attack per 33 years. However, the Bunn model parameters are not rigorously supported but instead are described as just one set of plausible estimates. Additionally, the parameters are point estimates that do not account for uncertainties in the process of terrorists obtaining and using nuclear weapons. Thus, it is difficult to assess the meaning of the 0.03 annual probability estimate.

4.3 Severity of Asteroid Collision and Violent Nuclear Conflict

Both asteroid collisions and nuclear weapons detonations involve explosions. Their effects are likewise similar. A primary difference is the absence of ionizing radiation from asteroid collisions.

The standard physical measure for the severity of asteroid collisions and nuclear detonations is the amount of energy released, in units of tons (T), kilotons (KT), or megatons (MT) of TNT equivalent.[10] The 2013 Chelyabinsk asteroid collision was about 20m in diameter and 500KT (Brown et al., 2013). This is about double the smallest size believed to be able to cause damage on Earth's surface; smaller collisions explode harmlessly in the upper atmosphere (Harris et al., 2015). The Chicxulub impactor was an estimated 10km and 10^8MT (Chapman & Morrison, 1994). Nuclear weapons have been made as small as around 10T (the U.S. W54 weapon) and as large as 50MT (the Soviet Tsar Bomba). There is no physical limit to how large of a nuclear

---

[10] This is a reasonable metric, though asteroids can cause additional damage due to their momentum (Boslough, 2010) and nuclear weapons can cause additional damage due to their ionizing radiation.

weapon can be built. Common nuclear weapon yields are tens to hundreds of KT, and some have yields of several MT (Kristensen and Norris, 2018a, 2018b, 2018c).

The extent of the damage depends on the amount of energy released and the location on Earth. The 1908 Tunguska collision caused ecological damage across a wide area of Siberia but no significant human harm, though if it had collided four hours later it could have hit Saint Petersburg (Longo, 2007). The locations of asteroid collisions are essentially random, so most occur at ocean locations. The locations of nuclear weapons explosions are not random. In military planning, most nuclear weapons are targeted at either cities or military installations, while test explosions are conducted in remote locations or underground to minimize harm.

The local harms from asteroid collisions and nuclear weapons explosions are relatively simple and well understood. The immediate vicinity is disturbed or destroyed. The Hiroshima and Nagasaki bombings provide indicative data. They were hit with bombs of 15-20KT yield detonated at altitudes around 500-600m (to maximize damage) over the center city. Fatalities were about 120,000 people in Hiroshima and 60,000 in Nagasaki; the Hiroshima number is likely larger due to flatter terrain and drier conditions that enabled the blast and accompanying firestorm to spread (Toon et al., 2007). Nuclear detonations with higher yields and at larger cities could bring many times more fatalities.

In comparison, local effects from asteroid collisions could be larger than single nuclear detonations due to their potential for larger event energies. However, local effects from asteroid collisions would typically see less human harm due to their occurrence at random locations, which are likely to be uninhabited or sparsely populated. Asteroid risk analyses commonly calculate local severity based on the population within a 2 to 4 psi blast overpressure damage area (Canavan, 1993, 1994; Garrick, 2008; Mathias, 2017; Stokes et al., 2003), which is based on studies of nuclear weapons (Glastone, 1962; Glastone & Dolan, 1977).

A sufficiently large asteroid collision at an ocean would cause a tsunami. The current literature lacks consensus on how severe the tsunami would be. Gusiakov et al. (2010) propose that several massive asteroid-caused tsunamis have occurred in recent millennia, but this proposition is hotly disputed (Bourgeois & Weiss, 2009; Goff et al., 2010; Pinter & Ishman, 2008). Other studies suggest that asteroid-caused tsunamis are much less severe (Gisler, Weaver, & Gittings, 2011; Korycansky & Lynett, 2005).

The most severe asteroid collisions and nuclear wars can cause global environmental effects. The core mechanism is the transport of particulate matter into the stratosphere, where it can spread worldwide and remain aloft for years or decades. Large asteroid collisions create large quantities of dust and large fireballs; the fire heats the dust so that some portion of it rises into the stratosphere. The largest collisions, such as the 10km Chicxulub impactor, can also eject debris from the collision site into space; upon reentry into the atmosphere, the debris heats up enough to spark global fires (Toon, Zahnle, Morrison, Turco, & Covey, 1997). The fires are a major impact in their own right and can send additional smoke into the stratosphere. For nuclear explosions, there is also a fireball and smoke, in this case from the burning of cities or other military targets.

While in the stratosphere, the particulate matter blocks sunlight and destroys ozone (Toon et al., 2007). The ozone loss increases the amount of ultraviolet radiation reaching the surface, causing skin cancer and other harms (Mills, Toon, Turco, Kinnison, & Garcia, 2008). The blocked sunlight causes abrupt cooling of Earth's surface and in turn reduced precipitation due to a weakened hydrological cycle. The cool, dry, and dark conditions reduce plant growth. Recent studies use modern climate and crop models to examine the effects for a hypothetical India-

Pakistan nuclear war scenario with 100 weapons (50 per side) each of 15KT yield. The studies find agriculture declines in the range of approximately 2% to 50% depending on the crop and location.[11] Another study compares the crop data to existing poverty and malnourishment and estimates that the crop declines could threaten starvation for two billion people (Helfand, 2013). However, the aforementioned studies do not account for new nuclear explosion fire simulations that find approximately five times less particulate matter reaching the stratosphere, and correspondingly weaker global environmental effects (Reisner et al., 2018). Note also that the 100 weapon scenario used in these studies is not the largest potential scenario. Larger nuclear wars and large asteroid collisions could cause greater harm. The largest asteroid collisions could even reduce sunlight below the minimum needed for vision (Toon et al., 1997). Asteroid risk analyses have proposed that the global environmental disruption from large collisions could cause one billion deaths (NRC, 2010) or the death of 25% of all humans (Chapman, 2004; Chapman & Morrison, 1994; Morrison, 1992), though these figures have not been rigorously justified (Baum, 2018a).

The harms from asteroid collisions and nuclear wars can also include important secondary effects. The food shortages from severe global environmental disruption could lead to infectious disease outbreaks as public health conditions deteriorate (Helfand, 2013). Law and order could be lost in at least some locations as people struggle for survival (Maher & Baum, 2013). Today's complex global political-economic system already shows fragility to shocks such as the 2007-2008 financial crisis (Centeno, Nag, Patterson, Shaver, & Windawi, 2015); an asteroid collision or nuclear war could be an extremely large shock. The systemic consequences of a nuclear war would be further worsened by the likely loss of major world cities that serve as important hubs in the global economy. Even a single detonation in nuclear terrorism would have ripple effects across the global political-economic system (similar to, but likely larger than, the response prompted by the terrorist attacks of 11 September 2001).

