Mitigation of the NEO Impact Hazard Using Kinetic Energy

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Kinetic energy impacts into an approaching Near-Earth object (NEO) on an Earth-colliding trajectory would be a very effective mitigation defense technique in some circumstances to protect Earth from the catastrophic effects of such a collision. The technology exists today to project kinetic energy over interplanetary distances and interact with comet and asteroid bodies to either deflect or fragment them. Technical details of how kinetic energy interacts with typical NEO materials are presented, along with some results from recent world-unique kinetic energy momentum deposition experiments. Qualitative target response phenomenology are discussed on cratering, momentum deposition, momentum enhancement factor, and fragmentation. A review of existing related data in the open technical literature is also presented and inferences drawn regarding the effectiveness of using kinetic energy to mitigate NEO impactors. Details of an actual Earth attempt at ramming a NEO (comet P/Grigg-Skjellerup) with kinetic energy (the Giotto spacecraft) will be described, along with some valuable lessons learned. Kinetic energy also provides a useful testbed for understanding the effects of other high energy sources on NEO materials. Future kinetic energy impact experiments and modeling opportunities are also articulated.

Introduction

Compelling evidence of a catastrophic asteroid impact on the Earth 65 million years ago (Alvarez et al., 1980 and Sharpton and Ward, 1990) has given rise to international discussions about the probability and prevention of future impacts. As a result of several recent near-misses (Morrison, 1992 and Scotti et al., 1991) and the comet Shoemaker Levy-9 impact of Jupiter in July 1994, considerable international attention has focused on defining the impact threat and determining potential hazard mitigation defense schemes for the protection of Earth against planetesimal impacts (Tedeschi, 1994). Initial studies indicate that hypervelocity impact is one of several favorable schemes for mitigating the possibility of Earth-impact by such bodies (Canavan et al., 1992 and Wood et al., 1995). A desirable characteristic for a defensive engagement would be to deflect the approaching body into a new, non-threatening trajectory by some type of momentum transfer or deposition. However, fragmenting the body into numerous pieces might make the problem worse, since some of the resultant debris might still possibly be on an Earth-impacting trajectory.

While there are some data on the fragmentation of planetesimal-type materials, e.g., basaltic rocks (Fujiwara et al., 1977) and ice (Kawakami et al., 1983), nowhere can one find experimental data on momentum deposition into such materials due to hypervelocity kinetic energy impacts. Of course, planetary geophysicists have been studying this type phenomena for years, but they can only infer the full-scale response of large asteroids to massive kinetic energy impacts (Housen and Holsapple, 1990). Simulating the macroscopic change in momentum of such bodies is difficult to do using modern shock-physics computational codes, e.g., hydrocodes, mainly due to inherent numerical limitations (Anderson, 1987). Therefore, a critical need exists to obtain well-characterized hypervelocity impact test data on actual NEO materials or NEO material analogs for code calibration purposes, and to conduct asteroid impact experiments in space to affect full-scale target response observational opportunities.

The scientific endeavors associated with geophysical planetary evolution also benefit directly from these types of impact tests. Hypervelocity impact interactions and their related catastrophic effects have traditionally been invoked as the major plausible mechanism that determines the mass spectra and velocity dispersions during planetary accretion and fragmentation (Hartmann, 1978). Modeling such impact interactions can be very complicated, especially when either the target or impactor are composed of natural materials which in many cases are inhomogeneous assemblages of minerals with faults, inclusions, grain and phase boundaries, and other imperfections which complicate the material response. The response of such materials to hypervelocity impact spans a wide range of material behavior, ranging from high impact temperatures and pressures, where hydrodynamic motion and thermodynamic effects predominate, to the low pressure regions where the mechanical properties dominate the process. In order to simulate such processes using sophisticated computer models it becomes necessary to understand the fragmentation effects of hypervelocity impact on related inhomogeneous targets through experimentation over a range of loading conditions, velocities, and target and projectile materials. Results from such experiments can then be used to test and validate computer models for the simulation of planetary interaction processes.

Why use kinetic energy?

Kinetic energy (KE) should be seriously considered for use in deflecting or disrupting threatening NEOs for the simple reason that it works. After all, kinetic energy is one of the fundamental drivers in the formation of our solar system; collisions between large bodies (and accretion) have been occurring for billions of years. When two objects collide there is an equal, but opposite, "reaction" on the receiving body caused by the incoming body, and total system momentum is conserved. The Second Law of Motion and the conservation of momentum (Halliday and Resnick, 1974) can therefore be exploited to do useful work on a NEO threatening to impact Earth. Kinetic energy is inherent to all things in motion, i.e., 1/2 x mass x (relative velocity)^2 for non-relativistic relative motions. The ability to project kinetic energy (smart payloads) over interplanetary distances (by rockets) is well demonstrated, e.g., the grand tour of the outer planets by Voyager, flybys of asteroids Gaspra and Ida by Galileo, and Halleys comet flybys by several international spacecraft probes. All the requisite technologies exist. All that remains would be to actually use them someday against an approaching NEO threat, and to possibly demonstrate them against a benign NEO to learn how to do such long-range kinetic energy impact projections against a new class of targets hitherto unengaged in the manner described.

