Appendix C

NATURAL METEOROIDS AS WEAPONS

Chapter Three and Appendix B used the physics of meteoroids as a starting point for developing an understanding of kinetic-energy weapons delivered from space. The discussions examined idealized meteoroids at sizes having effects that would be of tactical interest in conventional warfare. The impressive effects on earth of past large meteoroids suggest the possibility that natural objects—earth-crossing asteroids—could be used as weapons on a scale more suitable for strategic deterrence, as are nuclear arsenals. Such notables as Carl Sagan, in discussing means of preventing catastrophic natural collisions, have expressed concern about the possibility of deliberately deflecting an asteroid toward earth as a weapon (Harris et al., 1994; Sagan, 1994; Sagan and Ostro, 1994).

For nations that already have nuclear arsenals, asteroid weapons might be of only academic interest. Depending on the relative difficulty of acquiring a nuclear arsenal or equivalent weapons of mass destruction, the idea might be of more practical interest to other nations. The decision process and motivations that might lead some nation to acquire such weapons were discussed in Chapter Six.

This appendix will review some of the practical issues in employing asteroids as weapons. As in Chapter Three, the critical military issues are the suitability of the effect and the logistics of causing it. The review here will discuss suitability briefly and logistics in more detail. Suitability is determined by the size of the effect desired, which depends on the size, velocity, and composition of the asteroid. Logistics is a question of timely availability of an asteroid and the effort needed to find and use one when desired.

WEAPON SUITABILITY

By the time very small meteoroids impact the ground, they have slowed to several hundred or a few thousand miles per hour. These meteoroids are too small for this discussion. Very large asteroids or comets penetrate the atmosphere as if it were not there and strike the ground with full force. At the larger end of this scale (diameter ≥1 km) are asteroids, whose effects are too great to be useful for strategic deterrence. Threats of a mass extinction event are not likely to be credible. At the lower end of the scale are meteoroids large enough to survive reentry to strike the ground; these represent the upper bound of interest for strategic deterrence. Asteroids that can survive to a low enough altitude to have blast effects represent the lower bound.

Intermediate-size asteroids explode in the atmosphere. The altitude at which such objects begin to explode is approximately determined by equating the crushing strength of the material to the local atmospheric density and the square of the instantaneous velocity. Asteroids have median entry speeds of 13 to 17 km/sec (Chyba et al., 1994). Iron asteroids that are only 10 m in diameter retain most of this speed even in the lower atmosphere. Small iron meteorites have crushing strengths of as much as 4,000 atmospheres. A statistical analysis of the weakening due to fractures would suggest slightly lower strengths for an object with a diameter of several meters to a few tens of meters (Lewis, 1997, p. 380), with fragmentation beginning at about 1 to 10 km. Substantial blast and heat effect could occur on the ground below if the fragmentation takes place near the lower limit of that range.

There were at least three demonstrations of the effects in the 20th century alone (ordered from largest to smallest):

- Tunguska, Siberia, June 30, 1908. An asteroid weighing about 100,000 tons exploded at an altitude of between 2.5 and 9 km, with a yield equivalent to 40 megatons of TNT (Vasilyev, 1996). The blast felled trees over 2,500 km^2 and burned 1,000 km^2. Had this explosion taken place over an urban area in Europe, it might have produced 500,000 human casualties (Gallant, 1993).
- Sikhote-Alin mountains, Kamchatka Peninsula, 1947. An asteroid estimated to have originally had a mass of less than 1,000

tons fragmented at an altitude of around 5 km. The burst was high but did produce some ground effects, and the explosive yield was close to that of the Hiroshima and Nagasaki atomic bombs. Over 30 tons of material have been recovered from this event (Vasilyev, 1996).

- The Amazon, August 18, 1930. This smaller but still impressive impact occurred in a remote region. This yield was about one-tenth that of Tunguska, and reports of the event have resurfaced only in recent years (Schaefer 1998).