It is possible for asteroid collisions to cause nuclear war. An asteroid explosion could be misinterpreted as a nuclear attack, prompting nuclear attack that is believed to be retaliation. For example, the 2013 Chelyabinsk event occurred near an important Russian military installation, prompting concerns about the event's interpretation (Harris et al., 2015).

The ultimate severity of an asteroid collision or violent nuclear conflict use would depend on how human society reacts. Would the reaction be disciplined and constructive: bury the dead, heal the sick, feed the hungry, and rebuild all that has fallen? Or would the reaction be disorderly and destructive: leave the rubble in place, fight for scarce resources, and descend into minimalist tribalism or worse? Prior studies have identified some key issues, including the viability of trade (Cantor, Henry, & Rayner, 1989) and the self-sufficiency of local communities (Maher & Baum, 2013). However, the issue has received little research attention and remains poorly understood. This leaves considerable uncertainty in the total human harm from an asteroid collision or nuclear weapons use. Previously published point estimates of the human consequences of asteroid collisions[12] and nuclear wars (Helfand, 2013) do not account for this uncertainty and are likely to be inaccurate.

Of particular importance are the consequences for future generations, which could vastly outnumber the present generation. If an asteroid collision or nuclear war would cause human extinction, then there would be no future generations. Alternatively, if survivors fail to recover a large population and advanced technological civilization, then future generations would be

---

[11] Özdoğan, Robock, & Kucharik (2012); Xia, Robock, Mills, Stenke, & Helfand (2015).

[12] Chapman (2004); Chapman & Morrison (1994); Harris (2008); Morrison (1992).

permanently diminished. The largest long-term factor is whether future generations would colonize space and benefit from its astronomically large amount of resources (Tonn, 1999). However, it is not presently known which asteroid collisions or nuclear wars (if any) would cause the permanent collapse of human civilization and thus the loss of the large future benefits (Baum et al., 2019). Given the enormous stakes, prudent risk management would aim for very low probabilities of permanent collapse (Tonn, 2009).

It should be noted that the severity of violent nuclear conflict could depend on more than just the effects of nuclear explosions, because the overall conflict scenario could include non-nuclear violence. Indeed, it is possible for the nuclear explosions to constitute a relatively small portion of the total severity, as was the case in World War II.

4.4 Risk of Violent Non-Nuclear Conflict

Finally, it is necessary to discuss the risk of violent non-nuclear conflict. Only a small portion of violent non-nuclear conflicts are applicable, specifically the portion affected by nuclear weapons. More precisely, this section discusses non-nuclear conflicts involving one or more countries that possess nuclear weapons at some point during the lifetime of a nuclear deflection program.

Nuclear deterrence theory predicts that nuclear-armed adversaries will not initiate major wars against each other because both sides could be destroyed in a nuclear war. However, the theory does permit limited, small-scale violent conflicts between nuclear-armed countries. These conflicts likely would not involve nuclear weapons. Indeed, nuclear deterrence may even make small violent conflicts more likely, because the countries know that neither side wants to escalate the conflict into major war. This idea is known as the stability-instability paradox: nuclear deterrence brings stability with respect to major wars but instability with respect to minor conflicts. Empirical support for the stability-instability paradox has been found by some research (Rauchhaus, 2009), while other research has found no significant effect of the possession of nuclear weapons on the probability of conflicts of any scale (Bell & Miller, 2015; Gartzke & Jo, 2009).

If countries fully disarm their nuclear arsenals, such that they would never have nuclear weapons again, then there would be no nuclear deterrence to prevent the onset of major wars. A simple risk analysis could assume that the risk of major wars would be comparable to the risk prior to the development of nuclear weapons. The two twentieth century World Wars combined for around 100 million deaths in 50 years,[13] suggesting an annualized risk of two million deaths. However, two World Wars do not make for a robust dataset. Indeed, the robustness of these two data points is called into question by historical analysis finding that both world wars might not have occurred in the reasonably plausible event that the 1914 assassination of Archduke Ferdinand had failed (Lebow, 2014). Similarly, another historical analysis finds that the U.S. and Soviet Union would probably not have waged major war against each other even in the absence of nuclear deterrence (Mueller, 1988). Furthermore, these past events are not necessarily applicable to the future conditions of a post-nuclear-disarmament world. To the best of the present author's knowledge, no studies have analyzed the risk of major wars in a post-nuclear-disarmament world.

5. NUCLEAR DEFLECTION EFFECT ON ASTEROID RISK

As discussed in Section 3, this article assumes that non-nuclear deflection techniques will be used wherever possible. With this assumption, nuclear deflection is only beneficial for the

---

[13] WWII was a nuclear war, but only at the tail end and only for a small portion of total deaths.

portion of asteroid risk that cannot be addressed by non-nuclear means. Therefore, the analysis must consider the portion of asteroid risk that can be eliminated via non-nuclear deflection.

Perhaps the most promising non-nuclear deflection technique uses kinetic impactors to displace asteroids. Kinetic impactors use established technologies, unlike some of the more exotic techniques that have been proposed, such as solar sails and gravity tractors (NRC, 2010). Additionally, kinetic impactors could be highly effective. The success of a kinetic impactor depends on the mass of the asteroid and the lead time before it would strike Earth. Longer lead times permit smaller impacts to deflect the asteroid away from Earth. Koenig and Chyba (2007) propose that kinetic impactors could be effective for asteroids up to 500m given two decades lead time or up to 1km given one century lead time. For larger asteroids and/or smaller lead times, it may be possible to improve the efficacy of the kinetic impactor technique by using more impactors. It has been proposed that a flotilla with 100 or more kinetic impactors could deflect asteroids larger than 1km, and that nuclear explosives are only needed for asteroids 500m or greater with warning times in years to months.[14] A flotilla could substantially increase mission complexity and cost (Dearborn & Miller, 2015), though these factors are beyond the scope of the present study.

