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A Global-Zero world, one without nuclear weapons, might leave the planet more vulnerable.

The planet Earth is continually under bombardment.[1] Each day, roughly 100 tons of small meteoroids and space debris – some as large as a meter in diameter, but most smaller than a grain of sand – strike the atmosphere.[2] Moving at speeds in excess of 40,000 kilometers per hour, these meteoroids are often seen as bright streaks in the sky as they burn up from atmospheric friction.[3] Fortunately, because they are consumed high in the atmosphere, meteoroids and space dust pose no threat to humans or other life on Earth.

Unfortunately, there are larger objects in orbit around the Sun that can pose a significant threat to the planet. It is estimated that as many as a billion asteroids and possibly two trillion comets inhabit the solar system.[4] Asteroids range in size from a meter to hundreds of kilometers in diameter: the solid nuclei of comets can be several kilometers wide. For both asteroids and comets, the larger their size, the less frequently they appear in nature. While the vast majority of asteroids orbit between Mars and Jupiter, a very small percentage of them are on elliptical paths that cross Earth's orbital track, along with a much smaller number of comets. Of these, some invariably collide with our planet.[5]

On average, an asteroid between 30-50 meters in size strikes Earth every 100-200 years.[6] Such asteroids are capable of inflicting damage over a wide area and have the potential for killing thousands of people. Much larger asteroids, although exceptionally rare, can inflict catastrophic damage: an asteroid ten kilometers wide struck Earth 65 million years ago and extinguished most life on the planet, including all species of dinosaurs.[7]

In recent decades scientific understanding of the asteroid and comet population has grown, prompting efforts to protect the planet from a devastating collision. Known as 'planetary defense,' these efforts encompass locating and tracking threatening bodies as well as developing means for mitigating a potential impact. The general concept is to identify a threatening space object many years in advance and then deflect it, by changing its velocity, or fragment it into smaller pieces. Theoretically, mitigating potential impacts of small and mid-sized bodies – those up to 1000 meters in diameter – could be accomplished using non-explosive means, although the largest asteroids or those detected shortly before impact might only be deflected or fragmented using the explosive power of nuclear weapons.

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[1] James Howe served for twenty-seven years on active duty in the U.S. Coast Guard and has earned master's degrees from the U.S. Marine Corps War College, Harvard University (Extension School), and the American Military University.

[2] National Research Council, *Defending Planet Earth: Near-Earth-Object Surveys and Hazard Mitigation Strategies* (Washington, D.C.: the National Academies Press, 2010), 12.

[3] John S. Lewis, *Rain of Fire and Ice: The Very Real Threat of Comet and Asteroid Bombardment* (Lexington, KY: Perseus Publishing, 1996), 37.

[4] David J. Eicher, *Comets! Visitors from Deep Space* (New York: Cambridge University Press, 2013), 8.

[5] Clark Chapman and Ed Lu, "FAQ on the Chelyabinsk Meteor Impact," B612 Foundation, February 18, 2013, accessed June 21, 2014, https://b612foundation.org/news/faq-on-the-chelyabinsk-asteroid-impact/.

[6] National Aeronautics and Space Administration, *Near-Earth Object Survey and Deflection Analysis of Alternatives*, Report to Congress, March 2007, 6.

[7] Walter Alvarez, *T. Rex and the Crater of Doom* (New York: Vintage Books, 1997), 3-6.

ASSESSING THE THREAT

Each asteroid and comet is unique in its composition, shape, size, and orbit. While most small asteroids are solid masses, many larger asteroids are a collection of smaller bodies held together by a weak gravitational bond, akin to an orbiting pile of rubble. Other asteroids are known as binaries, with two bodies gravitationally associated with one another.[8] Typically, asteroids are composed of iron, carbon, or silica. Conversely, the nuclei of comets consist of frozen gases and dust. As they approach the Sun, the gases in the comet's nucleus evaporate and create the signature tail that often can be observed from Earth. Some comets have exhausted the store of frozen gases in their core and consist primarily of asteroid-like materials; from a distance it often is impossible to distinguish between these extinct comets and true asteroids.[9]

Asteroids originated from the failed formation of a rocky planet billions of years ago. Fragments of the planet remained in orbit around the Sun and, over the eons, suffered millions of collisions, breaking into smaller pieces. Most asteroids orbit the Sun once each 4-5 years and many have had their orbit changed through collision or, more likely, by the gravitational influence of Jupiter and other bodies.[10] Alternatively, comets originate from deeper in space. Most short-period comets emanate from the Kuiper Belt, located beyond Neptune, and have an orbital period of up to 200 years, while long-period comets hail from the Oort Cloud, a band of debris at the furthest reaches of the solar system, and can take between 200 and several thousand years to conduct one revolution around the Sun.[11]

Of the small percentage of asteroids that do not orbit in the main asteroid belt, scientists have discovered more than 12,000 that will pass within 1.3 Astronomical Units, or 200 million kilometers of the Sun.[12] These have been dubbed 'Near Earth Asteroids' and together with a much smaller population of comets are categorized as 'Near Earth Objects' (NEO).[13] Based on a variety of orbital characteristics, most NEOs pose no threat as they will never intersect Earth's track through space; only about one-fifth of NEOs will approach within 0.05 Astronomical Units (eight million kilometers) of Earth's orbit. These asteroids and comets are classified as 'Potentially Hazardous Objects' (PHO) and are the focus of planetary defense detection, tracking, and mitigation planning efforts.[14]