Smaller asteroids produce no more damage than the psychological effect on the viewing population (although demonstrating the capability of delivering an asteroid to earth precisely and on schedule would have high deterrence value). On October 9, 1997, a fireball was observed from Santa Fe to El Paso, where it finally exploded at a height of 36 km and released energy estimated to be equivalent to about 500 tons of TNT (Schiff, 1997). Assuming a stone asteroid—since no meteorites were recovered—the diameter was estimated to be 2 m and the mass 20 tons. Similar events happen a few times each year. This one was notable because the meteoroid exploded high over a major population center.

Much-more-energetic events have occurred recently. What was reportedly the brightest fireball to be seen by a satellite resulted from a explosion on February 1, 1994, 20 km over a remote area of the western Pacific Ocean; the yield was estimated at 11 to 110 kilotons. The object responsible was probably a stony meteoroid with a diameter of 7 to 15 m (*Satellites Detect Record Meteor*, 1994). If the El Paso object had been this size, the ground effects would have been very minor, but the population of El Paso would have had much more to talk about.

In 1996, a large asteroid designated “1996 JA1” approached earth—453,000 km at closest. This is slightly more than the distance to the moon, but some asteroids have been observed passing within a fraction of the earth-moon distance. This particular asteroid is distinctive because it was observed only four days before its closest approach and is believed to have had a diameter over 100 m. The impact of such an object would produce a ground or near-ground explosion equivalent to a 100-megaton weapon.

In summary, the suitability of weapon effect depends on the combination of size and materials. Precise control of the effects in an impact area would be very challenging. An object large enough to cause a big explosion would generally have a high enough β to suffer only minor angular changes in its trajectory due to atmospheric effects. But even for such objects, precisely predicting the extent of destruction would require understanding their internal composition, including possible internal fracture statistics or heterogeneity, to predict the altitude of breakup and the extent of blast effects from the breakup. The breakup of the Brenham stony-iron meteorite, for example, produced some specimens that are essentially iron metal and others that are mixtures of iron and olivine, a variety of stone.

LOGISTICS

Availability

Two well known groups of asteroids—the Atens and the Apollos—currently cross earth's orbit, and each originates in the main asteroid belt between Jupiter and Mars. Astronomers have discovered 190 that are over 1 km in diameter and estimate that there are 900. In addition, the 1,500 Amor asteroids are believed to be very large near-earth objects that could pose significant future danger, having the potential for global destruction.

Among the smaller, potentially useful objects may be over 1 million asteroids over 30 m in diameter that cross the earth's orbit (Rabinowitz et al., 1994; Shoemaker et al., 1995). The objects among them that are important for this discussion have diameters ranging from a few tens of meters to a few hundred meters, depending on whether they are stone or iron and on the effect desired. The relevant questions here are

- Can we reasonably expect to find enough of them?
- Do they pass near enough to the earth to be deflected enough for accurate collisions with the earth?
- Can this be done quickly enough?
- Can we expect to find them whenever necessary?

The lower bound on the availability of likely candidates can be determined from the history of actual natural collisions. The upper bound will depend on the amount of effort and lead time that can be devoted to deflecting what would otherwise be near misses into precise impacts. The frequency with which earth-asteroid collisions occur without assistance has been estimated from satellite observations and from extrapolations by counting lunar craters (Morrison et al., 1994). Objects of the 10-m diameter class impact almost annually. Stone objects this small fragment too high up to be useful weapons. Iron meteorites are observed in 3.2 percent of all falls (Lewis, 1997, p. 323). It would therefore follow that a 10-m iron asteroid—a Sikhote-Alin class object—strikes land on average once per century or so and the ocean twice as often. Objects with diameters of 100 to a few hundred meters impact earth naturally with a frequency of about one in a few thousand years (Morrison et al., 1994). Iron objects produce craters like the Barringer crater in Arizona. Stony objects produce air bursts like the Tunguska event in Siberia.

