Blast Designs For Neo Destruction and Deflection

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Large-scale blasting techniques developed for terrestrial construction and mining could, if applied to a threatening NEO, ensure its transformation into fragments too small (<50 meters across) to survive passage through Earth's atmosphere. Additionally, this approach could impart impulses to deflect the NEO. This approach would also be responsive to ongoing characterization of the NEO. Four NEOs were selected to illustrate the range of blast design and mitigation outcomes possible: Asteroids Itokawa, 1986 DA, and Eros, and comet Wild2. This paper addresses the overall concept for operations and discusses key features of the approach that are normally outside the realm of aerospace engineering.

I. Introduction

WHETHER asteroid or comet, many near-Earth objects (NEOs) have the potential to impact the Earth at some future time. Many have in the past. Prevention of such an impact is the topic of this conference; this paper discusses the application of distributed-energy means – explosives, whether conventional or nuclear – to this end. Rather than salvation being delivered in a single burst of energy, this approach distributes destructive energy within carefully selected parts of a threatening NEO. The advantage is responsiveness to unexpected spatio-temporal changes in NEO properties, and the ability to select the desired maximum fragment size.

The fragmentability of a NEO depends on its physical structure and the type of material it comprises. This is true regardless of the fragmentation method used. A mechanical classification proposed by Ref. 1 divides NEOs into four broad groups based on their components and structure, focused on how readily they can be broken up:

- Group 0. Ice composites – very weak, containing ices with or without organic compounds.
- Group 1. Friable rock – similar to Group 0, but with no volatile components. Also weak.
- Group 2. Hard rock – strong and brittle, the most similar to materials encountered in terrestrial mining and excavation practice.
- Group 3. Metallic:
  - 3a. Massive metal – may be ductile.
  - 3b. Rock-metal composites – would fracture mainly at rock-metal interfaces.

In addition to the fragmentability of a natural body in space, its size also affects the fragmentation techniques that can be applied. Although a mountain can be reduced to sand one pickaxe blow at a time, the time required would be prohibitive. More efficient means are needed. Therefore, Ref. 2 described an additional classification, one based on size expressed as the number of separate blasts[*] required to fully deal with a threatening NEO:

- Class 1. Requires only one blast of a few to several hundred charges. A single human-robotic team is needed for blast design and construction.
- Class 2. Requires between two and five simply layered blasts. One to several teams are needed, depending on the mitigation speed required.
- Class 3. Requires more than five blasts, with significant complexity, including multiple layers of blasts. Many human-robotic teams needed.

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[*] A blast is the initiation of one or more charges linked by a network of detonators.

Note that the population of NEOs as presently known is heavily biased by detection limitations toward Class 3, which provide the greatest risk of individual impacts lethal to humanity. Yet, Class 1 and Class 2 bodies are the greater hazard in terms of numbers.

These two classification systems have been combined to generate the matrix shown in Table 1. Each cell of this matrix will require a different pattern of blasts. This paper represents the first steps in developing techniques of distributed-energy blasting specifically for destruction and deflection of NEOs.

Table 1. Where the four selected NEOs fit into the blast design matrix, which is based upon NEO size (Classes 1-3) and fragmentability (Groups 0-3b).

	Class 1	Class 2	Class 3
Group 0			*Wild2*
Group 1		*Itokawa*	
Group 2			*Eros*
Group 3a			*1986 DA*
Group 3b			

To this end, one NEO was selected for each of the four main fragmentability categories. Very few NEOs have been studied in sufficient detail to permit a useful blast design study; this limited the choices rather severely. Itokawa, Wild2, and Eros have been visited by spacecraft for different lengths of time. What is known about 1986 DA has been gleaned from Earth-based radar observations.

Each cell of the blast design matrix will likely be defined by different NEO size limits. A Group 1, Class 1 body could be physically larger than a Group 2, Class 3 body. At this point, it is not clear what those limits will be, so in this paper we have assigned the selected NEOs to matrix cells solely on the basis of their size relative to an extrapolation of terrestrial blasting practice to the space environment.

II. Blasting for Fragmentation

Detonation of a single large explosive within a NEO is likely to waste its energy in the near-field region, and may not sufficiently fragment the rest of the target. The delivered energy density must be sufficient to create new fractures throughout the body with sufficient connectivity to keep the maximum fragment size below a pre-determined limit, which for this study is set at 50 m[3,4].

Distributed-energy blasting is also part of the utilization of the mineral resources that are available within NEOs. Fragmentation is of primary importance to mining and processing, as it is the first step in separating materials of interest from unwanted surrounding material, or of creating rock fragments of desired sizes, shapes, and configurations in quarrying operations.

The key to large-scale blasting in any venue is the efficient distribution of explosive energy in space and time. This requires placing charges of pre-determined sizes at appropriate depths in a three-dimensional pattern that reflects the properties of the material and the degree of fragmentation required, and then initiating the charges in the appropriate sequence.

Selection of the appropriate explosive mass per volume or mass of unbroken rock (powder factor, or specific charge) – the first step in blast pattern design – allows one to calculate the explosive mass required to pulverize all or part of a NEO, given its volume. On the Earth, a typical powder factor for a surface blast ranges from 0.5- to 0.76-kilogram explosive per cubic meter of rock, and produces fragments less than 3 meters in diameter. This powder factor is optimized for terrestrial brittle, hard rock. Non-brittle NEOs could be pulverized through this technique as well, but powder factor selection would require on-site calibration before full-scale use.

The dispersal of the explosive required to achieve the necessary powder factor within the target rock mass is accomplished by creating blastholes in the mass and filling them (wholly or partly) with the explosive. The major parameters of blast design include:

- Energy yield per unit volume or mass of explosive,
- Time intervals (delays) between detonations of individual charges or groups of charges,
- Number of charges (mass of explosive) grouped to be detonated simultaneously,
- Charge diameter,
- Blasthole depth,
- Inter-hole spacing, and
- Burden (distance between each charge and the nearest stiffness interface at the time of firing) – this varies during a blast as previously fired charges create new rock surfaces.

A. Explosives

The blasting agent used to fragment a NEO could be selected specifically for the purpose of the mission (fragmentation or deflection), but any explosive could be made to serve either purpose with the appropriate choice of blast design.

This paper assumes the availability of an explosive similar to terrestrial ANFO[†]-based emulsions. The explosive would have to be transported in cartridge form (available commercially) to prevent desiccation in space.