The efficacy of kinetic impactors suggests a relatively small portion of asteroid risk for which nuclear deflection is beneficial. Assuming a 10^5 year recurrence interval for 500m or larger asteroids,[15] it follows that there is at most a 10^{-4} probability of needing nuclear deflection per decade. In other words, at the beginning of a given decade, if all >500m asteroids are instantaneously detected, there is a $\sim 10^{-4}$ probability that one of them would be on trajectory to collide with Earth within the decade, in which case nuclear deflection would be needed. For asteroids that would not collide with Earth, no deflection would be needed. For asteroids that would collide with the Earth later than a decade away, kinetic impactors could be used; therefore, subsequent decades would not need nuclear deflection. Recalling the reported 90% detection for 1km diameter and 25% for 100m (Mainzer et al., 2011), the estimate can be reduced to $\sim 5 \times 10^{-5}$ per decade, which assumes 50% detection for 500m.

The $\sim 5 \times 10^{-5}$ per decade figure is an upper bound for the reduction in collision probability for >500m asteroids from nuclear deflection. It assumes that all currently undetected >500m asteroids are detected at the beginning of a given decade, when in fact only a portion of them are likely to be detected at any one time. Additionally, it assumes a 100% success rate for nuclear deflection missions, when in fact any given mission presumably has some nonzero chance of failure. Indeed, for sufficiently large and imminent collisions, nuclear deflection may not be viable, or may involve a substantial risk of fragmenting the asteroid and leaving some fragments on a trajectory to collide with Earth (Dearborn & Miller, 2015; NRC, 2010), though some research has found that only a small fraction of fragments would collide with Earth (Kaplinger, Wie, & Dearborn, 2014).

The above concerns collision probability. Regarding collision severity, asteroids >500m are within the range capable of causing severe global environmental damage. It follows that while the probability of needing nuclear deflection is low, the risk reduction from nuclear deflection is nontrivial. For illustration, if the collision results in 10^9 deaths, as was assumed by a National Research Council report (NRC, 2010), then nuclear deflection could save the equivalent of

---

[14] See NRC (2010, p. 74-79). Reinhardt et al. study NEO deflection in a risk model, finding at most a 29% risk reduction without nuclear explosives and as much as an 84% risk reduction with nuclear explosives (2014). However, this study does not consider flotillas of kinetic impactors and thus may overstate the role of nuclear explosives.

[15] See e.g. Fig. 2 of Harris (et al. 2015).

~$5\text{x}10^4$ lives per decade. The 10^9 figure should be taken for illustration only because the human consequences of such global environmental damage have not been rigorously quantified (Baum, 2018b).

6. NUCLEAR DEFLECTION EFFECT ON VIOLENT CONFLICT RISK

The effect of nuclear deflection on violent conflict risk is subtler and more difficult to quantify than the effect on asteroid risk. This section surveys some potential effects.

6.1 The Effect of Nuclear Weapons on Violent Conflict Risk

As a starting point, it is important to consider the overall effect of nuclear weapons on the risk of violent conflict. A major point of international debate is on the ongoing merits of nuclear weapons and whether (and under what circumstances) they should be disarmed. In risk terms, this can be expressed as the question of whether (and under what circumstances) the risk of violent conflict is larger with or without nuclear weapons. If the risk is larger with nuclear weapons, then this is a point in favor of disarmament, though there can also be other significant factors in disarmament decisions.

The effect of nuclear weapons on the frequency of violent conflict relates to the efficacy of nuclear deterrence. The absence of major war since World War II is sometimes taken as evidence that nuclear deterrence prevents or at least reduces the frequency of major wars (Mies, 2012), but the size of this effect is controversial and poorly understood.[16] Evidence for the effect of nuclear weapons on small-scale violent conflict is likewise mixed (Bell & Miller, 2015; Gartzke & Jo, 2009; Rauchhaus, 2009).

The effect of nuclear weapons on the severity of violent conflict derives from the outsized explosive power of nuclear weapons. In many scenarios, this results in an increase in severity, potentially a very large increase. For example, nonnuclear warfare may be unlikely to cause global devastation comparable to nuclear winter. That said, there are plausible scenarios in which nuclear weapons decrease the severity of war, such as in the Russian concept of “de-escalatory” nuclear strikes, which proposes limited use of nuclear weapons to end conflict on favorable terms before it escalates into all-out war (Sokov, 2014). There are also scenarios in which nuclear weapons have a relatively marginal effect on the severity, as was the case in World War II, though that may be a weak precedent given how much larger the world’s nuclear arsenals have since grown.

Another factor is that, in the event that the world completely disarms its nuclear arsenals, the residual risk of nuclear war may not be zero. This is because arsenals could be rebuilt, especially if the knowledge and industrial capacity to rebuild remain intact. Indeed, it has been argued that nuclear war may be more probable with zero nuclear weapons, because countries would initiate dangerous races to rebuild arsenals during crises (Schelling, 2009). Likewise, it has been proposed that complete disarmament should be accompanied by additional steps to prevent states from rebuilding nuclear arsenals, such as international controls over certain nuclear materials (Lodgaard, 2009). These ideas are largely theoretical and have not been evaluated in risk terms.

Overall, it is not readily clear whether nuclear weapons cause a net increase or decrease in the risk of violent conflict (Baum, 2018b). Indeed, as discussed in Section 4, the ongoing risk of

---

[16] Compare, for example, Lewis et al. (2014), arguing that nuclear deterrence almost failed in several instances, to Tertrais (2017), arguing that nuclear deterrence was not actually close to failing in these instances, or Mueller (1988), arguing that there would have been no third World War even without nuclear deterrence.

violent conflict is not well characterized. This is important to bear in mind for several aspects of the effect of nuclear deflection on violent conflict risk.

6.2 The Effect of Nuclear Deflection on Nuclear Weapons Disarmament and Proliferation

One argument made against nuclear deflection is that it conflicts with the policy goal of complete disarmament down to zero nuclear weapons (Graham & Schweickart, 2008). Recalling the analysis of Section 6.1, it is unclear what the net effect of complete nuclear disarmament would be on violent conflict risk, and it is similarly unclear what the net effect would be if there is disarmament of all nuclear weapons except for some designated for nuclear deflection. Regardless, at this time, it is not essential to evaluate the effect of nuclear deflection on complete nuclear disarmament. This is because the world has many more than zero nuclear weapons, and indeed many more than is needed for asteroid deflection. One study finds that an asteroid can be deflected with a single nuclear weapon, with larger asteroids requiring higher-yield nuclear weapons: 100T for a 100m asteroid up to 100KT for a 10km asteroid (Ahrens & Harris, 1992). A robust nuclear deflection program would maintain multiple nuclear weapons for redundancy or for the possibility of multiple incoming asteroids, but there clearly is room for extensive nuclear disarmament while still retaining an ample collection for asteroid deflection. Likewise, nuclear deflection would not be significant for "beating swords into ploughshares" (Mellor, 2007) because it would not make a significant dent in global nuclear arsenals.