The kinetic energy imparted to Earth from an asteroid or comet collision is determined by the mass and relative velocity of the impacting body. Because mass cannot be known with certainty for most asteroids or comets, rough estimates of potential damage are based on the physical size of the object. Smaller asteroids, between one and 30 meters in diameter, typically do not have sufficient mass to complete the journey through Earth's atmosphere and burn up, disintegrate, or explode before reaching the planet's surface. Such asteroid explosions are known as 'bolides' and typically create a large fireball. The shock wave from an aerial explosion is often large enough to cause damage on the ground, as seen in February 2013, when an asteroid estimated at 15-20 meters in diameter exploded over Chelyabinsk, Russia, injuring more than 1000 people.[15] Detection of these small asteroids is extremely difficult and less than 0.01 percent have been located; because they pose a limited threat, planetary defense efforts typically do not focus on

[8] Roger Dymock, *Asteroids and Dwarf Planets* (New York: Springer, 2010), 33-35.
[9] Lewis, 42-43.
[10] Martin Rees, ed., *Universe: The Definitive Visual Guide* (New York: DK Books, 2005), 170-172.
[11] Eicher, 9.
[12] National Aeronautics and Space Administration, "Near Earth Object Program," National Aeronautics and Space Administration, March 22, 2015, accessed March 22, 2015, http://neo.jpl.nasa.gov/stats/.
[13] William Ailor, "Planetary Defense Conferences: Sharing Information on NEO Threats and Mitigation" (paper presented at the meeting of the Working Group on Near Earth Objects of the Scientific and Technical Subcommittee of the United Nations Committee on the Peaceful Uses of Outer Space, Vienna, February 2011), 4.
[14] Lindley Johnson, "Near Earth Object Observations Program" (paper presented to the Planetary Defense Task Force, Cambridge, MA, April 15, 2010), 3.
[15] Chapman and Lu.

asteroids below 30 meters in diameter.[16]
It is the larger asteroids and comets that concern planetary defense practitioners, particularly the objects of intermediate size that have not yet been located, but could produce significant damage to Earth. A prime example is the asteroid or comet that exploded over Tunguska, Russia in June 1908. This celestial body, estimated at 40 meters in diameter, disintegrated and exploded over a heavily wooded area, creating a tremendous shock wave that flattened 2000 square kilometers of forest, as shown in Figure 1 – a blast nearly 200 times more powerful than those of the nuclear bombs used in World War II.[17] Had the Tunguska object exploded over a populated area hundreds if not thousands of lives could have been lost.

Asteroids between 30-100 meters in diameter are known colloquially as 'city killers' and could devastate a small region on Earth, as vividly demonstrated in Tunguska. Larger 100-300 meter 'nation killer,' 300-1000 meter 'continent killer,' and 1000-plus meter 'civilization killer' objects would inflict proportionally more damage: a massive crater created by the impact of a five-kilometer wide asteroid is depicted in Figure 2. The even larger asteroid that struck near the Yucatan Peninsula 65 million years ago – one of several known mass extinction events in the history of Earth – generated a global cataclysm of tsunamis, earthquakes, and fire. The thick shroud of smoke and debris created by the collision encircled the globe for hundreds of years and snuffed out nearly three-quarters of all living species on the planet.[18]

Many of the more than 12,000 NEOs detected so far are large asteroids. Ongoing surveys of outer space have located roughly 95 percent of the estimated population of 900 civilization-threatening asteroids that pass near Earth's orbit. As the size of threatening asteroids decreases, however, the percentage of those that have been detected also decreases. Of the 4800 continent killer PHOs estimated to be in existence, roughly half have been found, and only ten percent of nation killers have been located. As for the smaller yet still dangerous city killers, of which 500,000 are believed to exist, only one percent have been identified.[19] While thousands of comets have been discovered, the much longer period of their orbits creates a great deal of uncertainty as to how many may pose a hazard to the planet.[20]

There is roughly a 50-50 probability that a city killer asteroid will strike Earth during an average human lifespan, and a much lower probability for an impact by a larger space object. While the mean time between collisions from city killer asteroids is one or two centuries, the time between collisions with larger asteroids is measured in millennia, or even millions of years for those that can threaten mass extinction.[21] Nonetheless, the data available to forecast future threats is extremely limited and there is no way to ascertain with any degree of precision when the next major asteroid or comet collision will occur. There is no scientific doubt that Earth will face the hazard of a devastating asteroid or comet impact at some unknown point in the future.

COLLISION MITIGATION TECHNIQUES

A number of different methods have been posited for preventing an asteroid or comet from colliding with Earth. These proposed methods could be employed independently or in tandem.

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[16] Benjamin Deniston, "2013 Planetary Defense Conference: Rising to the Challenge," *21st Century Science & Technology* (Summer 2013): 29.
[17] National Aeronautics and Space Administration, "The Tunguska Impact – 100 Years Later," NASA Science, June 30, 2008, accessed February 18, 2014, http://science.nasa.gov/science-news/science-at-nasa/2008/30jun_tunguska/.
[18] Lynn Yaris, "Alvarez Theory on Dinosaur Die-Out Upheld: Experts Find Asteroid Guilty of Killing the Dinosaurs," Berkeley Lab, Lawrence Livermore National Laboratory, U.S. Department of Energy, March 9, 2010, accessed June 25, 2014, http://newscenter.lbl.gov/feature-stories/2010/03/09/alvarez-theory-on-dinosaur/ and John Kunich, "Planetary Defense: the Legality of Global Survival," *Air Force Law Review 41* (1997): 121.
[19] Deniston.
[20] Hans Rickman, "Current Questions in Cometary Dynamics," in *Comets II*, ed. M.C. Festou, H.U. Keller, and H.A. Weaver (Tucson: the University of Arizona Press, 2004), 205-206.
[21] National Research Council, 19.