Increasing the opportunities to employ one of these natural weapons requires increasing the range of near-misses to some maximum miss distance. As the area the maximum miss distance covers expands, the incidence of objects available to divert should increase in proportion to the increased cross-sectional area. For example, diverting asteroids that would otherwise miss earth by a distance as far as the average distance to the moon should multiply the incidence of "near-enough" misses by about 3,600. If it is possible to divert objects at such distances, suitable opportunities would be available as often as weeks or months apart, rather than years or centuries.

Effort

Diverting the course of an asteroid requires only a small Δv, if the deflection is done far enough in advance of earth impact. The displacement is proportional to both the lead time and Δv.[1] Done well

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[1] Calculations of the Δv needed to *protect* the earth often assume that the asteroid is predicted to strike the earth and that the minimum deflection is about one earth radius. The assumed lead times are often very long, reducing Δv estimates to numbers much smaller than those assumed here for an asteroid used as a weapon. Deflecting an object toward earth requires a larger Δv if the miss is predicted to be close but by a

in advance, diverting an asteroid that would otherwise come no closer than midway between earth and moon requires imparting a Δv of at least several tens of meters per second to the asteroid. Deflecting an asteroid within days of its closest approach to earth would require a very large Δv, on the scale of kilometers per second. It is only possible to deflect an intermediate-size asteroid well in advance.

The precision of the angle and timing of entry into the atmosphere determine the degree of control over the location of the impact. Because the lead time for deflecting an asteroid is long, it is precise control of the velocity vector applied to the asteroid, not the time deflection begins, that is important. An error of only about 1 percent could alter the impact point by about 1,000 km.[2] In practice, ensuring damage to a particular large, soft earth target would mean controlling the asteroid's Δv to at least 1 part in 10,000. Reducing the target error to the range of kilometers would mean controlling the Δv to 1 part in 100,000, an accuracy comparable to that of simple ballistic missiles. The instantaneous position and velocity of the asteroid must be known during the deflection process and must continue to be monitored afterward for perturbations to the asteroid's trajectory. Radio astronomy provides the means of obtaining such precise position and velocity measurements: the differential, very-long-baseline interferometry used to navigate deep-space probes.[3] And, because of their large mass, these objects inherently have βs high enough to preserve accuracy through atmospheric entry. The principal uncertainty would be in the altitude of fragmentation for asteroids chosen to achieve blast, rather than impact, effects.

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safe margin. Precise targeting would need to account for the enhancing effect of the earth's gravity well.

[2] Infrequent observations alone cannot provide sufficient trajectory precision for targeting. For example, a 1997 prediction claimed that a large Apollo asteroid, 1997 XF11, would approach earth on October 26, 2028, at a dangerous minimum miss distance of 28,500 km. Subsequent calculations using additional data revised the distance to 865,000 km. The width errors were, respectively, 2,550 km and 750 km. Even the improved error value would be inadequate if the goal were to manipulate a piece of this asteroid to impact on earth. Furthermore, the refined length uncertainty, at 174,000 km, was still large.

[3] The Deep Space Network's representative error budget for deep-space probe velocity measurements, under standard observing conditions, is about 0.1 mm/sec (Jet Propulsion Laboratory, 1997).

Other observers might eventually detect the changed trajectory and recognize the threat, perhaps using the same radio signals used for navigation. But what if the asteroid is not detected until the last part of its trajectory? In this case, the larger the object, the less chance even an advanced nation has of diverting it. Likewise, if the object is not already on course for impact, even the attacker can do little to correct the situation.

A nuclear weapon may be the only way to divert or fragment an asteroid of modest size in the days just before the expected impact—assuming one were available and ready to launch. Even then, the consequences would be uncertain, since this could just distribute the damage over a larger area, with higher-altitude bursts than the attacker intended. While this might be attractive for deflecting an asteroid *away* from earth on short notice, it would probably not have enough precision for deflecting an asteroid *toward* an earth target.[4] Given enough lead time, however, a number of other deflection methods are available.

