

ADROITLY AVOIDING ASTEROIDS!
CLOBBER, COAX OR CONSUME?

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Abstract

The idea of turning threatening asteroids into useful products to prevent them from colliding with Earth has been reinforced by recent analysis of the tremendous profit potential of their precious metals. "Consumption" is a third major option for preventing asteroid disasters. The other options are to use nuclear weapons ("clobber") or to gradually propel ("coax") the threatening body into a slightly different orbit. Our objective is to put the asteroid threat, it's potential solutions and space resources into a clear perspective. Even the better solutions have some uncertainty; and none seems universally applicable. Our most urgent recommendation is to robotically explore every type of near earth object (NEO). Based on our current limited knowledge, however, we believe that: (1) nuclear weapons approaches entail an unacceptable risk of compounding the threat; (2) propulsive remedies must often use extraterrestrial materials as propellant; (3) propulsive remedies must be applied carefully to deal with spinning and fracturing the asteroids; (4) consumptive remedies may not be well motivated by profits; (5) consumptive remedies beg the question of propulsive deflection; and (6) space resources may play their biggest role in providing the infrastructure for an asteroid protection. For now, we strongly lean towards "coaxing" threatening objects off harm's path.

The Asteroid Collision Hazard

Physical Collision Effects

The physical phenomena due to the collision of space objects with the Earth are well documented in the volume Hazards Due to Comets and Asteroids edited by Tom Gehrels out of the University of Arizona. Morrison, et al, give an excellent summary of these awesomely energetic events.⁹ Devastation is due to the prompt transformation of the incoming kinetic energies of these high velocity objects. Collision speeds exceed 20 km/sec for objects in asteroidal orbits, and exceed 50 km/sec for long period comets.

The results of such impacts depend heavily upon the size of the incoming object, and to a lesser extent upon its composition. NEO's in asteroidal orbits may be of either cometary or asteroid origin.

Earth's atmosphere is its shield. Objects less than 50 m diameter, unless ironlike, break up at high altitude causing no damage. But larger objects cause a high pressure shock wave at lower altitudes, with resultant blast and fire damage over very wide areas.

As an example, the Tunguska object of 1908 never reached the ground to cause a crater, but

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devastated 2,000 square kilometers of forest with the energy of a 20-50 megaton nuclear weapon!¹²

Should an incoming NEO strike the ocean, it will generate tsunami (tidal waves). Hills, et al, find a threshold of 200 m diameter for stony asteroids which can cause catastrophic tsunami. These are low, harmless waves in the deep ocean, but through conservation of energy, swell to extreme heights as they approach shallow coastal waters. A 400 m diameter asteroid hitting anywhere in the Atlantic Ocean would cause killer waves over 60 m high along both coasts.⁵ Human populations often concentrate in the world's highly vulnerable coastal cities, setting the stage for a disproportionate disaster.

Objects penetrating the atmosphere cause groundbursts and craters, as well as air blast on the way down. Impacting on land, a 75 m diameter object can destroy a city, a 160 m object can destroy an urban area, a 350 m object can destroy a small state, and a 700 m object can destroy a small country⁹.

Larger objects, of course, can destroy increasingly larger areas. But that is not the whole story. At around 2 km NEO diameter, perhaps less, the effects become global. There is a "nuclear winter" climate changes from dust ejecta, global destruction of ozone, and global ignition of fires from returning impact ejecta (from a 3 km object). From 7 km objects, mass extinctions of life are probable. Objects larger than 16 km diameter threaten the survival of all advanced forms of life.⁹

If a limestone layer is hit again, as it was 65 million years ago, the effects of carbonates in the air could dominate. There are also additional phenomena not yet analyzed, such as global acid sulfur aerosols, which could set the threshold for global effects and deaths even lower, to smaller incoming objects.