More significant for present policy purposes is the possibility that nuclear deflection could affect the rate of nuclear disarmament. The disarmament rate is a hotly contested international issue, with many non-nuclear-armed states and non-governmental organizations articulating the concern that the nuclear-armed states are not progressing on disarmament fast enough; the nuclear-armed states likewise defend their progress (Sauer, 2015). Many of these non-nuclear-armed states and non-governmental organizations are working to stigmatize the possession of nuclear weapons as a strategy to hasten nuclear disarmament (Borrie, 2014; Fihn, 2013). Nuclear deflection programs could weaken the possession stigma by claiming a legitimate and constructive role for nuclear weapons. This could in turn slow down nuclear disarmament. However, again recalling the analysis of Section 6.1, it is unclear what the net effect of slower nuclear disarmament would be on violent conflict risk.

It should be noted that the nuclear weapon possession stigma is ultimately a psychological phenomenon. As such, it can be affected not just by nuclear deflection programs, but also by merely *talking about* nuclear deflection. To the extent that spoken support for nuclear deflection could affect violent conflict risk, this should be factored into broader asteroid risk communication efforts (Billings, 2015).

Nuclear deflection programs could also affect nuclear proliferation. There is historical precedent for this in China's 1996 refusal to sign the CTBT. The refusal was nominally justified by China's interest in nuclear deflection, but that was suspected to be a cover explanation enabling China to continue nuclear testing in order to improve its military nuclear arsenal.[17] Such activities constitute "vertical proliferation", which is the expansion and improvement of existing nuclear arsenals (Sidel & Levy, 2007). Nuclear deflection could also cause horizontal proliferation, which is the creation of new nuclear arsenals by states that did not previously have them. The effect on vertical or horizontal proliferation could depend on whether nuclear deflection programs had participation from nuclear-armed or non-nuclear-armed states. The effect could also come via weakening the stigma on nuclear weapon possession, or by weakening

---

[17] See Garver (2001, p.359).

international treaties such as the CTBT. Regardless, once again it is unclear what the net effect on violent conflict risk would be.

6.3 The Effect of Nuclear Deflection on Nuclear Weapons Use

Nuclear deflection programs could affect the propensity of nuclear-armed states to use their weapons, which factor significantly in the risk of violent conflict. The key mechanism here is the stigma or norm against nuclear weapon use, often referred to as the nuclear taboo (Schelling, 2006; Tannenwald, 2005).

The nuclear taboo is often credited as a major factor, perhaps *the* major factor, explaining the absence of nuclear war since World War II.[18] Importantly, the taboo has been applied to all nuclear explosions, not just the violent ones, largely due to a general revulsion toward nuclear weapons. Non-violent explosions that have been protested on these grounds include test detonations and peaceful nuclear explosions for excavating canals or producing steam for electricity generation. The concern is that any acceptance of nuclear explosions increases their legitimacy and weakens the taboo, thereby making violent nuclear explosions more likely (Schelling, 2006). Tensions between nuclear deflection and various international treaties, as discussed in the extensive nuclear deflection legal scholarship,[19] could also weaken the taboo. Thus, Schelling (2006) writes: “I know of no more powerful argument in favor of the Comprehensive Test Ban Treaty, which the Senate rejected in 1999, than the potential of that Treaty to enhance the nearly universal revulsion against nuclear weapons. The symbolic effect of nearly 200 nations ratifying the CTBT, which is nominally only about testing, should add enormously to the convention that nuclear weapons are not to be used and that any nation that does use nuclear weapons will be judged the violator of the legacy of Hiroshima.”

In risk terms, the value of the taboo comes less from avoiding the mere use of nuclear weapons and more from avoiding their use at large scale. It is possible for nuclear weapons to be used in a limited fashion with limited effect on the aggregate severity of a conflict; World War II is a case in point. The concern is that if it becomes permissible to use some nuclear weapons, it becomes more likely that they would be used at scale. Thus, policy discussions speak of a “firebreak” between conventional and nuclear weapons as a clear place to draw the line so as to stay safely away from large-scale nuclear war (Schelling, 2006).

Whether the taboo does indeed bring a net risk reduction depends on the importance of the firebreak. If it is relatively feasible to have limited use of nuclear weapons without escalating to large-scale nuclear war, then the taboo is less important. The feasibility of avoiding escalation is difficult to evaluate, in part because there are no precedents to learn from. The only nuclear war thus far was World War II, but at that time escalation was impossible because there were no large nuclear arsenals. The issue of escalation is central to ongoing debates about nuclear weapons procurement, such as recent debates over US proposals to acquire more low-yield nuclear weapons intended for use in limited nuclear conflicts (Narang, 2018). If it is difficult to avoid escalation, then the taboo is important and nuclear deflection programs may increase the risk of violent conflict, perhaps quite substantially.

---

[18] Schelling (2006); Tannenwald (2005). There are competing explanations, such as the reluctance of the United States and the Soviet Union to wage any major war against each other (Mueller, 1988).

[19] Bucknam & Gold (2008); Chapman (1999); Gerrard & Barber (1997); Kunich (1997); Mayer (2015); Packer et al. (2013); Remo (1996); Schweickart et al. (2008); Su (2015); Sweet (1999).

7. POLICY ANALYSIS

7.1 Nuclear Deflection

In light of the preceding considerations, does nuclear deflection increase expected utility to human populations by causing a net reduction to the risks of asteroid collision and violent conflict? Recalling Equation (3), is D_u greater or less than zero? Section 5 found that nuclear deflection could reduce the probability of collision with asteroids of 500m or larger diameter by up to around $5x10^{-5}$ per decade, or $5x10^{-6}$ per year, so the question is whether nuclear deflection increases violent conflict risk by more or less than this amount.

This question is not easily answered. Indeed, it is not even clear whether nuclear deflection increases or decreases violent conflict risk. Nuclear deflection might weaken the stigma on possessing nuclear weapons, thereby slowing nuclear disarmament and prolonging the availability of nuclear deterrence, thereby reducing violent conflict risk. Nuclear deflection might also strengthen nuclear deterrence by facilitating nuclear proliferation. Nuclear deflection might also weaken the taboo on nuclear weapon use, facilitating strategies that reduce the severity of nuclear war such as Russia's concept of de-escalatory nuclear strikes. Proponents of nuclear deterrence or nuclear warfighting could plausibly support nuclear deflection on these grounds, regardless of any effect on asteroid collision risk.