High-energy density explosives, such as HMX[‡], would require lower launch mass and smaller-diameter blastholes than ANFO or ANFO-emulsion blasting agents. High-energy density explosives, however, do not create the large gas volumes generated by ANFO-type explosives that account for the efficient rock mass dispersal required for efficient terrestrial mining/quarrying operations.

Nuclear devices would provide the highest energy density explosive. To achieve the same fragmentation effect, the distance between charges should be approximately 137 $W_{kt}^{0.294}$ meters, where W_{kt} is the yield of the device in kilotons[5].

Comets may provide an alternative source for ANFO that avoids launching the high mass of bulk explosives from Earth. The commercial ANFO manufacturing process[§] extracts ammonia for the ammonium nitrate oxidizer and adds other compounds such as hydrocarbons, metals, or sulfur for the fuel. A wide range of materials suffices for the fuel if it is evenly divided throughout the AN and if stoichiometric balance is maintained. The mass of a plant to produce cometary ANFO would be significantly less than the mass of the ANFO itself, and the feedstock for the plant would be provided by the debris from blasthole drilling, supplemented if necessary by additional excavation.

Many comets contain 0.4 to 0.9 parts of NH_3 to 100 parts of water. Comet Hyakutake, for example, contains as much as 0.5 parts of NH_3 to 100 parts water[6]. Therefore, the mass fraction of NH_3 in Hyakutake and many other comets is well over that needed to fragment the comet. For Halley, the best studied comet, estimates of NH_3 and CH_4 content, relative to H_2O content with a relative abundance of 100, are 0.1-2 and 1.5-4.5, respectively[7]. These relative abundances are roughly equivalent to the NH_3 and CH_4 percent of the overall comet mass.

B. Blastholes

Blasthole drilling requires less energy with increasing blasthole diameter, although more, smaller holes distribute the explosive energy throughout the target mass more efficiently. If the target is pervasively jointed or contains veins of weaker material, smaller holes also cause less attenuation of the shock waves and give better distribution of the explosive energy near the tops of the holes.

The blastholes could be created by any guided excavation or drilling process that form refillable passages into the interior of the target volume. Standard terrestrial mining and construction blasting practice relies on linear blastholes of diameter 25 mm to 400 mm and length to 60 m. Other terrestrial applications expand both limits substantially by placing the drill within the hole, as with down-the-hole (DTH) hammer drills and tunnel boring machines (TBMs). In the TBM case, the key is gripping the wall of the hole to provide reaction forces (once the hole has been started), and electronic locating technology to maintain precise blast geometry throughout drilling. Global positioning satellite technology is limited in subsurface operations, but sequential down-hole laser stations provide the link to a global three-dimensional grid in Earth's underground and could do so within space bodies as well. DTH drills still require surface drilling rigs.

The crudest, but most direct, transferal of terrestrial drilling practice to NEO use is to transport surface drill rigs to the site (suitably modified for the hot and cold radiation-rich vacuum) and anchor them to a system that grips the NEO, or a substantial portion of it. Even TBMs will need something of this type to enable them to begin the drilling of each hole (termed "collaring"). The simplest approach for small NEOs would be to wrap a single length of robust cable around enough of the mass that the body's irregularities can hold the cable in place under the thrust and torque required by the drilling. This could be supplemented by local, smaller-capacity anchors for the cable and/or the collaring frame. For larger bodies the cable-wrap becomes logistically more difficult. A multiple-level network of cables and tethers may be required.

Group 0 bodies, which contain a significant fraction of volatiles in the form of ices, could be drilled by melting. This is done on Earth. Such an energy-intensive drilling process may need a dedicated power source, such as a solar collector or radioisotope heat generator. The temporarily melted volatiles thereby produced must be handled properly to avoid refreezing and closing the blasthole prematurely behind the drilling device.

Current-art drilling rates are limited not by the speed of fragmenting material at the drill face, but by the speed at which the debris produced can be removed from the hole. Terrestrial blasthole drills remove rock chips with a continuous stream of water (or less commonly, air). Melt-drills could direct their waste volatile streams to the

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[†] ANFO is a mixture of ammonium nitrate and long-chain hydrocarbons (commonly fuel oil).

[‡] HMX is "High-Molecular-weight rdX," a relatively insensitive nitroamine compound more powerful than ANFO.

[§] 3.17 million metric tons of ANFO or ANFO-based explosives were consumed by mining and construction in the United States in 2005[8].

simultaneous formation and impelling of continuous ice rods out of the hole behind the drill. This would require very precise guidance and would more likely be realized as robotically guided movement of long pieces of the ice rods instead of continuous growth alone.

Some drilling approaches would be more appropriate for placing local surface anchors. Single- or multiple-stage penetrators could be used for the first level of attachment. Then tethers to two or more penetration anchors could provide sufficient reaction force to drill deeper holes. Such bootstrapping could be continued for several levels, drilling deeper anchors at each level, until sufficient anchor force can be generated for drilling a blasthole. Earlier holes can be used for temporary anchor emplacement while drilling later holes.

C. Timing

Short (tens of milliseconds) time delays are incorporated between the detonations of portions of column charges (in multiply decked holes) or of groups of loaded blastholes to allow sufficient time for the rock to fracture and move. Too-short delays "choke" a blast, preventing proper fragmentation and locking the fragments together. The minimum delay time for burden detachment in hard, brittle rock is 3 millisecond/meter of burden. Longer delays produce better lateral relief, improving the conversion of explosive energy into material fragmentation and reducing excess vibration.

These delays can also be used to aim the blast impulses in the appropriate directions to control the resulting trajectories of the fragments. This could be combined with precise timing of blast initiation within a time window when the blast would generate the largest impulse toward nonhazardous trajectories.

Fig. 1 illustrates the different results from a surface mine blast created by a change in timing of the initiation of the charges.