Public Perceptions & Misperceptions of Asteroid Hazards

Horrible!!! - But Unlikely? The tragic sensationalism of what would happen with any collision of an asteroid or comet is not lost upon the media. Reporters readily play up the hype which goes with an "end of the world" prediction. Unable to emotionally deal with such a threat, they sometimes discredit it. Since it is not common experience among people now alive, the public has a credibility gap. The "snicker factor" is indeed an issue which must be overcome. The collision topic is seldom ignored. But extremes of reaction, over hype or disbelief, are too typical.

In a valiant effort to establish credibility, the scientific community strives for mathematical rigor and dispassionate statements. Scientists spout numbers in exponents and use the term "low probability." Both can be inappropriate at times.

The majority of the public does not understand negative exponents. And even the well educated think that "low probability" means "unlikely to happen." Those people who do accept an asteroid collision as the root of the dinosaurs demise, often mistakenly believe it means we have another 65 million years to wait for the next such disaster.

A Question of "When?" Not "Whether?" What is the mathematical truth? The equations, numbers and probabilities commonly used are not wrong. They are just the wrong math to answer the central question about such catastrophic collisions: "Will asteroid catastrophes happen again?"

To find the answer, we need only use the relative chance of an earth collision being the final destiny of a given NEO (20-25%), the NEO population, and probability formula for nonoccurrence. This population is inferred, with low uncertainty, from both crater counts and

asteroid searches.

To answer the question "Will they happen?" most optimistically with respect to collisions of global consequences, take a large NEO size threshold (3 km) and a minimum population (200 objects). The resultant probability of no global event is less than 4×10^{-20} . There's an infinitesimally small chance that it will NOT happen!

Similarly with respect to killer tsunami. Optimistically again, use a large threshold size (300 m) and a small population (10,000 objects). The chance of no killer tsunami is less than 2.6×10^{-458} ! This is a truly, truly small chance it WON'T happen.

This same data can be used to find how many hits we can expect from the NEO's out there now. The low expectation can be found from the low relative destiny and a low population. The high expectation is found from combining the larger of these two factors.

We can expect from 400 to 6250 tsunami, and 25 to 875 events of global consequence from the present population of near earth asteroids. Our uncertainty is large because our uncertainties have compounded. These numbers will be increased by the addition of new comets, and the continuing creation of NEO's.

Are such numbers credible? Indeed they are. Rampino, et al, have shown that there are over two dozen sharp extinction events in the geological record of the past half billion years.¹¹ They correlate with crater ages and stratigraphic evidence of impacts. And Steel, et al, have argued that extinction events happen in clusters, repeating at millennium time scales.¹³

The chances of such disasters, which are now commonly misunderstood as "unlikely," can now be better, and more readily, understood as "inevitable!" The central question is no longer "whether" these catastrophes will happen, but "when" will they happen.

When, Indeed? The probabilities per year commonly quoted for collisions with various size NEO's are correctly interpreted as "infrequent," instead of as "unlikely." But valid as they may be, these statistics still trigger an inappropriate societal response, inaction. Governments and society are not geared toward solving infrequent problems. Nor are they good at dealing with problems that haven't occurred recently. Asteroid collisions with Earth are both.

Statistics are the mathematics of our ignorance. They are our way of coping with facts which are too numerous or too unobservable. Asteroid collisions should not remain in that category. NEO's are detectable and, within limits, predictable. The authors agree with the viewpoint of Morrison, who has emphasized that the responsible course for society is to SEE exactly what is out there and KNOW when they will hit.¹⁰ With a vigorous, yet modestly priced search effort, knowledge can replace ignorance in a couple decades.²

Potential Solutions to NEO Hazards

Typical proposals for mitigating collisions have included destruction and deflection. For destruction to be effective, all resultant pieces of the threat object must either be small enough to assure burnup in the upper atmosphere, or must be assured to miss Earth.