The most straightforward nonnuclear approach is to attach a device to the asteroid to act as a mass launcher, using the asteroid's own material as propellant and the sun as a power source. Consider a device that could produce exit speeds of about 1 km/sec.[5] Deflecting an asteroid large enough to create effects comparable to those of the Sikhote-Alin event with a lead time before impact of less than a month would require ejecting at least several tens of tons of asteroid material. This could be done in one day if the continuous firing rate were 1 kg every few seconds. The launcher would be required to make tens of thousands of shots, and an error in a single shot would cause a noticeable target error. Prolonged firing would require a greater total number of shots, which would only partially reduce the firing rate.

Beginning the deflection months in advance would reduce the effort required and keep the firing rate low. Here, the Δv results from a

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[4] In any case, a country that already had nuclear weapons would probably not need to use asteroids for deterrence.

[5] Sizing studies for lunar colonies have produced theoretical descriptions of such mass launchers. An early NASA study of space habitats describes mass drivers of larger capacity than our asteroid mover (Johnson, Holbrow, and editors, 1977).

large number of small nudges over a substantial period, so several times more effort would be needed than for a single large push (if that is even possible). The greater control that the prolonged multiple-shot process yields is, however, well worth the extra effort. Some of the key technical issues are development of a reliable mass launcher and the mining and preparation of asteroid material for use as propellant. Given enough lead time, the power needed for the mass launcher could also power the mining effort.

The amount of solar power needed for a mass launcher is large but not unthinkable for small asteroids. Firing 1 kg/sec at a speed of 1 km/sec requires 1 MW of power, assuming a mass launcher conversion efficiency of 50 percent.[6] A 2,500-m^2 solar array with 30-percent efficiency would be needed at a distance from the sun similar to that of the earth. Depending on the location of the asteroid at the time the maneuver begins, the distance might be as much as twice the earth-sun distance, which would require a solar array with four times the area.

Given a longer lead time than the postulated one month for moving something the size of the Sikhote-Alin object, the solar array could be smaller. Moving a massive Tunguska-like object would require two orders of magnitude (100 times) more energy. A reasonable level of effort for large objects like these could require a mass launcher to operate for months.[7] The equipment needed to convert an asteroid into a guided projectile would weigh tons, yet would have to be delivered at a velocity matching that of the asteroid. Depending on where delivery begins, this might be as prodigious a feat of propulsion as nudging the asteroid.[8]

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[6] The average launcher power for the minimal iron asteroid mass that could penetrate close to ground with very high velocity would be an order of magnitude less. The approximation is for an object weighing on the order of 10,000 tons (i.e., explosive yield of about 200 kilotons).

[7] Even if it were possible to scale the mass launcher to eject material more rapidly from the larger objects, the power source would have to provide hundreds of megawatts—on the scale of a nuclear power plant.

[8] Another concept often considered for moving asteroids—the solar sail—requires very long lead times for a reasonable size sail and is therefore unattractive for diverting asteroids to weapon use, except perhaps to push one into a more convenient orbit years in advance.

Timing

The above discussion made it clear that the lead time for deciding to employ a specific asteroid as a deterrent will be at least months. Some preparations could be made years in advance that might eliminate some of the delay: surveying candidate asteroids, prepositioning propulsion capabilities, perhaps even modifying likely as teroid orbits to improve their availability. For use as a nuclear-equivalent deterrent, such preparations might even be necessary.

The history of nuclear deterrence would make such a lengthy response delay seem unreasonable. After all, in the time it would take to prepare and deliver an asteroid strike, an opponent might be able to force the asteroid wielder to relinquish its belated asteroid response. Thus, even with the best of preparations to shorten delays, the owner of an asteroid deterrent must convince potential opponents of the inevitability of its response. It helps that an asteroid on a collision path with the earth presents some physical basis for a perception of inexorability—particularly if the identity and location of the asteroid are not readily and quickly available to the defender. But the real difficulty would be human: conveying the credibility of a commitment to an irreversible, devastating response, even though a substantial delay that would allow time for second thoughts, recriminations, political changes, and opponent responses. In some cultures with longer memories and long-held grudges, a few months' commitment to purpose might be trivial.