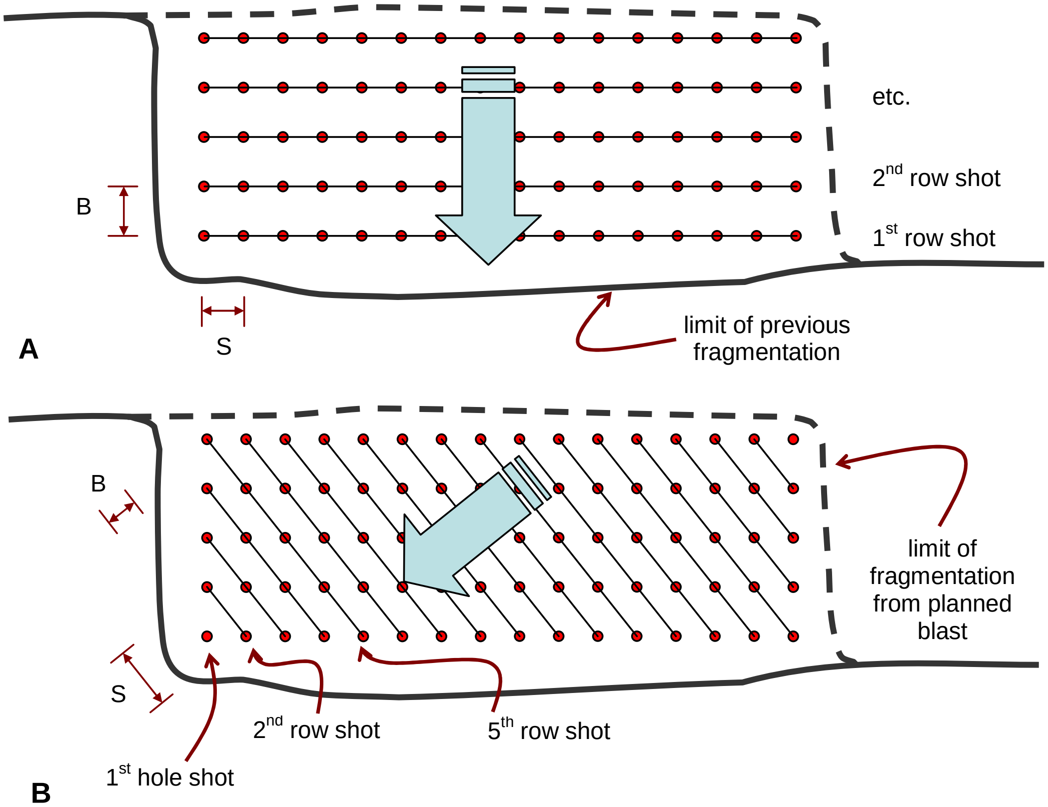

Figure 1. An example of the effects of different delays on the same blast geometry, shown in plan view. B = burden, S = spacing. Red circles are blastholes drilled into the page; they are linked by initiation lines. Broad blue arrows show the resulting direction of motion of the rock fragments. Note also the effect of the delay choices on the values of burden and spacing (shown on the left in each diagram).

D. Blast Designs for Asteroids and Comets

Several types of blasts (single-sided, double-sided, and ring shots) are possible for dismembering NEOs. The application of any particular blast geometry depends on the shape and structure of the body remaining from the previous shot and on the particular purpose of the present shot.

The single-sided blast design applies the strongest unidirectional impulse to the remaining body (Fig. 2). Double-sided shots are paired, whether symmetrically or asymmetrically (Fig. 3), and ring shots permit subtle momentum corrections to be made at relatively high angles to the pre-existing NEO trajectory (Fig. 4).

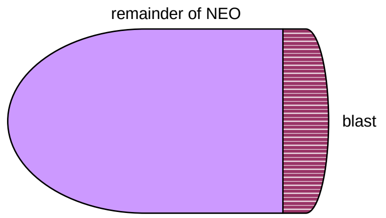

Figure 2. A single-sided blast. Unidirectional impulse can be applied to the NEO. Blastholes can be parallel (shown) or radial (see Fig. 3B).

In all three types of blast designs, the blastholes can be oriented parallel to each other, whether parallel or angled to the desired impulse vector; radial to the impulse vector; or intermediate between these two extremes. The examples shown in this paper are somewhat arbitrary since there is not nearly enough information available to make accurate choices. Much study would go into the selection of individual blast patterns in the actual cases, both prior to and after mission arrival on-site.

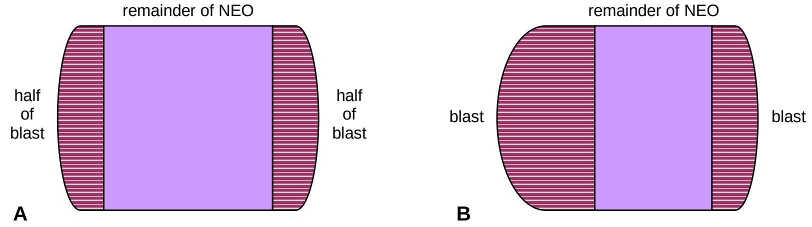

Figure 3. Double-sided blasts, again with parallel blastholes. A Symmetric. B Asymmetric.

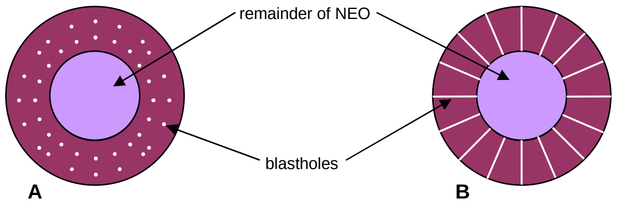

Figure 4. Ring blast. A Parallel. B Radial.

III. The Target NEOs

The selected NEOs, one comet and three asteroids, are discussed here and in subsequent sections in order of increasing size. Their basic properties are listed in Table 2 and their relative sizes are illustrated in Fig. 5. Here the large size and wide differences in relative volumes become apparent. These differences, in addition to the differences in blast design required by their various constituents, lead to strikingly different mitigation requirements.

A. Itokawa

The smallest of the four NEOs, Itokawa was visited by the Hayabusa mission during late 2005. Its extreme roughness, varying surface terrain, and indistinct craters suggest that it is likely a rubble pile (Fig. 6).

Table 2. Basic properties of the four selected NEOs.

	general shape	volume (m^3)	mass (kilotons)	bulk density (g/cm^3)	relative volume
Itokawa	contact binary, simplified to triax. ellipsoid	1.84E+07	3.49E+04	1.9	1
Wild2	triax. ellipsoid	4.75E+09	7.13E+06	1.5	260
1986 DA	spherical	6.37E+09	3.19E+10	5	347
Eros	irregular	2.51E+12	6.69E+12	2.67	136,304

B. 81P/Wild2

Wild2 is the comet visited by the Stardust spacecraft in 2004, which collected particles from its coma. Ref. 9 describes Wild2 as "a thick hamburger patty, with a few bites taken on the edges," although it is modeled for this study as a much simpler ellipsoid of revolution (Fig. 7). The surface topography exhibited features of greater material strength than had been expected, such as relatively large craters or vents with steep walls, and angular topography.