Other analysts would likely reach different conclusions. Indeed, a hallmark of the study of violent conflict risk is the preponderance of expert disagreement, on matters such as how close various historical incidents came to nuclear war (Lewis et al., 2014; Tertrais, 2017), the importance of nuclear weapons to deterrence (Mueller, 1988), and the prospect of limited nuclear weapon use escalating to large-scale use (Narang, 2018). It should likewise be expected that different analysts would reach different conclusions on the effect of nuclear deflection on violent conflict risk, and on the overall merits of nuclear deflection. This is not to say that the matter is hopeless. To the contrary, a primary value of risk analysis is to lay out the issues, clarify points of disagreement, and reach a better overall understanding of the policy decision.

With that in mind, what follows is the author's own judgment on the balance of risks affected by nuclear deflection. First, nuclear deflection is judged to cause a net increase in violent conflict risk, mainly by weakening the taboo on nuclear weapon use, with other effects on violent conflict risk being smaller or too ambiguous to factor in. Second, the annual probability of nuclear war is estimated at around 0.1 to 10^{-4}, as is loosely suggested by previous studies (Barrett et al., 2013; Hellman, 2008). This range is 20 to 20,000 times larger than the $5x10^{-6}$ upper bound annual probability of asteroid collision affected by nuclear deflection. This leaves the question of whether the effect of nuclear deflection on the nuclear weapon use taboo increases the annual probability of nuclear war by more than $5x10^{-2}$ to $5x10^{-5}$. This effect is particularly uncertain, but it is the present author's judgment that yes, the effect is probably that large, such that nuclear deflection would cause a net increase in risk. However, the present author has low confidence in this conclusion, due to the myriad uncertainties throughout the issue.

The above discussion treats nuclear deflection programs uniformly, without considering the particulars of how nuclear deflection programs could be designed. For example, it has been suggested that the effect of nuclear deflection programs on violent conflict risk would be better if the programs have a high degree of international cooperation (Baum, 2015; Remo, 2015). The effects of nuclear deflection program design may be important but are beyond the scope of this article.

Finally, it is worth recalling that nuclear deflection may only be necessary in the event of the detection of an Earthbound asteroid that could only be deflected by nuclear explosion. In this event, nuclear deflection could reduce the collision probability by ~1, i.e. it would change a near-certainty of collision to a near-certainty of no collision. Even with a substantial probability of mission failure, such that collision avoidance is not assured, the effect would very likely dwarf any potential effect on nuclear weapon risk. Thus, while nuclear deflection programs may increase net risk at present, that would likely change if an asteroid requiring nuclear deflection were detected.

7.2 Other Policy Options

Though they are not the focus of this paper, it is worth briefly noting that there are some other policy options with the potential to reduce asteroid and/or nuclear weapon risks without posing a risk-risk tradeoff. These include further asteroid detection and development of non-nuclear deflection options. The sooner asteroids are detected, the more likely humanity will be able to deflect any Earthbound asteroids away, and to do so without nuclear explosives.

Another policy option is international cooperation. The asteroid threat provides a common "enemy" against which all nations can partner to fight. There have been several calls for international cooperation on asteroid risk reduction,[20] including for deflection.[21] Cooperation on the asteroid threat could reduce tensions between adversarial nuclear-armed states, or, at a minimum, it would presumably not increase tensions.

Finally, policy can seek to aid survivors of asteroid collisions and nuclear weapon explosions. As discussed in Section 4.3, the two types of events have similar effects, which creates strong synergies in survival policies. For example, large nuclear wars and asteroid collisions both threaten the global food supply, which can be addressed by the same extreme food security measures (Baum, Denkenberger, Pearce, Robock, & Winkler, 2015). Other measures could help survivors by preparing medical triage and evacuating devastated areas (Garshnek et al., 2000), increasing local self-sufficiency (Maher & Baum, 2013), or arranging resources that would be of value for rebuilding civilization (Dartnell, 2014).

8. CONCLUSION

Nuclear explosives could be highly effective at deflecting Earthbound asteroids away from Earth, but they may also increase the risk of violent conflict. Insofar as policy seeks to keep the world safe from both risks, it should account for this potential risk-risk tradeoff. This article presents an attempt to do so. The analysis is inconclusive due to substantial uncertainties in the risks and the effects of nuclear deflection on the risks, but it nonetheless makes progress on mapping out the relevant factors.

In this article, the author's judgment is that nuclear deflection probably results in a net increase in risk to human welfare, unless a sufficiently large and imminent Earthbound asteroid has been detected. However, this judgment is held with low confidence, and other analysts may reach different conclusions given the available evidence. Further research could provide better guidance, but at least some of the uncertainties may be difficult to reduce, especially those related to rare or unprecedented violent conflict scenarios.

---

[20] NRC (2010); Interagency Working Group for Detecting and Mitigating the Impact of Earth-Bound Near-Earth Objects (2018).

[21] Baum (2015); Bucknam & Gold (2008); Remo (2015); Schweickart et al. (2008).

A firmer conclusion is that nuclear deflection would bring a net risk reduction if an Earthbound asteroid is detected that can only be deflected by nuclear explosives. In this case, the effect of nuclear deflection on violent conflict risk appears to be quite small compared to the effect on asteroid collision risk.

More generally, this article demonstrates the value of an integrated approach to global risk governance. As this article shows, two seemingly unrelated risks—one astronomical, one geopolitical—are interrelated in a way that requires analyzing both risks to inform policy decisions. This presents an inherent challenge, because it is more difficult to master two quite different types of risks. An additional challenge comes from the ambiguous nature of some of the risks. Violent conflict risk analysis has significant uncertainty, and the effect of nuclear deflection on violent conflict risk is further uncertain, but these uncertainties must be addressed in order to evaluate the merits of nuclear deflection. The analysis may be difficult, but it is essential for guiding policy in directions that make the world safer.

Acknowledgments

Tony Barrett, John Remo, Robert Downes, Amy Mainzer, two anonymous reviewers, and Area Editor Warner North provided helpful comments on an earlier version of this paper. Andrea Owe and Robert de Neufville assisted in manuscript preparation. Any remaining errors are the author's alone. The views expressed in this paper are the author's and do not necessarily reflect the views of the Global Catastrophic Risk Institute.

References

Ahrens, T. J., & Harris, A. W. (1992). Deflection and fragmentation of near-Earth asteroids. *Nature, 360*(6403), 429–433.

Alvarez, L.W., Alvarez, W., Asaro, F., & Michel, H. V. (1980). Extraterrestrial cause for the Cretaceous-Tertiary extinction. *Science, 208*(4448),1095-1108.