Three key variables will help guide the selection of the appropriate response to a predicted strike: the time until impact and the size and composition of the asteroid or comet. Other factors such as the amount of spin or the shape of the asteroid may also drive the mitigation strategy.[22]

Potential mitigation techniques using existing technology – or technology that can be modified for planetary defense in a short time span – can be placed into three general categories: 'slow push' methods, kinetic impacts, and nuclear strikes. Most of these methods are designed to deflect the asteroid by changing its velocity so that it passes Earth harmlessly. The earlier a deflection can be undertaken, the less total change in velocity will be necessary. For interventions more than a decade in advance of the collision, a change of only about one centimeter per second typically is sufficient.[23] In addition to deflection techniques, another mitigation method is to fragment the object, so that no large pieces remain to strike the planet.[24]

The 'slow push' methods span a variety of techniques that could, in theory, deflect most city and nation killer asteroids, both solid and porous, provided the threat was detected one or more decades in advance. Lasers or concentrated solar rays could be beamed onto the asteroid, causing surface material to burn off while generating a small counterforce; one concept would employ a series of large Earth-orbiting satellites to harness sunlight for this purpose.[25] A second method would employ robotic spacecraft to hover close to the asteroid so that the slight gravitational attraction between the two bodies would, over several years, alter the asteroid's velocity. Other proposed methods would attach rocket motors to the surface of the asteroid, modify the albedo of a rotating asteroid to change the amount of photon re-radiation, or mine the asteroid's surface, ejecting materials at high speed – all to produce a slight cumulative change in the velocity of the threatening body.[26]

Kinetic impacts would involve flying a spacecraft into the asteroid to impart, through the collision, sufficient kinetic energy to alter the asteroid's velocity. Technologically, this is the simplest mitigation technique and is likely to be the preferred option for protecting against smaller threatening bodies, or in cases where multiple decades are available to deflect asteroids up to 1000 meters in diameter.[27] Depending on the size of the asteroid and the time before impact, however, a number of kinetic strikes might be necessary. Kinetic strikes would be most effective against solid objects but far less useful for altering the velocity of porous bodies or 'rubble pile' asteroids.[28] Kinetic strikes designed to eject a maximum amount of surface material from the asteroid or comet into space would most effectively change its velocity.[29]

Nuclear strikes may be the only available option for mitigating the threat of a larger asteroid or where there is little time between initial detection and the expected collision with Earth.[30] Explosive

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[22] Bong Wie, "Hypervelocity Nuclear Interceptors for Asteroid Deflection or Disruption" (paper presented at the 2011 IAA Planetary Defense Conference, Bucharest, Romania, May 9-12, 2011), 2.

[23] Keith A. Holsapple, "About deflecting asteroids and comets," in *Mitigation of Hazardous Comets and Asteroids*, ed. M.J.S. Belton, T.H. Morgan, N. Samarasinda, and D.K. Yeomans (New York: Cambridge University Press, 2004), 114.

[24] R.B. Adams et al, *Survey of Technologies Relevant to Defense from Near-Earth Objects*, NASA/TP-2004-213089 (Huntsville, AL: National Aeronautics and Space Administration, 2004), 62-65.

[25] University of California Santa Barbara, "News Release: California Scientists Propose System to Vaporize Asteroids That Threaten Earth," University of California, February 14, 2013, accessed March 30, 2014, http://www.ia.ucsb.edu/pa/display.aspx?pkey=2943.

[26] National Aeronautics and Space Administration, *Near-Earth Object Survey and Deflection Analysis of Alternatives*, 20.

[27] Jesse D. Koenig and Christopher F. Chyba, "Impact Deflection of Potentially Hazardous Asteroids Using Current Launch Vehicles," *Science and Global Security* 15 (2007): 67.

[28] Christian Gritzner and Ralph Kahle, "Mitigation technologies and their requirements," in *Mitigation of Hazardous Comets and Asteroids*, ed. M.J.S. Belton, T.H. Morgan, N. Samarasinda, and D.K. Yeomans (New York: Cambridge University Press, 2004), 177.

[29] National Research Council, 73-74.

[30] Wei, 1.

force from a nuclear weapon could create, in an instant, sufficient kinetic energy to alter the velocity of all but the largest asteroids. The immense power of a nuclear device detonated on, near, or under the surface of a threatening space object could deliver several orders of magnitude more force, in one instant, than the kinetic impact or slow push techniques.[31] Alternatively, a nuclear explosion could be used to break the asteroid into thousands of pieces, so that only a small percentage of the object's mass would strike the atmosphere.