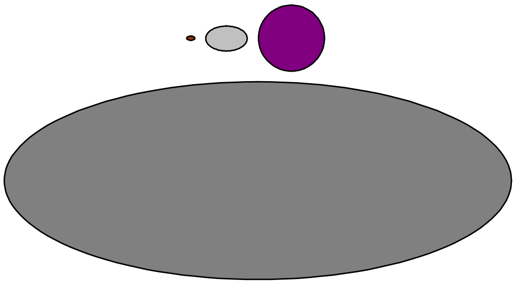

Figure 5. Relative sizes and simplified shapes of the four target NEOs (Top L-R: Itokawa, Wild2, 1986DA; Bottom: Eros).

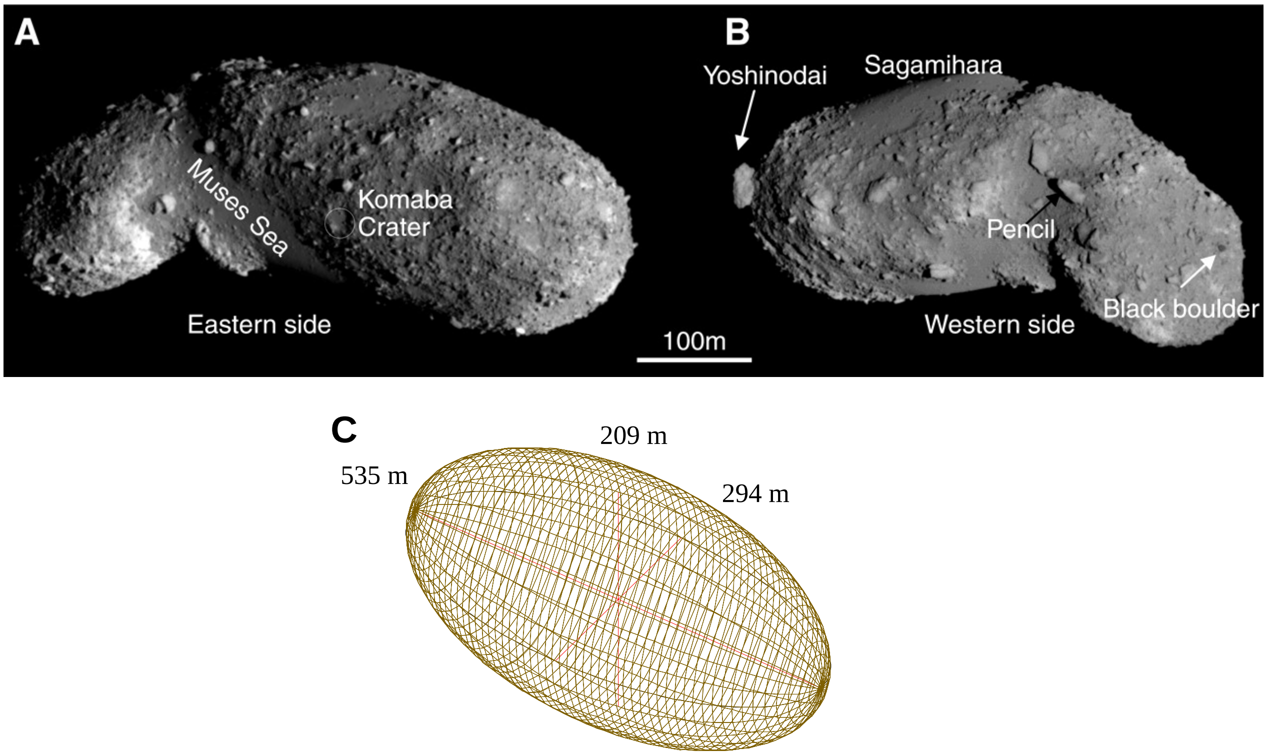

Figure 6. A) and B) Global images of Itokawa[10]. Reprinted with permission from AAAS. C) Simplified wireframe model of Itokawa.

The density of Wild2 is not well-constrained. Although comet densities have been estimated at 0.3 to 0.7 g/cm^3, extrapolation of the estimates calculated by Ref. 11 produced densities from 1.6 to 6.2 g/cm^3, depending on the method and assumptions used. A value of 1.5 g/cm^3 was selected arbitrarily from the middle of these combined ranges.

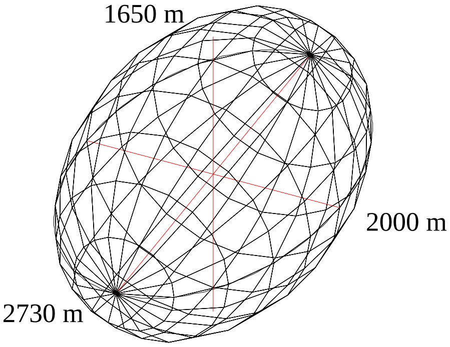

Figure 7. Simplified wireframe model of Wild2.

C. (6178) 1986DA

1986 DA is the least-characterized of the four bodies, yet what is known makes it of interest to this study. Its relatively smooth surface and high reflectivity suggest metallic composition[12]. Its shape is very irregular and possibly bifurcated, but in the absence of more precise data, a sphere had to be used for the blast designs (Fig. 8).