Barrett, A. M., Baum, S. D., & Hostetler, K. R. (2013). Analyzing and reducing the risks of inadvertent nuclear war between the United States and Russia. *Science and Global Security, 21*(2), 106–133.

Baum, S. D. (2015). Should nuclear devices be used to stop asteroids? *Bulletin of the Atomic Scientists*, 16 June.

Baum, S. D. (2018a). Uncertain human consequences in asteroid risk analysis and the global catastrophe threshold. *Natural Hazards, 94*(2),759–775.

Baum, S. D. (2018b). Reflections on the risk analysis of nuclear war. In B. J. Garrick (Ed.), *Proceedings of the Workshop on Quantifying Global Catastrophic Risks* (pp. 19-50). Los Angeles, CA: University of California, Garrick Institute for the Risk Sciences.

Baum, S. D. & Tonn, B. E. (2015). Confronting future catastrophic threats to humanity. *Futures* (72), 1–3.

Baum, S. D., Denkenberger, D. C., Pearce, J. M., Robock, A., & Winkler, R. (2015). Resilience to global food supply catastrophes. *Environment, Systems, and Decisions, 35*(2), 301–313.

Baum, S. D., & Barrett, A.M. (2017). Towards an integrated assessment of global catastrophic risk. In B. J. Garrick (Ed.), *Proceedings of the First International Colloquium on Catastrophic and Existential Risk* (pp 41-62). Los Angeles, CA: University of California, Garrick Institute for the Risk Sciences.

Baum, S. D., Armstrong, S., Ekenstedt, T., Häggström, O., Hanson, R., Kuhlemann, K., et al. (2019). Long-term trajectories of human civilization. *Foresight*, *21*(1), 53–83.

Bell, M. S. & Miller, N. L. (2015). Questioning the effect of nuclear weapons on conflict. *Journal of Conflict Resolution, 59*(1), 74–92.

Billings, L. (2015). Words matter: A call for responsible communication about asteroid impact hazards and plans for planetary defense. *Space Policy, 33*, 8–12.

Borrie, J. (2014). Humanitarian reframing of nuclear weapons and the logic of a ban. *International Affairs, 90*(3), 625–646.

Boslough, M. (2010). The nature of airbursts and their contribution to the impact threat. Sandia National Laboratories report SAND2010-8425C

Bostrom, N. & Ćirković, M. (2008). *Global Catastrophic Risks*. Oxford: Oxford University Press.

Bourgeois. J. & Weiss. R. (2009). "Chevrons" are not mega-tsunami deposits—a sedimentologic assessment. *Geology, 37*(5), 403–406.

Broome, J. (1991). "Utility". *Economics & Philosophy, 7*(1), 1–12.

Brown, P. G., Assink, J. D., Astiz, L., Blaauw, R., Boslough, M. B., Borovička, J., et al. (2013). A 500-kiloton airburst over Chelyabinsk and an enhanced hazard from small impactors. *Nature, 503*(7475), 238–241.

Bucknam, M. & Gold, R. (2008). Asteroid threat? The problem of planetary defence. *Survival, 50*(5),141–156.

Bunn, M. (2006). A mathematical model of the risk of nuclear terrorism. *Annals of the American Academy of Political and Social Science, 607*(1), 103–120.

Canavan, G H. (1993). Value of space defenses. In G. H. Canavan, J. C. Solem, & J. D. G. Rather (Eds.), *Proceedings of the Near-Earth Object Interception Workshop* (pp. 261-274). Los Alamos, NM: Los Alamos National Lab.

Canavan, G. H. (1994). Cost and benefit of near-Earth object detection and interception. In T. Gehrels (Ed.), *Hazards due to comets and asteroids* (pp. 1157-1190). Tucson, AZ: University of Arizona Press.

Cantor, R. A., Henry, S., & Rayner, S. (1989). *Markets, Distribution, and Exchange After Societal Cataclysm*. Oak Ridge, TN: Oak Ridge National Laboratory.

Centeno, M. A., Nag, M., Patterson, T.S.,, Shaver, A., & Windawi, A.J. (2015). The emergence of global systemic risk. *Annual Review of Sociology, 41,* 65–85.

Chapman, C. R. (1999). History of the asteroid/comet impact hazard. http://www.boulder.swri.edu/clark/ncarhist.html

Chapman, C. R. (2004). The hazard of near-Earth asteroid impacts on earth. *Earth and Planetary Science Letters, 222*, 1–15.

Chapman, C. R. & Morrison, D. (1994). Impacts on the Earth by asteroids and comets: Assessing the hazard. *Nature, 367*(6458), 33–40.

Collins, G. S., Melosh, H. J., & Marcus, R. A. (2005). Earth impact effects program: A web-based computer program for calculating the regional environmental consequences of a meteoroid impact on Earth. *Meteoritics & Planetary Science, 40*(6), 817-840.

Dartnell, L. (2014). *The knowledge: How to rebuild our world after an apocalypse*. New York, NY: Penguin.

Dearborn, D. P.S., Miller, P. L. (2015). Defending against asteroids and comets. In J. N Pelton, F. Allahdadi (Eds.), *Handbook of cosmic hazards and planetary defense* (pp, 733-754). Cham, Switzerland: Springer.

Federation of American Scientists (2018). Status of world nuclear forces. https://fas.org/issues/nuclear-weapons/status-world-nuclear-forces

Fihn, B. (Ed.) (2013). Unspeakable suffering: The humanitarian impacts of nuclear weapons. Geneva, Switzerland: Reaching Critical Will.

Garrick. J. B. (2008) *Quantifying and controlling catastrophic risks*. Burlington, MA: Academic Press.

Garshnek, V., Morrison, D., & Burkle, F. M. Jr. (2000). The mitigation, management, and survivability of asteroid/comet impact with Earth. *Space Policy, 16*, 213–222.

Gartzke, E. & Jo. D. J. (2009). Bargaining, nuclear proliferation, and interstate disputes. *Journal of Conflict Resolution; 53(*2), 209–233.

Garver. J. W. (2001) *Protracted contest: Sino-Indian rivalry in the twentieth century*. Seattle, WA: University of Washington Press.

Gerrard, M. B. & Barber, A. W. (1997). Asteroids and comets: US and international law and the lowest-probability, highest consequence risk. *NYU Environmental Law Journal, 6*, 4–49.

Gisler, G., Weaver, R., & Gittings, M. (2011). Calculations of asteroid impacts into deep and shallow water. *Pure and Applied Geophysics, 168*(6-7), 1187–1198.