Technology

Industrial-scale rocket propulsion is the fundamental technology necessary for turning asteroids into weapons. None of its elements are unknown. Proof of principle is well understood. Conceptual design studies are available in the literature on space and lunar colonization, although particular devices of the right size would need engineering development. Only the scale of the enterprise gives pause and invites comparison with World War II's Manhattan Project.

As the nation mobilized for war, total U.S. defense outlays went from about $2 billion a year to a peak of about $80 billion a year over five years (Clinton, 1997). The country spent about $2 billion in total (about $20 billion in 1996 dollars) to develop the scientific basis of atomic weapons and the industrial processes and infrastructure for extracting and refining the needed materials (Purcell, 1963, p. 13; JSC, 1998).[9] Because of the sense of urgency, the project pursued parallel development paths—four paths for materials extraction, two paths for weapon design—without waiting for success in prerequisite elements of the program before committing resources to dependent elements. Yet for all its unprecedented scale, extravagant urgency, and remarkable success, the Manhattan Project was relatively modest compared to what would be required for asteroid weapons.

Generating solar power in space for transmission to earth would provide a better reference point for our purposes. In 1977, the first proposals to develop a such a capability, with a capacity of 5 GW, estimated a cost of $102 billion (about $254 billion in 1999 dollars) (Landis, 1990). Later proposals tried to reduce the cost by using lunar material to produce the solar cells and other elements of the power infrastructure, which presumed a separate investment in lunar transportation and facilities (Landis, 1998). The transportation, space materials, and manufacturing technologies needed for that exercise are precisely those required to convert asteroids into suitable weapons and are of roughly the same scale.

Clearly, a "Manhattan Project" for an asteroid weapon would be large and difficult to conceal, except perhaps as an element of a larger, nominally civil, program that required a similar large-scale space infrastructure, such as a program for generating power economically in space or for extracting lunar materials for various large-scale activities in space.

ALTERNATIVES

Aside from the limited range of possible effects and the great uncertainty about the precision of an effect, one clear argument against asteroids as weapons is that smaller, cheaper means of acquiring an equivalent to a nuclear deterrent are available. The preceding com-

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[9] When it was first decided to commit resources to industrial-scale production of atomic bomb materials, the estimate of future needs was only $400 million (Smyth, 1945, p. 115).

parison with the Manhattan Project highlights the fact that the infrastructure costs for asteroid weapons are at least an order of magnitude greater than the cost for developing and producing nuclear weapons.

Had it not been for the fortunate interruption of the Persian Gulf War, Iraq would have provided an example of the practicality of a covert, third-world "Manhattan Project." With that object lesson still fresh, the availability of nuclear materials and technology may have undergone enough scrutiny to make other alternatives attractive to those who would like to acquire a weapon of mass destruction. Unfortunately, chemical and biological weapons are much less expensive and much easier to proliferate than are nuclear weapons (OTA, 1993a; OTA, 1993b). While the alternatives may lack the impressive physical destruction of a nuclear or asteroid weapon, their potential for wholesale and indiscriminate lethality should make them reasonable substitutes for deterrence.

SUMMARY

With some patience, waiting perhaps a month or two, suitable asteroids could be routinely found that would produce weapon effects equivalent to nuclear weapons with yields ranging from tens of kilotons to many megatons. With some effort, they could be diverted to weapon using technology (and extensive supporting infrastructure) similar to that for exploiting lunar materials, generating solar power with satellites, or defending against asteroids. However, at best, it would take months after a decision to use one as a weapon to reach the desired conclusion. Because much cheaper, more responsive weapons of mass destruction are readily available, this one is likely to remain safely in the realm of science fiction.