The explosive yield of a nuclear weapon is vastly greater than that of an equivalent size of conventional, chemical explosive, such as the commonly used trinitrotoluene (TNT). The first nuclear weapon – a plutonium fission device exploded during the Trinity test in July 1945 – had an explosive yield estimated at 20,000 tons (20 kilotons) of TNT. Seven years later, the first thermonuclear fusion bomb was tested and yielded 10,400,000 tons (10.4 megatons) of explosive energy. The largest nuclear weapon ever demonstrated was a Soviet device exploded in October 1961. Dubbed *Tsar Bomba*, it produced more than 50 megatons of energy. Small, battlefield tactical nuclear weapons were fielded by both the U.S. and the USSR, with yields often in the single kilotons; modern fission devices tested by India, Pakistan, and North Korea produced yields in a similar range.[32]

There is an ample stockpile of nuclear devices potentially suitable for a planetary defense mission. The United States currently possesses around 7100 nuclear weapons, 2080 of which are strategically deployed and the remainder of which are in storage, reserve, or awaiting dismantlement. U.S. nuclear weapons are designed as bombs, to be dropped on target by aircraft, or warheads, to be launched aboard land-based or submarine-based ballistic missiles. While larger weapons were developed, currently the maximum yield in the U.S. arsenal is around one megaton, with most weapons designed to yield 100-500 kilotons.[33] Russia has a similar number of nuclear weapons, with about 1640 deployed, several thousand in reserve or awaiting dismantlement, and 2000 with tactical yields. Other major nuclear powers include France, with less than 300 operational weapons; China, with about 240 warheads; Great Britain, with a total stockpile of around 225; and India, Israel, and Pakistan, each with roughly 100 devices.[34]

EMPLOYING NUCLEAR WEAPONS

The general concept for a planetary defense mission using a nuclear weapon would be to launch a warhead aboard a rocket capable of interplanetary travel, to intercept the threatening body at the optimal spot in its orbit in order to maximize the effectiveness of the deflection or fragmentation. The nuclear device could be detonated in one of three configurations: as a stand-off blast above the surface, on the surface, or beneath the surface of the asteroid or comet.[35] One concept for a nuclear explosive asteroid interceptor is shown in Figure 3.

A stand-off blast could be used for deflection, as it would provide a massive force to alter the object's trajectory while minimizing the possibility of fracturing. In comparison to surface or sub-surface blasts, a stand-off detonation would require a less sophisticated intercept maneuver and could be accomplished using a simpler delivery system. The nuclear device would be maneuvered close to the asteroid, notionally to a height equal to 25 percent of the asteroid's radius and above a specific hemisphere of the asteroid to

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[31] National Aeronautics and Space Administration, *Near-Earth Object Survey and Deflection Analysis of Alternatives,* 21-24.

[32] Comprehensive Test Ban Treaty Organization, "Types of Nuclear Weapons," Comprehensive Test Ban Treaty Organization, January 2012, accessed April 7, 2014, http://www.ctbto.org/nuclear-testing/types-of-nuclear-weapons/.

[33] Hans M. Kristensen and Robert S. Norris, "US nuclear forces, 2015," Bulletin of the Atomic Scientists, March 3, 2015, accessed March 21, 2015, http://thebulletin.org/2015/march/us-nuclear-forces-20158075.

[34] Daryl Kimball, "Nuclear Weapons: Who Has What at a Glance," Arms Control Association, February 2015, accessed March 22, 2015, http://www.armscontrol.org/factsheets/nuclearweaponswhohaswhat.

[35] Holsapple, 123-125.

enhance the deflective force.[36] Upon detonation, the thermal impulse and nuclear radiation generated in the explosion would be absorbed by surface materials, which would instantly heat up or vaporize.[37] This would peel off a layer of rock and eject it into space, imparting a reactive force to alter the asteroid's velocity. Computer modeling has shown that a typical stand-off blast could ablate about one percent of an asteroid's total mass.[38] The higher above the surface the nuclear weapon was detonated, the thinner and wider would be the layer ejected.[39]

In most cases the preferred direction of the velocity change would be along or directly opposite the asteroid's orbital path, in order to change the period of the object's revolution around the Sun and avoid the forecast collision with Earth.[40] This concept of speeding up or slowing down the threatening body, rather than pushing it sideways, applies to all long-lead-time deflection techniques including slow push and kinetic impact methods. However, for deflection missions that occur close to the time of collision with Earth – notionally when the asteroid is on its terminal orbit before impact – a sideways deflection using a large explosive force could be the most effective mitigation strategy.[41]

Surface and sub-surface blasts could be used either for deflection or fragmentation. The most efficient transfer of energy from a nuclear weapon to an asteroid would occur when the device was exploded beneath the surface of the object; in comparison to a stand-off blast a sub-surface detonation would transfer up to 100 times more energy.[42] However, surface or sub-surface blasts would increase the possibility that a planned deflection would instead fragment the asteroid. To avoid this possibility, time permitting, an exploratory mission to the threatening asteroid or comet could ascertain its material composition and internal structure, and the most effective mitigation strategy could be devised with that data.[43]

A surface or sub-surface blast would create a large crater and eject a mass of debris into space. The deeper the sub-surface device was located, the more effectively energy would be imparted to the asteroid. This is important for fragmentation missions where the threatening body would be blasted into thousands of smaller pieces. One analysis found that for fragmentations conducted three or more years ahead of a projected impact, more than 99.999 percent of an asteroid's original mass would miss Earth completely.[44]