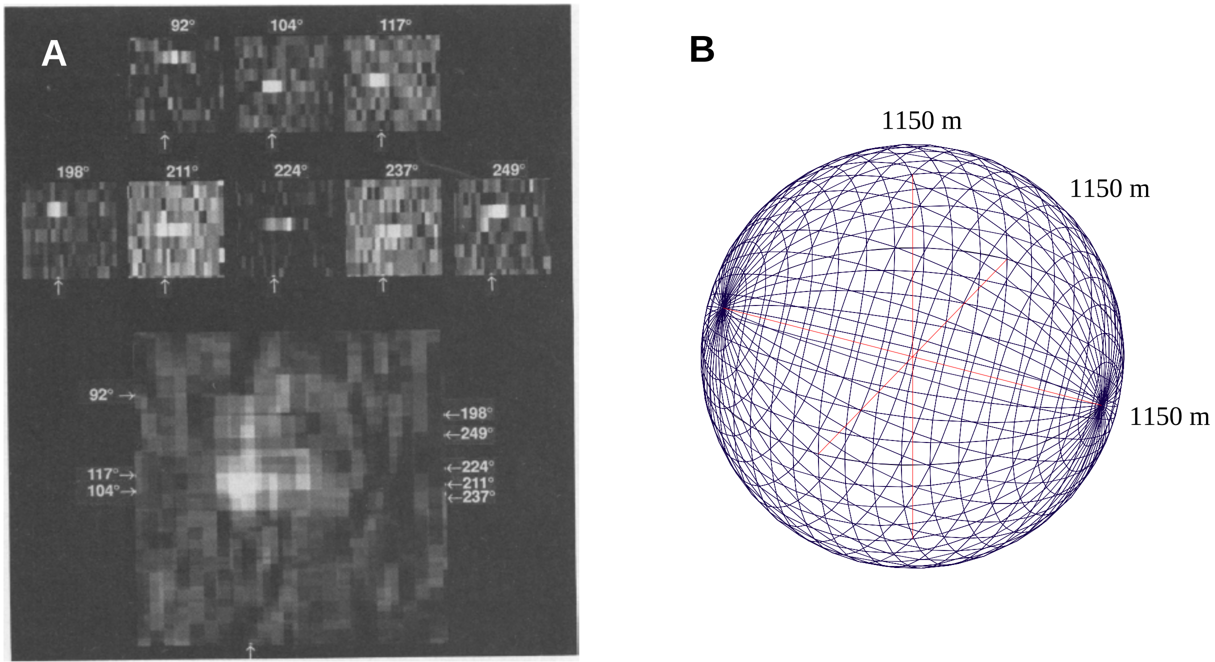

Figure 8. A) Radar images of 1986 DA[13]. Reproduced with permission from AAAS. B) Simplified wireframe model of 1986 DA.

D. Eros

Eros is the largest by far of the bodies studied. It also is the one characterized in the greatest detail, having been the target of the NEAR mission in 2000-2000 (Fig. 9). Its internal structure may be dominated by large fracture systems, although these are evidenced more by subtle morphological features rather than its gross shape[13]. There may be some remnant structure from a precursor body as well as accretional layering, though probably not melt layering. All these will affect the design of any excavations or blasting of Eros.

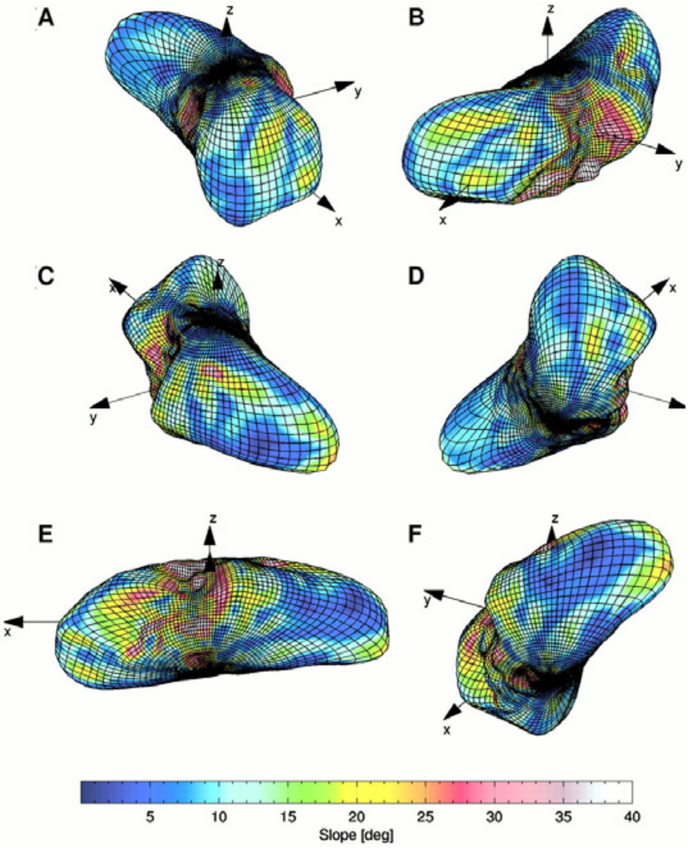

Figure 9. Six perspective views of a three-dimensional shape model of 433 Eros[14]. Reproduced with permission from AAAS. Length of long axis is 33 km.

IV. Mitigation of the Target NEOs

The varied sizes and constituents of these four NEOs permit us to explore equally varied approaches to mitigation of the hazards they pose. Table 3 outlines the distributed-energy blasting approaches discussed here, with the time required being calculated by assuming overall system availability of 50%. This may be an optimistic value. The parameters used to calculate these results are discussed in the subsections below.

The general approach to is to turn Class 3 bodies into a number of Class 2 bodies, either all at once or in a phased deconstruction. In such cases the limiting factors are related to the number of robotic, human-supervised teams that can be fielded. When team numbers become too large to be feasible, then the focus of the blast designs becomes that of imparting appropriate impulses to move the bodies, or over-

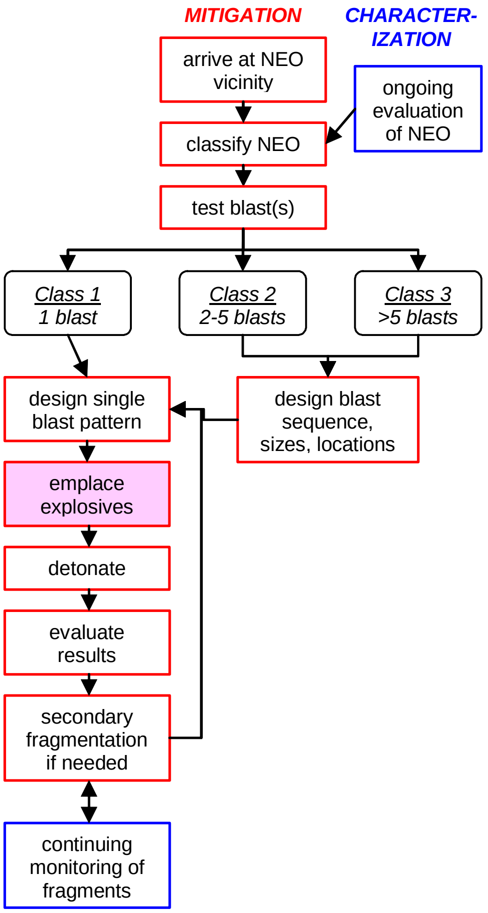

Figure 10. Schematic diagram of a blasting mission[2]. Red outlines indicate the mitigation mission. Blue outlines indicate the evaluation mission.

large fragments thereof, out of possible Earth-impact windows, rather than that of destroying the body entirely.