Glasstone. S. (1962). *The effects of nuclear weapons*. Washington, DC: United States Atomic Energy Commission.

Glasstone, S. & Dolan, P. J. (1977). *The effects of nuclear weapons*, 3rd edition. Washington, DC: United States Department of Defense and Department of Energy.

Goff. J., Dominey-Howes, D., Chagué-Goff, C., & Courtney, C. (2010). Analysis of the Mahuika comet impact tsunami hypothesis. *Marine Geology, 271*(3), 292–296.

Government Accountability Office (2014). Nuclear weapons: Actions needed by NNSA to clarify dismantlement performance goal. Washington, DC: Government Accountability Office.

Graham, J. D. & Wiener, J. B. (1995). *Risk vs. risk: Tradeoffs in protecting health and the environment.* Cambridge, MA: Harvard University Press.

Graham. T. & Schweickart, R.L. (2008). NASA's flimsy argument for nuclear weapons. *Scientific American* (March), 34–36.

Gusiakov, V., Abbott, D. H., Bryant. E. A., Masse, W. B., & Breger, D. (2010). Mega tsunami of the world oceans: Chevron dune formation, micro-ejecta, and rapid climate change as the evidence of recent oceanic bolide impacts. In T. Beer (Ed.). *Geophysical hazards: Minimizing risk, maximizing awareness* (pp. 197-227). Dordrecht, Netherlands: Springer.

Häggström, O. (2016). *Here be dragons: Science, technology and the future of humanity*. Oxford, UK: Oxford University Press.

Harris, A. W. (2008). What Spaceguard did. *Nature, 453*(7199), 1178–1179.

Harris, A. W. & D'Abramo, G. (2015). The population of near-Earth asteroids. *Icarus, 257*, 302-312.

Harris, A. W., Canavan, G. H., Sagan. C., & Ostro, S. J. (1994). The deflection dilemma: Use versus misuse of technologies for avoiding interplanetary collision hazards. In T. Gehrels (Ed.). *Hazards due to comets and asteroids*, (pp. 1145-1156). Tucson, AZ: University of Arizona Press.

Harris, A. W., Boslough, M., Chapman, C. R., Drube, L., Michel, P., &, Harris, A. W. (2015). Asteroid impacts and modern civilization: Can we prevent a catastrophe? In P. Michel, et al. (Eds.), *Asteroids IV* (pp. 835-854). Tucson, AZ: University of Arizona Press.

Helfand, I. (2013). *Nuclear famine: Two billion people at risk*. International Physicians for the Prevention of Nuclear War.

Hellman, M. (2008). Risk analysis of nuclear deterrence. *The Bent of Tau Beta Pi* (Spring), 14–22.

Interagency Working Group for Detecting and Mitigating the Impact of Earth-Bound Near-Earth Objects (2018). *National near-Earth object preparedness strategy and action plan*. Washington, DC: National Science and Technology Council.

Kahneman, D. & Sugden, R (2005). Experienced utility as a standard of policy evaluation. *Environmental and Resource Economics, 32*(1), 161–181.

Kaplinger, B., Wie, B., & Dearborn, D. (2014). Earth-impact modeling and analysis of a near-Earth object fragmented and dispersed by nuclear subsurface explosions. *Journal of the Astronautical Sciences, 59*(1-2), 101–119.

Koenig. J. D & Chyba, C.F. (2007). Impact deflection of potentially hazardous asteroids using current launch vehicles. *Science and Global Security, 15,* 57–83.

Korycansky, D. G. & Lynett, P. J. (2005). Offshore breaking of impact tsunami: The Van Dorn effect revisited. *Geophysical Research Letters, 32(*10).

Kristensen, H. M. & Norris, R.S. (2018a). Chinese nuclear forces, 2018. *Bulletin of the Atomic Scientists, 74(*4), 289–295.

Kristensen, H. M. & Norris, R.S. (2018b). Russian nuclear forces, 2018. *Bulletin of the Atomic Scientists, 74*(3), 185–195.

Kristensen, H. M. & Norris, R.S. (2018c). United States nuclear forces, 2018. *Bulletin of the Atomic Scientists, 74*(2), 120–131.

Kunich, J. C. (1997). Planetary defense: The legality of global survival. *Air Force Law Review, 41*, 119–162.

Lave, L. (1981). *The strategy of social regulation: Decision frameworks for policy*. Washington, DC: Brookings.

Lebow, R. N. (2014). *Archduke Franz Ferdinand lives! A world without World War I*. St. Martin's Press.

Lewis, P., Williams, H., Pelopidas, B., & Aghlani, S. (2014). *Too close for comfort: Cases of near nuclear use and options for policy*. London, UK: Chatham House.

Lodgaard, S. (2009). Toward a nuclear-weapons-free world. *Daedalus, 138*(4), 140–152.

Lofstedt, R. & Schlag, A. (2017). Risk-risk tradeoffs: What should we do in Europe? *Journal of Risk Research, 20*(8), 963-983.

Longo, G. (2007). The Tunguska event. In P. T. Bobrowsky & H. Rickman (Eds.), *Comet/asteroid impacts and human society* (pp. 303-330). Berlin, Germany: Springer.

Maher, T. M. Jr. & Baum, S. D. (2013). Adaptation to and recovery from global catastrophe. *Sustainability, 5*(4), 1461–1479.

Mainzer, A., Grav, T., Bauer, J., Masiero, J., McMillan, R. S., Cutri, R. M., et al. (2011). NEOWISE observations of near-Earth objects: Preliminary results. *Astrophysical Journal, 743*(2), 156, doi: 10.1088/0004-637X/743/2/156.

Mainzer. A., Bauer, J., Grav, T., Masiero, J., Cutri, R. M., Wright, E, et al. (2014). The population of tiny near-Earth objects observed by NEOWISE. *Astrophysical Journal, 784*(2), 110, doi: 10.1088/0004-637X/784/2/110.

Mathias, D. L., Wheeler, L. F., & Dotson, J. L. (2017). A probabilistic asteroid impact risk model: Assessment of sub-300m impacts. *Icarus, 289*, 106-119.

Mayer H. (2015). Is a special legal regime for planetary defence measures necessary? 4th IAA Planetary Defense Conference, IAA-PDC-15-06-06.

Mellor, F. (2007). Colliding worlds: Asteroid research and the legitimization of war in space. *Social Studies of Science, 37(*4), 499–531.

Mies, R. (2012). Strategic deterrence in the 21st century. *Undersea Warfare, 48*, 12–19.