A difficult challenge for carrying out a sub-surface burst involves placement of the nuclear device, particularly in circumstances with short-lead time where the device must be transported directly to the asteroid at high velocity. To assure effectiveness in fragmentation or deflection, the nuclear weapon must strike the asteroid at a precise impact angle and penetrate to the proper depth. Unfortunately, a high velocity impact is likely to vaporize the nuclear device upon contact. To allow the nuclear warhead to burrow to the proper depth, a two-segment penetrator configuration could be employed. As originally conceived by Russian researchers and refined at the Asteroid Deflection Research Center at Iowa State University, a hypervelocity nuclear interceptor could be comprised of a dual-bodied spacecraft, with the forward section serving as a kinetic impactor and the aft section containing the nuclear weapon. Upon impact, the kinetic device would blast open a narrow crater in which the

[36] Ibid., 117.
[37] Donald B. Gennery, "Deflecting Asteroids by Means of Standoff Nuclear Explosions" (paper presented at the 2004 Planetary Defense Conference, Orange County, CA, February 23-26, 2004), 1.
[38] D.S. Dearborn, S. Patenaude, and R.A. Managan, "The Use of Nuclear Explosives to Disrupt or Divert Asteroids" (paper presented at the Planetary Defense Conference, Washington, DC, March 5-8, 2007), 20.
[39] Sam Wagner, Alan Pitz, Dan Zimmerman, and Bong Wei, "Interplanetary Ballistic Missile (IPBM) System Architecture Design for Near-Earth Object Threat Mitigation," Asteroid Deflection Research Center, Iowa State University, January 2009, accessed April 17, 2014, http://www.adrc.iastate.edu/files/2012/09/IAC-09.D1.1.1.pdf.
[40] Dearborn, Patenaude, and Managan, 3.
[41] Wei, 6.
[42] Ibid., 1.
[43] Dearborn, Patenaude, and Managan, 20.
[44] Ibid., 1.

nuclear device would explode microseconds later, effectively transmitting the full force of its energy to the asteroid.[45]

The yield of the nuclear device needed for a planetary defense mission would depend on a variety of factors, such as the size and composition of the threatening body and the amount of velocity change desired. To fully fragment a 1000-meter asteroid composed of silicate, research has shown that a nuclear explosion of 1.0 to 3.0 megatons is needed. To deflect the same asteroid a decade or more in advance of projected collision, a 300-kiloton stand-off blast would suffice.[46] Even successful fragmentation 15 days ahead of impact with Earth is possible for a 100-meter asteroid using a 100-kiloton device.[47]

In planning planetary defense missions, a margin of safety must be included to account for orbital perturbations. Although potential collisions with Earth can be estimated decades in advance, all objects traveling through space are subject to gravitational forces that can induce slight changes to their orbits. As asteroids and comets pass through the solar system they may experience small but disruptive gravitational pull from the planets, other asteroids, or the Sun.[48] The orbit of the asteroid Apophis is illustrative: it is projected to pass close to Earth in 2029 and 2036, but due to potential perturbations there are 146,500 kilometers of positional uncertainty – 23 times the radius of the Earth – for the 2036 passage.[49] Should an asteroid like Apophis need to be deflected, the total change in velocity induced must alter the orbit so that the asteroid misses Earth by a distance greater than the sum of the uncertainties, plus an additional safety margin.

Fully capable space launch systems will be essential for any planetary defense operation. As with nuclear weapons themselves, there currently are several space lift systems available, all of which have been rigorously tested, have proven reliability, and are capable of delivering the necessary nuclear device and support systems to intercept a threatening body. For example, the Delta IV Heavy launch vehicle, used by the Department of Defense to place national security assets into orbit, is capable of transporting more than 8400 kilograms of payload on an interplanetary trajectory. This is more lift capability than is needed to carry an American nuclear weapon, such as the B83 warhead, which weighs 1118 kilograms, along with requisite command, control, and telemetry systems.[50]

ISSUES AND CHALLENGES

The maturity of the U.S. nuclear weapons complex coupled with highly reliable and readily available space launch and control systems makes employment of a nuclear weapon for planetary defense a realistic option, with far less developmental risk than for the more exotic techniques that have been proposed. Only the use of a kinetic impactor poses fewer technical hurdles.

A nuclear mission would involve two basic acts: delivery of the weapon to the target, and the detonation. Direct delivery was demonstrated successfully in the July 2005 Deep Impact mission, in which an American robotic spacecraft was flown purposefully into the Tempel 1 comet, seen in Figure 4.[51] Nonetheless, new technological breakthroughs may be needed, particularly related to operating on or near the surface of an asteroid, for situations where a nuclear device would be placed on or buried beneath the asteroid's surface before detonation. The recent difficulties encountered by the European Space Agency's Philae spacecraft when

[45] Wei, 2.
[46] Holsapple, 115.
[47] Brian Kaplinger, Pavithra Premaratne, Christian Setzer, and Bong Wei, "GPU Accelerated 3D Modeling and Simulation of a Blended Impact and Nuclear Subsurface Explosion" (paper presented at the AIAA Guidance, Navigation, and Control Conference 2013, Boston, MA, August 19-22, 2013), 16.
[48] Wei, 3.
[49] Wagner, Pitz, Zimmerman, and Wei, 2.
[50] Ibid., 4-11 and Norman Polmar and Robert S. Norris, *The U.S. Nuclear Arsenal: A History of Weapons and Delivery Systems Since 1945* (Annapolis, MD: Naval Institute Press, 2009), 61.
[51] National Aeronautics and Space Administration, "Deep Impact," NASA Science, May 13, 2014, accessed June 27, 2014, http://science.nasa.gov/missions/deep-impact/.

landing on and anchoring to Comet 67P/Churyumov-Gerasimenko highlight the challenges of operating in a microgravity environment.[52]

Detonation has also been demonstrated. Prior to agreeing to a ban on the practice, in July 1962 the U.S. successfully exploded a 1.4 megaton warhead more than 240 miles above the Earth in a test called Starfish Prime, and the Soviet Union conducted its own thermonuclear explosion at extremely high altitude that same year.[53] These demonstrations quelled any doubts that a nuclear device would work in the harsh environment of space.