Fig. 10 outlines the general approach to applying distributed-energy blasting to NEOs. It shows the cyclic nature of blasting a large volume, which must be done in stages.

The time necessary to travel (one-way) between Earth and each of the targets, the total mass to be transported (including equipment), and the number of launches necessary are listed in Table 4 (Ref. 15), assuming the use of Boeing Delta-IV Heavy launch vehicles and no on-site manufacture of explosives. This applies only to the mitigation mission. The characterization mission would require its own launch scenario for each target. Both missions would ideally continue until the size and orbit of each fragment had been confirmed to pose no further threat to the Earth. This would require long-term monitoring, but after a certain time window has been declared safe (duration to be determined), the human component would be withdrawn. The extreme length of these missions for all but the Class 1 bodies would require crew rotation and equipment recycling, so the necessary launch assets would be greater by a factor that depends on the length of safe human habitation in micro-gravity. Until that length of time exceeds the two-way transit time by a sufficient amount, only non-crewed robotic missions will be possible. In addition, the extreme number of launches needed for all but Class 1 bodies points to the necessity of acquiring explosives ingredients onsite.

A. Itokawa

Upon confirmation of its gravity-dominated rubble-pile status, Itokawa could be fragmented with a single large blast using a powder factor just great enough to disrupt its gravity “cementation”. This would depend on precise determination of its porosity and porosity variation. Higher material porosity requires higher powder factors to overcome the energy-dissipative effect of the void spaces. This critical powder factor is very difficult to estimate remotely; its determination would depend on careful on-site calibration shots. The best available alternative is to shoot Itokawa in paired blasts from the ends inward (Fig. 11) using the drilling pattern shown in Fig. 12.

Table 3. Basic parameters for destroying or deflecting the target NEOs with distributed-energy blasting.

Destination NEO	General Approach	# Blasts	Explosive Mass (kg)	Drilling (km)	# Teams	Time On-Site (yr)
Itokawa	destruction	6	1.10×10^4	6.6	1	0.5
Wild2	phased destruction	10	4.75×10^6	2,522	20	4
1986 DA	deflection	3	2.24×10^8	346	10	2
Eros	splitting & later deflection	17	3.82×10^9	1.36×10^5	500	20.4

Table 4. Maximum delivered payload mass trajectory results and number of required launches[16]. These estimates are for mitigation only and do not include evaluation.

Destination NEO	Departure Date	Flight Time	m_{PAY} [kg]	Number of Launches
Itokawa	May 18, 2036	6 months	5981.94	6
Wild 2	November 11, 2028	7 months	686.22	7.508×10^3
1986 DA	March 4, 2019	6 months	1215.42	1.843×10^8
Eros	February 8, 2035	8.5 months	2839.75	1.349×10^6

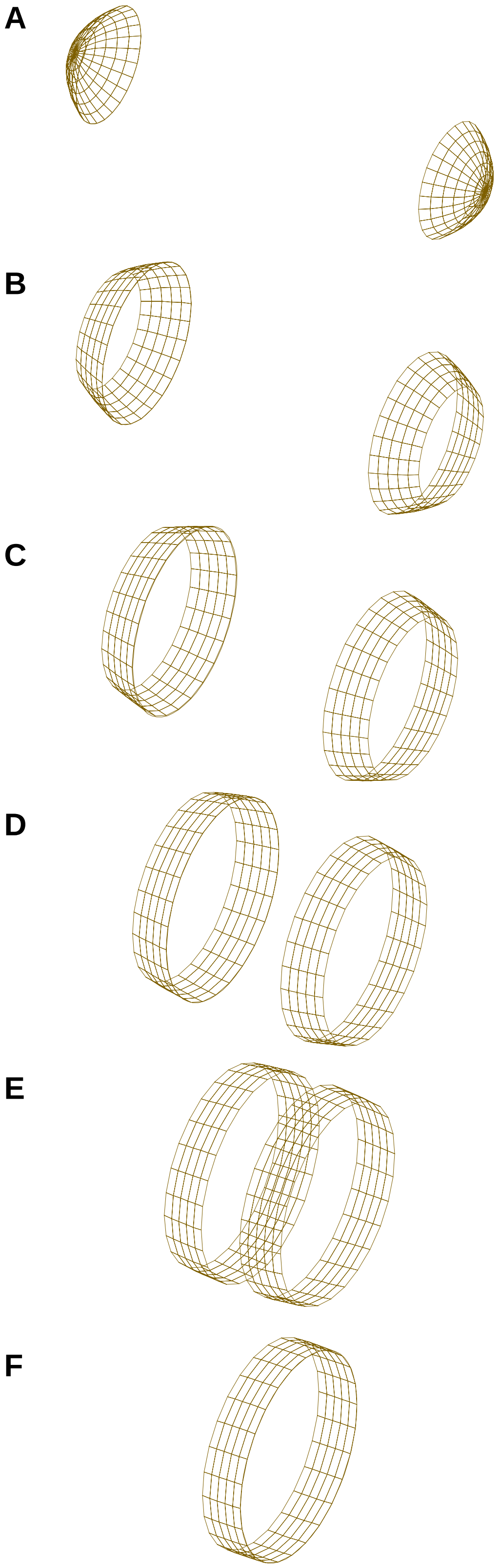

Figure 11. The blasts proceed with double-sided shots from the ends (A) inward to the final, largest blast (F) that is the only single-sided shot. The asteroid core remaining after each blast is not shown, for clarity.

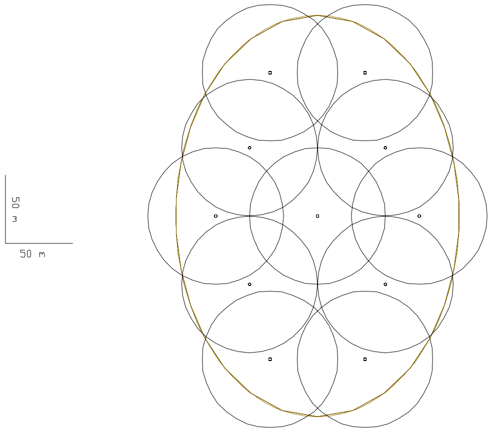

Figure 12. A blasthole layout for the last slice of Itokawa (Fig. 11F), showing 50-m radii of influence around each blasthole.