Mills, M. J., Toon, O. B., Turco, R. P., Kinnison, D. E., & Garcia, R. R. (2008). Massive global ozone loss predicted following regional nuclear conflict. *Proceedings of the National Academy of Sciences, 105*(14), 5307–5312.

Morrison, D. (1992). The Spaceguard survey: Report of the NASA International Near-Earth-Object Detection Workshop. Washington, DC: NASA.

Mueller, J. (1988). The essential irrelevance of nuclear weapons: Stability in the postwar world. *International Security, 13*(2), 55–79.

Narang, V. (2018). The discrimination problem: Why putting low-yield nuclear weapons on submarines is so dangerous. *War On The Rocks* (8 February). https://warontherocks.com/2018/02/discrimination-problem-putting-low-yield-nuclear-weapons-submarines-dangerous

National Aeronautics and Space Administration (2007). Near-Earth object survey and deflection analysis of alternatives: Report to Congress.

National Aeronautics and Space Administration Jet Propulsion Laboratory (2018), Center for Near Earth Object Studies. Discovery statistics. https://cneos.jpl.nasa.gov/stats/totals.html (Accessed 22 June 2018)

National Research Council (2010). Defending planet Earth: Near-Earth object surveys and hazard mitigation strategies. Washington, DC: National Academies Press.

Ng, Y.-K (2003). From preference to happiness: Towards a more complete welfare economics. *Social Choice and Welfare, 20*(2), 307–350.

Özdoğan, M., Robock, A., & Kucharik, C. (2012). Impacts of a nuclear war in South Asia on soybean and maize production in the Midwest United States. *Climatic Change, 116*, 373–387.

Packer, J., Kurr, J. A., & Abelkop, A. (2013). The policy trajectory of United States asteroid deflection planning. *Timely Interventions, 1*(1), DOI 10.5195/ti.2013.9.

Pinter. N. & Ishman, S. E. (2008). Impacts, mega-tsunami, and other extraordinary claims. *GSA Today, 18*(1), 37–38.

Popova, O. P., et. al. (2013). Chelyabinsk airburst, damage assessment, meteorite recovery, and characterization. *Science, 342*(1069), 1069-1073.

Rauchhaus, R. (2009). Evaluating the nuclear peace hypothesis: A quantitative approach. *Journal of Conflict Resolution, 53*(2), 258–277.

Reinhardt, J. C., Chen, X., Liu. W., Manchev, P., & Paté-Cornell, M. E. (2016). Asteroid risk assessment: A probabilistic approach. *Risk Analysis, 36*(2), 244–261.

Reinhardt, J. C., Daniels, M., & Paté-Cornell, M. E. (2014). *Probabilistic analysis of asteroid impact risk mitigation programs.* Honolulu, HI: Probabilistic Safety Assessment and Management PSAM (12 June).

Reisner, J., D'Angelo, G., Koo, E., Even, W., Hecht, M., Hunke, E., et al. (2018). Climate impact of a regional nuclear weapons exchange: An improved assessment based on detailed source calculations. *Journal of Geophysical Research: Atmospheres, 123*, 2752–2772.

Remo, J. L. (1996). Policy perspectives from the UN international conference on near-Earth objects. *Space Policy, 12*(1), 13–17.

Remo, J. L. (2015). The dilemma of nuclear energy in space. *Bulletin of the Atomic Scientists, 71*(3), 38–45.

Sauer, T. (2015). The NPT and the humanitarian initiative: Towards and beyond the 2015 NPT Review Conference. Deep Cuts Working Paper No. 5 (April).

Schelling, T. C. (2006). An astonishing sixty years: The legacy of Hiroshima. *American Economic Review, 96*(4), 929–937.

Schelling, T. C. (2009). A world without nuclear weapons? *Daedalus, 138*(4), 124–129.

Schweickart, R. L., Jones, T. D., von der Dunk, F., Camacho-Lara, S., & Association of Space Explorers International Panel on Asteroid Threat Mitigation (2008). *Asteroid threats: A call for global response*. Houston, TX: Association of Space Explorers.

Sidel, V. W. & Levy, B. S. (2007). Proliferation of nuclear weapons: Opportunities for control and abolition. *American Journal of Public Health, 97*(9), 1589–1594.

Sokov, N. N. (2014). Why Russia calls a limited nuclear strike “de-escalation”. *Bulletin of the Atomic Scientists* (13 March). https://thebulletin.org/2014/03/why-russia-calls-a-limited-nuclear-strike-de-escalation.

Stokes, G. H., Yeomans, D. K., Bottke, W. F., Jewitt, D., Chesley, S. R., Kelso, T. S, et al. (2003). Study to determine the feasibility of extending the search for near-Earth objects to smaller limiting diameters. *Report of the Near-Earth Object Science Definition Team at the Request of NASA’s Office of Space Science*, Solar System Exploration Division.

Su, J. (2015). Measures proposed for planetary defence: Obstacles in existing international law and implications for space arms control. *Space Policy, 34*, 1–5.

Sweet, K. (1999). Planetary preservation: The need for legal provision. *Space Policy, 15,* 223–231.

Tannenwald N. (2005). Stigmatizing the bomb: Origins of the nuclear taboo. *International Security, 29*(4), 5–49.

Tertrais B. (2017). “On the brink”—really? Revisiting nuclear close calls since 1945. *The Washington Quarterly, 40*(2), 51–66.

Tonn, B. E. (1999). Transcending oblivion. *Futures, 31*, 351–359.

Tonn, B. E. (2009). Obligations to future generations and acceptable risks of human extinction. *Futures, 41*(7), 427–435.

Toon, O. B., Zahnle, K., Morrison, D., Turco, R. P., & Covey, C. (1997). Environmental perturbations caused by the impacts of asteroids and comets. *Reviews of Geophysics, 35*(1), 41–78.

Toon, O. B., Turco, R. P., Robock, A., Bardeen, C., Oman, L., & Stenchikov, G. L. (2007). Atmospheric effects and societal consequences of regional scale nuclear conflicts and acts of individual nuclear terrorism. *Atmospheric Chemistry and Physics, 7*(8), 1973–2002.

Torres, P. (2016). Agential risks: A comprehensive introduction. *Journal of Evolution and Technology, 26*(2), 31-47.

Tyler, P. E. (1996). Chinese seek atom option to fend off asteroids. *New York Times* (27 April).

Xia, L., Robock, A., Mills, M., Stenke, A., & Helfand I. (2015). Decadal reduction of Chinese agriculture after a regional nuclear war. *Earth’s Future, 3*, 37–48.