Operationally, warning time is a key parameter for planetary defense missions. With only a very small percent of the total population of potentially hazardous asteroids and comets currently known, it is very plausible that a threatening object will be discovered where there is little time for mitigation, in which case nuclear weapons may provide the only solution. One way to preserve a larger menu of mitigation options is to detect, catalog, and track the full population of PHOs in the solar system as early as possible.

While U.S. and international detection efforts have increased significantly over the past two decades, primarily through a network of civilian and government-operated observatories, the limitations of using terrestrial telescopes make this a very inefficient undertaking.[54] A massive advantage could be gained by employing a space-based telescope dedicated specifically for this purpose, as currently being planned by the nonprofit B612 Foundation, whose *Sentinel* spacecraft, scheduled for launch in 2018, is expected to identify up to 90 percent of all asteroids larger than 140 meters as well as a many asteroids as small as 30 meters in diameter.[55] Even with a much more comprehensive survey, however, there will not be complete coverage of the asteroid population and the appearance of a threatening comet could occur at any time, since many comets are in orbits lasting multiple hundreds or thousands of years – again potentially necessitating the use of a nuclear explosion as a last ditch, short-notice defense.

A second operational concern relates to the physical characteristics of many asteroids and comets. It will be difficult to determine the proper blast location and nuclear yield to defend against rubble pile, oddly shaped, binary, and rapidly rotating bodies. Further, for comets, the precise makeup of their nuclei is "among the more elusive questions of solar system science."[56] An attempt to deflect or fragment a threatening comet using the enormous impact of a nuclear explosion may inadvertently create large fragments with negligible dispersal velocity, potentially leading to several devastating impacts on Earth.[57] This supports the need for early detection as well as for conducting exploratory missions to threatening objects decades in advance of collision, in order to best ascertain their physical characteristics.

A third issue regards the possibility that a deflection or fragmentation effort could shower Earth with radioactive materials. The public has acute concerns over the dangers of radiation, which were on full display following the 2011 disaster at the nuclear power plants in Fukushima, Japan. From a scientific standpoint, the likelihood that any dangerous radiation from asteroid fragments or a poorly diverted object would pose a health threat on Earth is extremely small, and orders of magnitude less of a risk than posed by the fallout created during atmospheric testing of

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[52] Peter B. de Selding, "European Spacecraft Touches Down on Comet," SpaceNews, November 12, 2014, accessed March 22, 2015, http://spacenews.com/42527european-spacecraft-touches-down-on-comet/.

[53] Gilbert King, "Going Nuclear Over the Pacific," Smithsonian.com, August 15, 2012, accessed April 12, 2014, http://www.smithsonianmag.com/history/going-nuclear-over-the-pacific-24428997/?no-ist.

[54] National Research Council, 29-50.

[55] B612 Foundation, "Sentinel Mission: Making the Map," B612 Foundation, January 2014, accessed March 22, 2015, https://b612foundation.org/sentinel-mission/.

[56] Paul R. Weissman, Erik Asphaug, and Stephen C. Lowry, "Structure and Density of Cometary Nuclei," in *Comets II*, ed. M.C. Festou, H.U. Keller, and H.A. Weaver (Tucson: the University of Arizona Press, 2004), 352.

[57] Wei, 3.

nuclear weapons in the 1950s and early 1960s.[58] Nonetheless, dealing with public perceptions and the vocal opposition that is likely to arise will be a significant aspect of any effort to employ nuclear weapons for planetary defense.

A final operational question surrounds command and control: what nation or nations will lead the mitigation effort against a threatening asteroid? Today, the answer is murky, as there are no agreed upon international conventions that directly address this issue. The primary source of international space law, the 1967 *Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies* (*Outer Space Treaty*), is silent on the issue of planetary defense, but does include guidance that could be deemed applicable. The treaty states as fundamental principles that the use of outer space is for peaceful purposes and for the benefit of all mankind, and that international cooperation is highly desired, particularly "in the interest of international peace and security."[59] This language, which was written decades before planetary defense became an issue in space policymaking circles, could be interpreted as supporting an international effort to mitigate a known asteroid or comet collision threat.

In 2013, in the spirit of the *Outer Space Treaty* and in reaction to the Chelyabinsk bolide, the United Nations Committee on the Peaceful Uses of Outer Space chartered a working group to evaluate potential mitigation schemes.[60] Nonetheless, there is no assurance that should a threat be identified, the UN will be able to muster international support for a mitigation mission. There is likely to be squabbling over leadership of the project and nonproliferation concerns over safeguarding weapons secrets, should a nuclear strike be the best or only option. Under such circumstances it may fall upon the shoulders of the United States or a likeminded group of nations to carry out on their own initiative a planetary defense operation. Since the 1990s, for example, Russia has made occasional overtures about working with the United States on nuclear planetary defense activities, although no concrete progress has been made toward a formal cooperative effort.[61]

There are also significant political and legal issues related to the use of nuclear explosions for a planetary defense effort. A plan to use nuclear weapons in space likely would face strident political and public opposition, based on the view that safer mitigation means would be available, and bolstered by restrictive language contained in the *Outer Space Treaty*.[62] Article IV of the treaty states that nations shall not "place in orbit around the Earth any objects carrying nuclear weapons or any other kinds of weapons of mass destruction, install such weapons on celestial bodies, or station such weapons in outer space in any other manner."[63] Such unambiguous language makes no exception for defense of the planet. To address this hurdle in the face of a known threat, the language of the *Outer Space Treaty* could be revised, the UN could pass a resolution to provide an exception for the mission at hand, or the involved nations could work outside the purview of the treaty – all solutions that are bound to generate controversy.