The initiation delays, in the simplest case, would be the same for all blastholes. The capability exists for different delay patterns, though, that would shove the remaining, unfragmented body sideways as a secondary effect.

Even a rubble pile such as Itokawa will require sufficient explosive force to prevent the disrupted material from re-aggregating within a time window that causes it to become an impact hazard again.

B. 81P/Wild2

This comet is relatively large (Class 3), and its expected high percentage of ices requires that a moderately high powder factor be used. These two factors require a great deal of explosive mass. However, materials from the comet itself can be used to produce a blasting agent similar to commercial ammonium nitrate-fuel oil. This would greatly reduce the most massive requirement for the mission.

The blast design for Wild2 would begin in a manner similar to that applied to Itokawa. Wild2 would be slabbed symmetrically with double-sided blasts until the remaining portion is roughly the same length as its diameter. Then a series of ring blasts would be shot until the core that is left is itself less than 50 m across (Fig. 13).

C. (6178) 1986 DA

This asteroid appears to consist of nickel-iron metal, and its high bulk density – in the vicinity of 5 g/cm^3 – requires a high powder factor (1.5 kg/m^3). 1986 DA is roughly twice the size of comet Wild2, which makes its total destruction within a reasonable time duration less feasible. Therefore, it is used here as an example of using distributed-energy blasting to impart an impulse to the entire body. The exact nature of the desired impulse is not determinable at this point, so some rather arbitrary assumptions are made in the spirit of showing how such a blast, or series of blasts, could be designed and carried out.

The density of 1986 DA is assumed to be constant throughout the body, and its shape is assumed to be a sphere. To create a blast that deflects the asteroid, the blastholes can be drilled parallel to each other, creating a single-sided shot, or radially, creating a ring shot, as shown in Fig. 14 and Fig. 15. The former case could generate a single

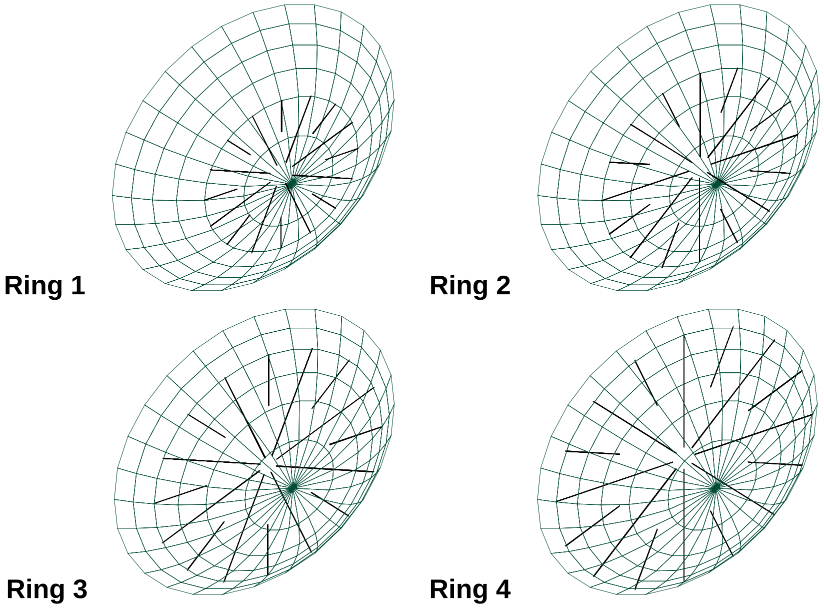

Figure 13. Close-up view of blasthole rings 1 through 4 of half of the first blast for fragmenting Wild2. The other half of the blast would be taken off the opposite end of the body at the same time. Note the very acute angles of the blastholes with respect to the surface of the body, especially in the earlier rings.

impulse vector. More complex delay selection could impart various subtle characteristics to either type of blast. In all cases, careful timing of the start of the blast with respect to the asteroid's rotation state and its relationship to the terrestrial impact window is required.

The single-sided blast would consist of enough blastholes to cover a sector of the sphere, all oriented parallel to the desired impulse vector at the moment of initiation. The size of the sector would be controlled by the impulse magnitude desired and the burden and spacing required for fragmentation. The blast could begin by initiating the center blastholes first, followed by increasingly distant blastholes. As the initiation spreads outward, the impulse from each delay has a greater moment arm with respect to the center of mass, to correct wobbles induced by heterogeneities in the interior of the asteroid during earlier delays of the blast. It is possible that more detailed studies may show that the energy distribution efficiency of the opposite case – beginning the blast at the outer holes and propagating inward toward the center – might generate a better overall result.

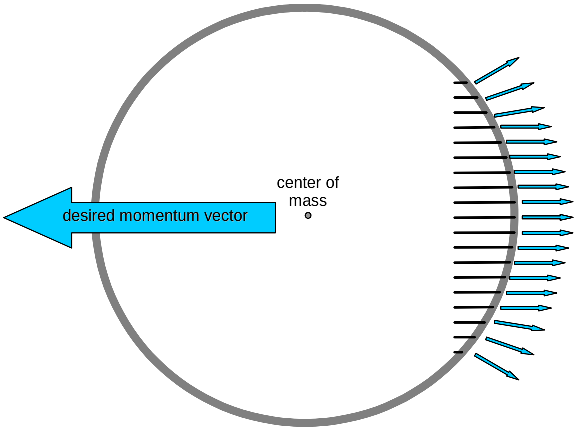

Figure 14. Deflecting 1986 DA with a single-sided blast, showing individual blasthole impulse vectors and the desired resultant momentum vector. Not to scale.

A ring shot is set up physically in a manner similar to those shown in Fig. 11 for blasts six through ten of Wild2. The resulting impulse vector is, on a first analysis, more narrowly focused than that from a double-sided shot. The blastholes of this ring shot are oriented so they would intersect the desired resulting impulse vector of the body at an acute angle or a range of acute angles (Fig. 15). The ring of blastholes farthest from the center of mass would be initiated first, then the next closest one, and so on. Further fine-tuning is possible by modifying the initiation delays to shoot finite arcs of blastholes in a particular sequence. Again, precise timing of the start of the blast is important to ensure the maximum effect and to avoid increasing the impact risk.