Deflection requirements vary according to when and how they are applied. The most advantageous deflection is a small acceleration, or deceleration, applied along the orbital path near the time of the NEO's perihelion passage. This disrupts the timing of the impending collision. About 1 cm/sec of velocity change applied a few years in advance can change the impact point by one earth radius. Longer lead times, or multiples of this velocity, can give an assured miss.

Terminal defense strategies require much larger lateral deflections (perpendicular to the orbital velocity). How large depends greatly upon conditions. The closer the object is to final impact, the greater the absolute deflection needed.

Propulsive mitigation schemes (coaxing) strive for deflection, of course. Impacting and explosive schemes (clobbering) can be intended to either destroy or deflect, usually the latter. "Consuming" the threat NEO for valuable products is a newer notion, one that has not been debated much.

Clobbering schemes can be applied in an intercept mode, either in advance, or in a terminal defense mode. Propulsive coaxing or consumption, on the other hand, each require one or more rendezvous with the threat object.

Clobbering Asteroids

Clobbering schemes involve an impact of mass, or high energy, with the threat object, usually on a very brief, subsecond time scale.

If the goal is destruction, a buried nuclear explosion is usually envisioned. This approach couples the most energy into the threat object. The problem becomes one of assuring thorough fragmentation. This is extremely difficult in any case. And in view our high degree of ignorance about the structures of NEO's, this approach enjoys very little favor.

The goal of clobbering, however, is usually not destruction but deflection. Unwanted fragmentation becomes a complication to be avoided. A momentum change is what desired, but an energy input is the means of achieving it. When energy is delivered abruptly, the risk of fracture is high. All such clobbering solutions strive to achieve a balancing act: enough energy for the desired result, but low enough energy delivered

carefully enough to avoid inadvertent fragmentation.

Mass impactors (kinetic energy projectiles) of practical size impart far too little direct momentum to the relatively massive objects of concern. It's the cratering they would cause which, via the ejecta, delivers much more momentum. But even this is insufficient for most threat NEO's. Sufficiently massive projectiles would require many launches, plus great amounts of propellant to reach the target.

A clever "billiards shot" scenario has been devised to improve the kinetic energy approach.³ This starts with the deflection of a small asteroid which in turn deflects a larger one. This is continued until a sufficient size asteroid impacts the real threat NEO. One difficulty, of course, is having a sufficient availability of intermediate size, favorably situated asteroids.

The most favored solution amongst the "clobbering" options is the standoff nuclear burst. Ahrens and Harris offer an excellent detailed explanation.¹ Neutrons and x-rays deposited just below the surface cause shock pressure waves to propagate through the body and a tensile failure of the surface layer. This blowoff material imparts the desired momentum change to the threat object. Due to the broad exposure area, a minimum of rotational momentum is added to the target also.

The drawback of this concept is still the risk of fragmentation. Figure 1. from Tedeschi¹⁴ of Sandia National Laboratories shows how shock waves propagate through the full body. Transmission and reflection of this shock at each flaw and material interface (with resultant tensile forces) can cause fragmentation at any crack, and/or back surface spall at the far side. Should this happen, the net momentum change would be reduced, and the

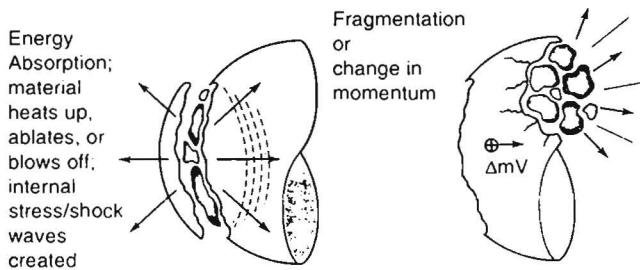


Figure 1. Asteroid response to a standoff nuclear burst (Tedeschi).

whole mitigation problem would be severely compounded by the now multiple threats.

Coaxing Asteroids

Coaxing, or propulsive, schemes deliver energy more slowly. This greatly reduces the risk of fragmentation, and adds an opportunity for greater control. The risks are mostly possible unwanted rotations of the NEO.