In addition to the constraints of the *Outer Space Treaty*, other international agreements must be considered. Public outcry over nuclear testing and other events helped lead the United States, USSR, and United Kingdom to sign the Limited Test Ban Treaty in 1963, which prohibited nuclear explosions in space, as well as in the atmosphere

[58] Dearborn, Patenaude, and Managan, 20.
[59] I. Diederiks-Verschoor and V. Kopal, *An Introduction to Space Law*, 3rd ed. (New York: Wolters Kluwer, 2006), 161-162.
[60] United Nations Office for Outer Space Affairs, "Recommendations of the Action Team on Near-Earth Objects for an international response to the near-Earth object impact threat," Press Release, February 20, 2013.
[61] Kathy Gilsinan, "The Enemy of an Asteroid is My Friend, TheAtlantic.com, August 9, 2014, accessed March 22, 2015, http://www.theatlantic.com/international/archive/2014/08/asteroid-defense-us-russia-ukraine/375799/.
[62] Clark Chapman, "How not to save the planet," *New Scientist* 194, no. 2611 (July 7, 2007): 19.
[63] Diederiks-Verschoor and Kopal, 162.

and underwater.[64] This was followed by an international effort to implement a Comprehensive Test Ban Treaty (CTBT), which prohibited nuclear testing anywhere (although this treaty has neither entered into force nor been ratified, the United States voluntarily ended all explosive nuclear testing in 1992).[65] Should field testing or the use of a nuclear device for a planetary defense mission be necessary, it would require a significant change in U.S. policy, as well as that of other participating nuclear powers.

In the legal arena, a government seeking to use nuclear weapons for planetary defense must be prepared to address liability concerns. Under the *Outer Space Treaty* and the 1972 *Convention on International Liability for Damage Created by Space Objects*, the nation that launches an object into outer space "shall be absolutely liable to pay compensation for damage caused by its space object on the surface of the earth or to aircraft in flight."[66] This framework of strict liability could impact the decision to employ nuclear weapons, considering the tremendous financial risk for the launching state.

This risk takes many forms: the damage created by a failed launch, should the nuclear warhead land back on Earth; an unsuccessful deflection mission, where the asteroid or comet strikes the planet in a different location than originally forecast; and a fragmentation mission where a large piece of the target survives atmospheric friction and impacts the surface. To safeguard against liability hazards, a UN-chartered planetary defense mission could indemnify the launching and participating states from damages, or these states could choose to withdraw from the relevant treaties for the duration of the mission.

A final, long-term challenge surrounds the aspirational goal espoused by many world leaders, including the sitting U.S. President, to rid the planet of all nuclear weapons.[67] With thousands of bombs, warheads, and tactical weapons in existence, there is little likelihood that complete nuclear disarmament will occur in the near future. Still, should international consensus develop over time to winnow the world's nuclear arsenals, it is possible to foresee a future with drastically shrunken or completely expunged nuclear stockpiles.

In such a future, there may come a juncture where an asteroid or comet has been detected on a collision course with Earth, the threat cannot be addressed by non-nuclear means, and no nuclear weapons are available for deflection or fragmentation. This scenario would require the rebirth of a nuclear weapons complex and the development and manufacture of a new warhead – actions that could require critical time leading up to the projected impact.[68] To avoid this fate, maintaining a level of nuclear weapons capability to address possible planetary defense needs should be accounted for in future nuclear disarmament agreements.

CONCLUSIONS

The threat from collision by asteroid or comet is not a short-term issue, but one that will forever shadow the human species. There is no doubt that Earth will be struck by large asteroids or comets in the future. Only the timing is unknown.

No other currently feasible mitigation technique provides the high levels of energy needed for asteroid deflection or fragmentation as the detonation of a nuclear weapon. While non-nuclear slow push or kinetic impact methods may be suitable for smaller asteroids or those detected decades before collision, it is likely that a nuclear explosion will be the only adoptable solution for fending off the largest threatening bodies or where an inbound asteroid or comet is first identified

[64] Walter A. McDougall, ... *The Heavens and the Earth* (Baltimore: The Johns Hopkins University Press, 1985), 273-274.
[65] Office of the Secretary of Defense, 5.
[66] Diederiks-Verschoor and Kopal, 174.
[67] Barack Obama, "Remarks by President Barack Obama," speech delivered Prague, Czech Republic, April 5, 2009, The White House, accessed April 15, 2014, http://www.whitehouse.gov/the_press_office/Remarks-By-President-Barack-Obama-In-Prague-As-Delivered.
[68] Dearborn, Patenaude, and Managan, 21.

with little time before impact.