D. Eros

This is a very large body, and to fragment it entirely into pieces smaller than 50 m would take an extremely long time and require very significant robotic and human resources. Its irregular shape also makes the use of a few simple blasts to change its trajectory, as were illustrated for 1986 DA, equally problematic, although with experience on smaller bodies, such an approach might be possible in the future. The approach suggested for Eros, therefore, is to split it into several main pieces and design blasts for each to change their momenta individually. In addition, to reduce the still very substantial amount of explosives and drilling required, the blasting is designed for hypothetical sub-kiloton nuclear explosive devices instead of ANFO or ANFO-based explosives. Only the splitting blast is

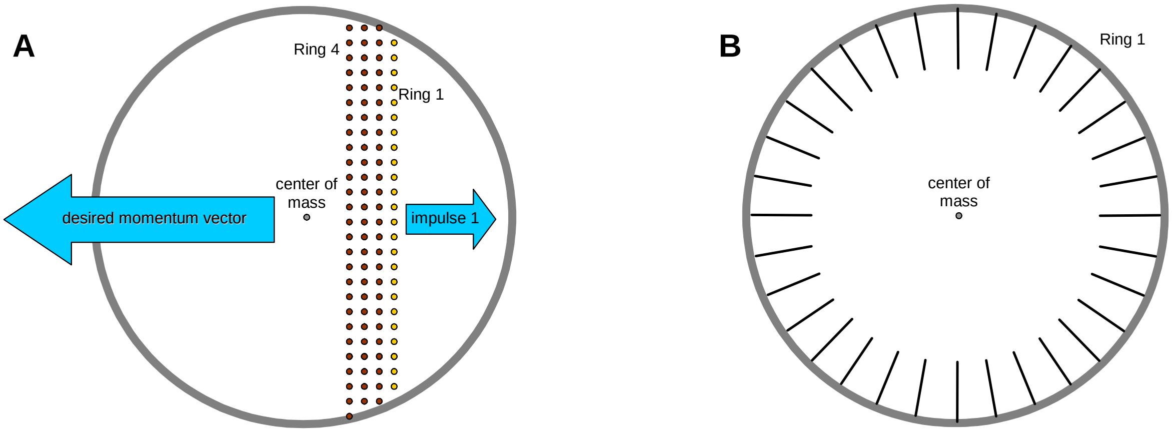

Figure 15. Two schematic views of deflecting 1986 DA with a ring shot, using radial blastholes. Not to scale. A) Side view, showing four blasthole rings. Ring 1 is shot first, followed by Rings 2 through 4, in order. B) Rear view, showing blasthole radial orientation. The impulse vector from each ring points out of the page. Although shown perpendicular to the desired momentum vector, they could be angled to it.

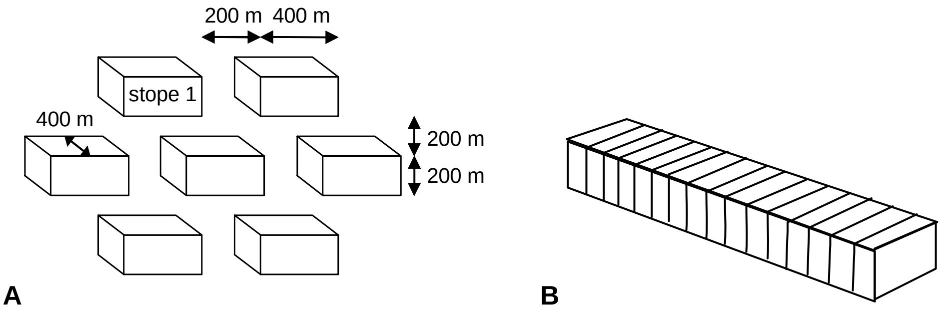

Figure 16. A schematic diagram showing: A) One stope group of the mined openings for "perforating" Eros. Each group contains seven stopes. B) Seventeen of these stope groups would be excavated 400 m apart along Eros' shortest axis to create a weak zone there.

outlined here.

A series of open stopes (Fig. 16) would be mined out within Eros' narrowest dimension, which is roughly parallel to the Y-axis shown in Fig. 9. The excavation will require significant time and must remain stable for the duration, so the stopes are separated by a series of pillars where the stone is left in place (this is standard terrestrial practice, if not at such a large scale). When the stopes are completed, a major portion of the thickest pillars will be fragmented in a series of very large mass blasts. This will initiate failure of the entire mined area. The two "halves" of Eros will separate. The resulting fragments, Class 3 bodies in their own right, would then be fragmented or deflected themselves, as discussed in previous sections.

V. Issues

Technological issues fall into several general categories: getting drillers, drill rigs, and explosives to the target sites, early warning of NEO approach so that time is sufficient for drilling and blasting operations, drilling under microgravity conditions, and predicting the impulse delivered to the NEO by each blast in order to predict NEO trajectory changes.

Getting drillers, drill rigs, and explosives in sufficient quantities into NEOs is problematic, especially for the larger bodies, given our current deficiencies in heavy-lift launch vehicle technology created by the Carter Administration's cancellation of all unmanned launch vehicle programs in favor of the Shuttle program. Resolution of orbital lift capability deficiencies is a political issue, not technological, and is beyond the scope of this study.

Sufficient early warning to allow placement of drill/blast equipment and supplies onto NEOs in sufficient time for mitigation may also be problematic. Further research into this concept should address specific time estimates for drill and blast operations once the equipment and supplies are onsite, to allow comparison with early warning capabilities. This would establish whether current early warning capabilities will allow this type of solution to the NEO problem, or if significant improvements would be required before dristributed-energy blasting could be considered.

The best test of microgravity blasting operational capability would be to drill and blast under microgravity conditions, which has not been demonstrated yet. As a stopgap measure, further research into this concept should include specific simulations of drilling in microgravity fields to estimate the effects on fluid flows, debris removal, and bit efficiencies.

In order to better predict the effects of blasting on the trajectory of an NEO, more detailed composition and geometry information for the NEO in question is required.

VI. Conclusion

The best approach to NEO impact hazard mitigation is to develop a number of complementary techniques whose applicabilities overlap. Drill and blast techniques may work well for some classes and compositions of bodies, and taken together with other means of mitigation can deal with any of the potential Earth-impactors currently existing in the Solar System. Distributed-energy blasting will not be a quick fix solution, but the capability to fragment hazardous NEOs in a tightly controlled manner will be a necessary part of the portfolio of mitigative strategies.

Acknowledgments

Production of ANFO from cometary materials was proposed by the late Richard Gertsch in 1995, and research in this area continues. We sincerely acknowledge the work of Brent Barbee in creating mission scenarios for this project[15]; successfully dealing with NEOs will require continued collaboration among colleagues in many previously un-allied fields of science and engineering.

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