Propellant Requirements. To impart a given momentum to the

threat object, the product of propellant mass and exit velocity must equal that same momentum, but in the opposite direction.

Table 1 shows the propellant requirements for imparting a velocity change of 1 cm/sec to NEO's of increasing size. The basic numerics are true for any propulsive concept. NEO masses and the larger propellant masses are given in metric tonnes (t). All entries are exact, except the approximate NEO diameters which vary with density.

Specific impulse (I_{sp}) is the major variable, with odd increments chosen to yield round numbers for propellant mass. Steam rockets and other low exit velocity systems are represented by the low specific impulses toward the left. Chemical rockets are in the middle (300 sec range). Nuclear thermal rockets and electric propulsion have the higher performances and specific impulses in the right hand columns.

If we wish to minimize the total energy required, we should use a very low exit velocity (low specific

Table 1. Propellant Mass Needed for NEO Deflection of $\Delta V = 1\text{cm/sec}$

Approx. NEO Diameter	NEO Mass (t)	Threshold of:	Isp (sec)						
			1.02	10.2	102	255	408	1019	10190
10 m	1E+03	Steam	1 t	100 kg	10 kg	4 kg	2.5 kg	1 kg	0.1 kg
20 m	1E+04		10 t	1 t	100 kg	40 kg	25 kg	10 kg	1 kg
40 m	1E+05	Airbursts	100 t	10 t	1 t	400 kg	250 kg	100 kg	10 kg
100 m	1E+06	Craters	1000 t	100 t	10 t	4 t	2.5 t	1 t	100 kg
200 m	1E+07	Tsunamis	10000 t	1000 t	100 t	40 t	25 t	10 t	1 t
400 m	1E+08		1E+05 t	10000 t	1000 t	400 t	250 t	100 t	10 t
1 km	1E+09		1E+06 t	1E+05 t	10000 t	4000 t	2500 t	1000 t	100 t
2 km	1E+10	Global effects	1E+07 t	1E+06 t	1E+05 t	40000 t	25000 t	10000 t	1000 t
4 km	1E+11		1E+08 t	1E+07 t	1E+06 t	4E+05 t	2.5E+05 t	1E+05 t	10000 t
10 km	1E+12	Mass extinction	1E+09 t	1E+08 t	1E+07 t	4E+06 t	2.5E+06 t	1E+06 t	1E+05 t
20 km	1E+13		1E+10 t	1E+09 t	1E+08 t	4E+07 t	2.5E+07 t	1E+07 t	1E+06 t

Small shove. Use propellants from anywhere.

NTR engine life should be long.

Use extraterrestrial volatiles as NTR propellant.

Not a reasonable solution.

impulse). This, of course, raises the propellant requirements.

For large NEO's, the pusher propellant needed is very expensive to launch and deliver from Earth, even using high specific impulse pushers. The delivery propellant far exceeds the pusher propellant. The cost becomes formidable for low energy (low I_{sp}) systems. If it were necessary to use only terrestrial resources, then it would be clearly better to launch high energy sources than to launch massive amounts of propellant.

But there are indeed far more practical solutions. Propulsive schemes for asteroid deflection usually use extraterrestrial resources, most often the mass of the NEO itself.

System Concepts. Melosh, et al, describe a number of non-nuclear deflection concepts,⁸ while Willoughby, et al, elaborate on nuclear propulsive options.¹⁵

Solar sails are fuelless propulsion systems which use which use solar radiation pressure at very low thrust. However, for the massive loads of even small asteroids, enormous sails on the order of 100 to 1000 km diameter, and many years of propelling, would be required. This would require space construction techniques far in the future.

Lasers or microwaves could be used to ablate material from the threatening asteroid, to generate momentum. If based on Earth, they could take advantage of large power sources. Geometry would limit the possible directions of thrust. But the main problem, at the long distances, is beam divergence. Energy spread too widely would not ablate material. If based in space, power would be a more limiting factor. The low conversion efficiencies of such devices would place big demands on power generation, and also on radiative cooling. Deflecting small asteroids

could be practical. But large asteroids would require systems to be transported nearby.