For future generations, new technologies may displace nuclear weapons as a tool for planetary defense. The use of directed beams of neutral particles could in theory be transmitted over extremely large distances to ablate the surface of an asteroid. Chemical or biological compounds or mechanical 'eaters' might be developed to consume enough of an asteroid's physical structure to render it harmless when it strikes the Earth's atmosphere. Equally compelling, should methods be devised to contain and store it, small quantities of anti-matter could be used either as a strong explosive or to propel the threatening body to a safe orbit.[69]

These techniques, however appealing in theory, are generations away from development, if at all. With today's technology, it is a simple truth that the use of a nuclear device to prevent collision with Earth of a large asteroid or comet remains the most effective solution in a wide range of scenarios. The operational, legal, political, and public perception challenges related to the use of nuclear weapons to defend against a hazardous space object are vast, but must be addressed and overcome if nuclear weapons become necessary for planetary defense.

The development of nuclear weapons has been seen by many as a tragic turn in history, unleashing for the first time the potential power to destroy human civilization. How extraordinary it would be, then, if a monstrous asteroid on a collision course with Earth – the same primordial force of nature that exterminated the dinosaurs and that today could eliminate humanity – was deflected from its orbit by the well-timed impulse of a man-made thermonuclear explosion.

Rather than act as the destroyer of mankind, nuclear weapons would serve as its most vital defender.

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[69] Gritzner and Kahle, 183-184.

Figure 1. Trees felled by the 1908 Tunguska explosion. Photo courtesy of the Leonid Kulik Expedition.

Figure 2. Aerial view of the Manicouagan impact crater, Quebec, Canada. Roughly 100 kilometers wide, this crater was created more than 200 million years ago when an asteroid estimated at five kilometers in diameter struck Earth. Photo courtesy of NASA/Near Earth Object Program.

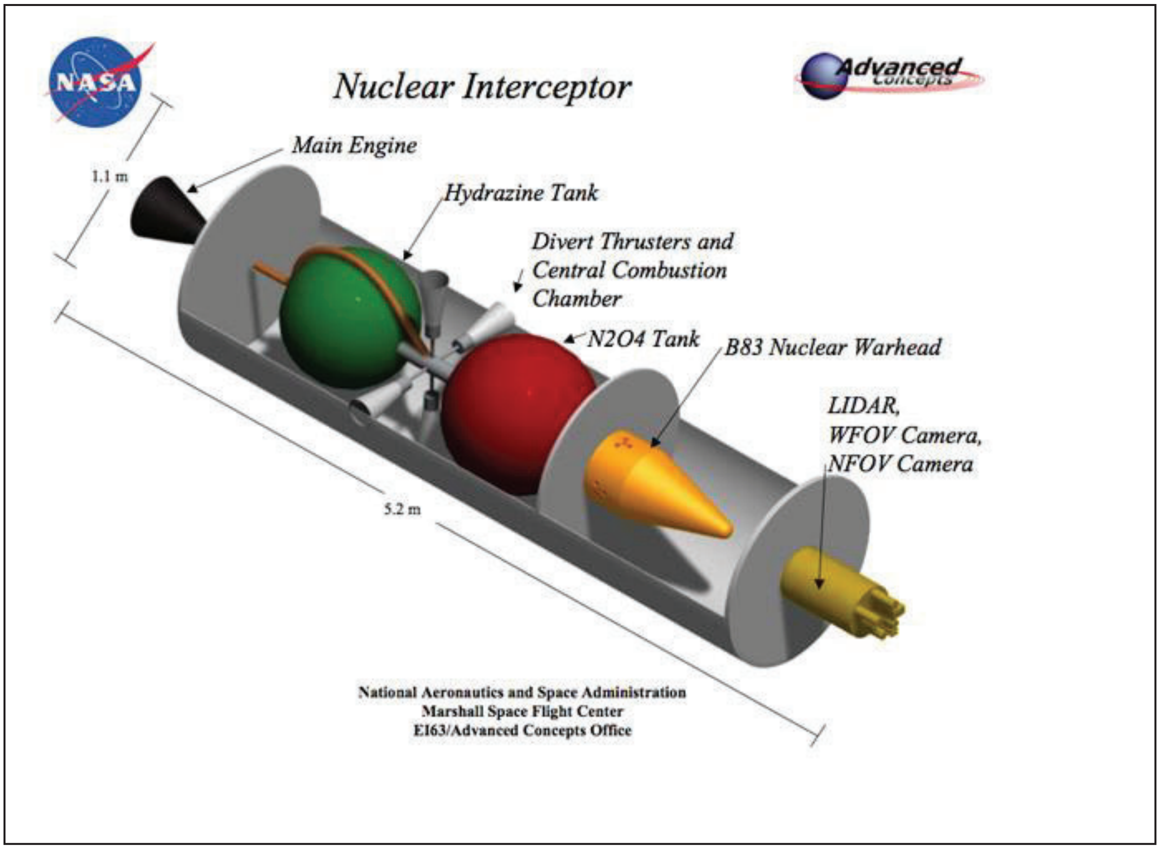

Figure 3. NASA nuclear interceptor concept, developed in 2007 and suitable for use in stand-off or surface detonations to deflect a threatening asteroid or comet. The B83 warhead has a programmable yield of up to 1.2 megatons. Image courtesy of NASA/Marshall Space Flight Center.

Figure 4. Comet Tempel 1 after being struck by the Deep Impact space probe in July 2005. Photo courtesy of NASA/Jet Propulsion Laboratory.