Melosh introduces a solar collector deflection system which vaporizes a spot on the asteroid with the help of focusing mirrors. In some respects this could be a plausible solution. Kilometer class collectors could deflect multi-kilometer diameter asteroids, given a decade of operation. Keeping the collector and mirrors clean is an unsolved problem. The need for stationkeeping propellants and difficulties with energy absorption by metallic asteroids may be limitations.

High performance electric rockets, with specific impulse (fuel efficiency) in the thousands of seconds, require very little propellant. We can see from Table 1 that it may be reasonable to deflect NEO's up to a few hundred meters diameter using electric propulsion. And this is without requiring extraterrestrial material. Either solar or nuclear power could be used, but nuclear is preferred for simplicity. The limitation is propellant throughput. For large NEO's it would be difficult to eject the necessary mass in sufficiently short time to use the dynamic advantage near perihelion.

Thermal rockets, conversely, would take maximum advantage of extraterrestrial material. Any gas or liquid obtainable in space could be heated and ejected as propellant. They would be much more propellant versatile than chemical rockets trying to do the same thing. The latter would require highly quality controlled fuels and oxidizers, in appropriate proportions, and at great risk of failure if tolerances are not met. Nuclear thermal rockets would be highly preferable over solar. The nuclear rocket is more geometrically flexible for dealing with rotation control, and the power from the nuclear reactor is more available while far from

perihelion for producing the volatile propellants.

The review of nuclear thermal rocket candidates for NEO deflection by Willoughby, et al, discusses four viable technologies which could be used in the relatively near term, in less time than it will take to do our NEO searches.¹⁵ They can be run at a variety of temperatures, with lower temperatures leading to longer engine life. The shading in Table 1 which indicates where extra-terrestrial propellant is desirable is further divided into two areas. In one, engine life is not an issue no matter which technology is chosen. One engine will do the job from a burn life standpoint. In the other shaded area for very large NEO's, engine burn life must be considered. Two of the technologies are better than the others and multiple engines are warranted. Given the magnitude of the impending disaster, this solution is still a tremendous bargain.

Rotational Issues. Will any push on a rotating NEO achieve what we want? Must we remove its spin first? How much will its spin change as we push it?

Willoughby, et al, have analyzed these issues of NEO rotation.¹⁵ Rotations must be handled very carefully, but they are not a barrier to using propulsion for collision mitigation. Rotation issues apply to all concepts which concentrate energy or push on local areas of an NEO.

As an example, consider a common NEO shape, the contact binary. What would be the spin imparted if we push it by 1 cm/sec, but without regard for spin control?

If this idealized contact binary consists of two rigidly joined spheres of 10^9 tonnes each, a burn of 8000 t of propellant would be needed to impart the velocity change. For an engine mounted on the end, the integrated increase in spin would be 2460 revolutions per

day! Clearly, our asteroids can be spun (or despun) much more readily than they can be pushed.

The spinning problem is compounded by the fact that real NEO's are very irregularly shaped. Their inertial tensors, I , have nonzero cross products. This means that a spin imparted about one axis will cross couple into the others. The exact nature of I will be difficult to predict upon first observation, as the NEO will be spinning slowly about its primary axis.

At least two rotational control approaches are possible:

In one approach, the NEO is despun in a trial and iteration process. The tensor I is deduced during this process. The main pusher rockets are then mounted to push nearly through the center of gravity with minimum moment arms. Several rockets would readily give a balanced torque in each direction about the estimated center of mass.

Despite minimal torques, we can anticipate that the object will begin to rotate slightly about each axis as shown. Sensors placed about the NEO can detect these rotational accelerations. A logic network (now programmed with the I tensor) then controls the relative thrust of each engine, just as if the NEO were a spacecraft. Or if desired, small vernier rockets of any type can be placed with long moment arms to keep our NEO properly aimed. Their thrust should also contribute to the desired velocity change.

In the second approach, we use an engine slewing technique which allows the NEO to remain spinning. By thrust vectoring our rocket engines, we keep the impulse directed along the orbital path. During one phase of the thrusting we will be increasing the spin; while during another phase we will be decreasing spin. Several engines would probably be used, since complex rotations will sometimes put any given engine in an unworkable

thrusting position. Sensors and logic networks are deemed necessary in this method also.

Realizing how easily NEO's can be spun, and how strong the internal tensile stresses must be for large spinning objects, we can see that spinning might be a solution as well as a problem. Controlled "breakup by spin-up" could send our threat NEO flying into fragments, with better dispersal than fracturing a nonspinning object. It could, given sufficient time to reassess the orbits of each fragment, solve our problem completely or reduce it to smaller threatening fragments.

The keys to a controlled breakup are knowledge and timing. Detailed survey of the object should identify its materials, fractures and homogeneity. We expect fractures to be the norm, because it is prior collisions in the main belt which have caused asteroids to become earth crossers. NEO's of cometary origin may not have been fractured, but will have low tensile strength inherently. Timing of the breakup can be aided by well placed high explosives, or by deliberate partial severing.

Consuming Asteroid Threats

Lewis has recently reaffirmed his long standing suggestion that consumption of asteroids for profit can be a solution to threatening objects.⁷ This resurgence has been prompted by the work of Kargel who has calculated the enormous market value of NEO products imported to Earth.⁶

According to Kargel, a suitable metallic NEO could be processed in its entirety. A 1 km diameter NEO would have over 400,000 t of gold and platinum group metals. That's worth \$5 trillion at current prices. It's availability would probably depress the market, reducing its value to just under \$1 trillion, but it would enhance our quality of life by opening up many new industrial

uses for platinum group metals.

More friable (crumbly) NEO's could be more easily worked than the metallics, and could be magnetically screened to yield similarly rich ores. These would also be rich sources of volatiles highly marketable in space.

Icy NEO's of cometary origin would also be rich sources of volatiles with enormous economic leverage on space transportation and human expansion.

With the high value of NEO products, it would seem quite desirable to solve our threat problem at a great profit.

Evaluating Our Options

We evaluate our collision mitigation options primarily by asking "Will they work?" And, if so, against which of types of NEO's.

The question of cost seems hardly relevant in cases where the consequences are so dire. However, the cost of maintaining a ready defense that is rarely used, and is subject to funding discontinuation, would be relevant. Cost becomes relevant only for comparing options that work with high confidence.

The question of readiness also not very relevant. For the next few decades we will be blind to those disasters which may befall us from NEO's. Mitigation solutions which can be ready in 15-20 years are suitably ready.

Mechanical Models of Asteroids

Gertsch, et al, have defined classifications for the physical structure of NEO's which are useful for evaluating our options.⁴ They divide them into five mechanical types: ice composites, friable, solid rock, gravel rock, and stainless steel (iron-like). The ice and friables are excellent sources of water and carbon. The friables are also a rich, highly workable source of metals.

Table 2 Intercept Options for Deflecting Large NEO's

	Comments	Ice	Friable	Gravel	Hard Rock	Iron-like
Kinetic Impactor - Ahrens	Impractically large mass					
Kinetic Impactor "Billiard balls" - Melosh	Very complex	 Large fragments	?? Fragments?	?? Fragments?	?? Fragments?	??
(Sub)surface Nuclear Burst - Ahrens		 Large fragments	 Fragment high risk	 Fragment high risk	?? Fragment high risk	?? Effectiveness? Fragments?
Standoff Nuclear Burst - Tedeschi	Uses neutron deposition	?? fragment risk	?? Fragment high risk	?? Fragment high risk	? Fragments if fractured	? Fragments if fractured
Lasers - Melosh	Inefficient Complex	??	??	??	??	 Inadequate absorbtion?
Microwaves - Melosh	Inefficient Complex	??	??	??	??	??

References refer to concept description, not necessarily to the evaluation.

Intercept Options

Table 2 presents our evaluations of mitigation schemes which are suitable for use in an intercept mode. They could be our only option against a first pass comet, since rendezvous seems impossible.

The "thumbs down" symbol means that the concept is understood NOT to be viable. A "happy face" means it should work. A "question mark" implies uncertainty: either due to major questions in development, or to uncertain interactions with that particular mechanical type of NEO. A "double question" indicates both uncertainties exist.

Simple kinetic impactors have been shown to be insufficient for NEO's of any meaningful size. The

enhanced "billiard ball" kinetic impactor would surely fracture icy bodies, compounding the risk. There would be a huge uncertainty in its development. And, it could also fragment the majority of objects.

The subsurface nuclear burst would surely fragment most NEO's, and perhaps hard rock. Embedding the bomb properly is an issue for hard rock and iron-like NEO's.

Lasers and microwaves are inherently poor in efficiency, and complex to implement in space. At great distances from earth bases, it's unlikely the energy could be sufficiently concentrated. Laser energy would be poorly absorbed by metallic NEO's.

The standoff nuclear burst remains as the only plausible option

Table 3 Rendezvous Options for Deflecting Large NEO's

	Comments	Ice	Friable	Gravel	Hard Rock	Iron-like
Solar sail - Melosh	Impractically large sails					
Solar Collector - Melosh	Km - class collectors					 Unlikely to work
Solar powered mass driver - Melosh	Km - class collectors labor intensive?	 Uncertain use of mass	 Set up equipment?	 Set up equipment?	 Difficult to process mass	 Very difficult to process mass
Break-up by spin-up - Willoughby	Rockets + explosive	 Can NEO hang together long enough?	 Too crumbly	 Too crumbly	 Plausible if fractured	 Plausible if fractured
Rocket with space resources - Willoughby	Nuclear rocket with water		 Too soft?	 Too crumbly. Must transport propellant.	 Must transport propellant	 Must transport propellant
Consume threat for profit - Lewis	Transportation demanding	 Economic trades prevail	 Economic trades prevail	 unprofitable material	 Unprofitable material	 Difficult processing? Dangerously large fragments?

References refer to concept description, not necessarily to the evaluation.

in an intercept mode. But even it fares poorly. Much testing and development would be needed to assure it would not fragment weak NEO's. With stronger NEO's, the result would depend upon the specific fractures already present.

Rendezvous Options

Protection schemes requiring rendezvous seem much more desirable, as summarized in Table 3. With practice, we believe, all except the solar sail can be made to work. But no solution seems universally applicable to all NEO's.

Except for iron-like NEO's, the solar collector seems viable if development hurdles are overcome.

The solar powered mass drivers

look questionable for icy bodies (with hard irregular ice chunks) and is inappropriate very hard bodies.

Breakup by spin-up may be good for noncrumbly objects. It may have strong advantages. But testing and perfecting would be essential.

Nuclear thermal rockets have the potential to be universally applicable, if certain difficulties could be surmounted. Ways must be found to distribute the force while pushing weak or crumbly NEO's. For dry NEO's, water must be imported. However, by the time search efforts have detected the threat NEO's they will also have detected thousands of water sources in near earth space. Water should be cheaply accessible in quantity for the deflection mission of any NEO.¹⁵

Consumption of the threat NEO does not look as attractive as we might hope. The threat NEO may not be the right composition. Or, if it is the right stuff, the timing may be wrong. It will, of course, come close to the Earth at some time. For safety, we would rather consume it well in advance of disaster. Close earth passes are unlikely then. But for profit we want to ship our products cheaply, just before final earth approach. These are contradictory constraints.

Another major problem with consumption is that it begs the question of propulsion. To ship the products requires much more velocity change than does creating a miss.

Summary

The NEO threat is truly horrible beyond experience. We have shown that more are "inevitable," not "unlikely." The question is "When will they happen?" Any time. Nobody knows when. But we could find out for certain in a couple decades with a prudent search program. Sadly, such a program is not happening yet.

Many schemes have been proposed for mitigating collisions from NEO's. Which will work? Again, no one knows. Some schemes, we can be sure, won't work.

The assumption that nuclear weapons are the answer is probably wrong, and is certainly unfounded. Often they could worsen the problem by fracturing NEO's.

The better remedies seem to be propulsive and use extraterrestrial resources.

The right solution will depend upon the mechanical structure of each threat NEO. A thorough robotic exploration of many types of NEO's

would reduce risk and help focus efforts on good solutions.

Robotic NEO exploration would also accelerate the use of extra-terrestrial resources, which is most likely the foundation for earth protection. It's unlikely we will actually consume threat NEO's, but protecting our Earth should prove profitable as well as vital.

References

1. Ahrens, T. J., and A. W. Harris 1994. Deflection and Fragmentation of Near-Earth Asteroids, Hazards Due to Comets and Asteroids, University of Arizona Press.
2. Bowell, E., and K. Muinonen 1994. Earth-crossing Asteroids and Comets: Groundbased Search Strategies, Hazards Due to Comets and Asteroids, University of Arizona Press.
3. Caravan, G. H., J. C. Solem and J. D. G. Rather 1992. Proceedings of the Near-Earth-Object Interception Workshop, Los Alamos National Laboratory.
4. Gertsch, R., J. Lewis, G. Maryniak and J. Remo 1995. Near Earth Resources, International Conference on Near Earth Objects, United Nations.
5. Hills, J. G., I. V. Nemchinov, S. P. Popov and A. V. Teterev, 1994. Tsunami Generated By Small Asteroid Impacts, Hazards Due to Comets and Asteroids, University of Arizona Press.
6. Kargel, J. S. 1994. Metalliferous asteroids as potential sources of precious metals, *J. of Geophysical Research*, Vol. 99, No. E10, pages 21,129-21,141.
7. Lewis, J. S. 1994. Platinum apples of the asteroids, *Nature*, Vol. 372, pages 499-500.
8. Melosh, H. J., I. V. Nemchinov and Yu. I. Zetzer 1994. Non-nuclear Strategies for Deflecting Comets and Asteroids, Hazards Due to Comets and Asteroids, University of Arizona Press.
9. Morrison, D., C. R. Chapman and P. Slovic 1994. The Impact Hazard, Hazards Due to Comets and Asteroids, University of Arizona Press.
10. Morrison, D., 1995. Statements at the International Conference on Near Earth Objects, Explorers Club, New York, NY.
11. Rampino, M. R., and B. M. Haggerty 1994. Extraterrestrial Impacts and Mass Extinctions of Life, Hazards Due to Comets and Asteroids, University of Arizona Press.
12. Simonenko, V. A., V. N. Nogin, D. V. Petrov, O. N. Shubin and J. Solem 1994. Defending the Earth Against Impacts from Large Comets and Asteroids, Hazards Due to Comets and Asteroids, University of Arizona Press.
13. Steel, D. I., D. J. Asher, W. M. Napier, and S. V. M. Clube 1994. Are Impacts Correlated in Time? Hazards Due to Comets and Asteroids, University of Arizona Press.
14. Tedeschi, W., 1995. Mitigation of the NEO Impact Hazard Using Kinetic Energy, Sandia National Laboratories, Albuquerque, NM.
15. Willoughby, A. J., M. L. McGuire, S. K. Borowski and S. D. Howe 1994. The Role of Nuclear Thermal Propulsion in Mitigating Earth-threatening Asteroids, Hazards Due to Comets and Asteroids, University of Arizona Press.