The conduct of precursor missions would allow intelligent technology downselect decisions to be made someday in the event of an actual emergency where kinetic energy might be called upon to protect the Earth. The effects of kinetic energy against NEO analog materials are well understood up to about 8 km/sec impact velocity, somewhat understood up to about 15 km/sec, and not so well understood beyond this. The physics behind kinetic energy impacts are shown in simple format in Fig. 1. The impactor strikes the NEO, creating a hydrodynamically induced crater and internal shock waves (on microseconds to milliseconds timescales) which propagate into the target (over timescales of many milliseconds to as much as 1000's of milliseconds), ultimately causing some type of target body response, i.e., an induced velocity (trajectory) change due to momentum deposition on the one extreme to body fragmentation and mass dispersion on the other.

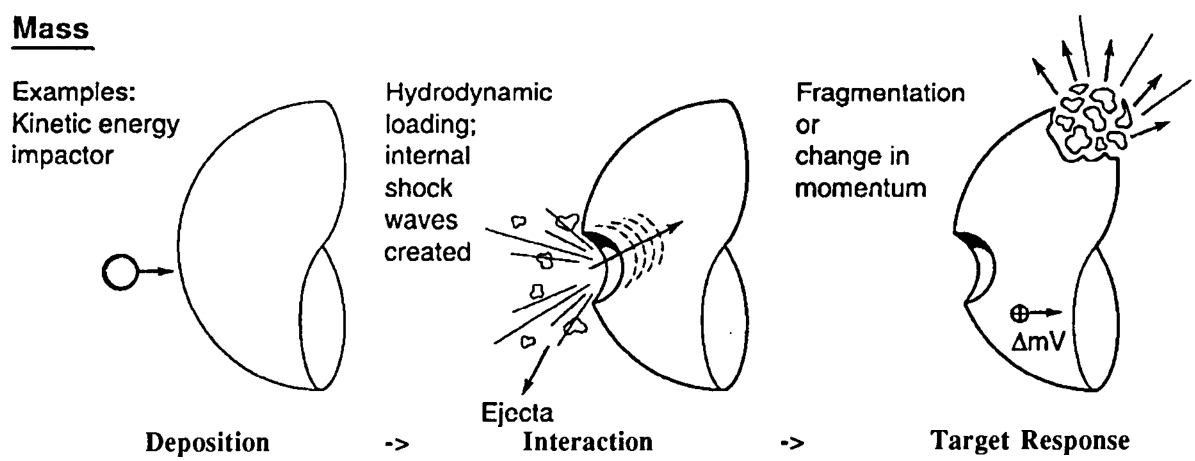


Figure 1. The kinetic energy coupling process into NEOs.

Critical issues

There are three critical issues which need to be extensively studied, if not actually resolved, before we can have confidence in the use of kinetic energy to reliably deflect or disrupt NEO bodies. They are given here as:

1. How hard can we push a NEO?

2. How hard will a NEO let us push it?

3. What are a NEOs material properties?

Upon cursory examination, these three issues may seem to be related, and in fact they are. We obviously can "push" a given NEO harder and harder by either increasing an impactor's mass or its velocity. It is obvious that increasing velocity buys us more since kinetic energy increases quadratically with increasing velocity, whereas KE only increases linearly with increasing mass. Initially, lower values of impactor kinetic energy relative to the mass of the NEO results in the formation of a small crater on the target, with some target body material blown outward and the net result being a change in target momentum (see Fig. 1). At higher values of impactor (projectile) KE per target unit mass, i.e., E_p/M_t, the crater in the target continues to grow in size. At some point, however, the target body will fragment thereby identifying the limit of how hard a body will let us push it. Above a certain E_p/M_t threshold, commonly called the fragmentation strength or specific strength (Mcknight, 1991 and Housen and Holsapple, 1990), where the largest remaining fragment is less than about half the original target mass, the target fragments into a spectrum of fragment sizes and dispersion velocities. This basically leads into the third issue - that of what are the material properties of the target body.

A number of target parameters ultimately will determine how hard we can push a NEO and how hard it will let us push it, thereby defining the need for NEO material properties. These properties can be fundamental in nature, or derived. Fundamental properties of interest include: material identification, molecular composition, density, volume, inheterogeneities and inclusions on both micro- and macro-scales, thermal and dynamic state, and three-dimensional structure. Derived properties include tensile and compressive elastic and plastic strength regimes - under both static ($<10^1$ sec^{-1}) and dynamic ($>10^8$ sec^{-1}) loading conditions - and including fragmentation, conductivity, thermal capacitance, and thermodynamic (EOS - Equation of State) properties under high pressure and temperature loading conditions, among others. An excellent treatment of the subject of material properties is given in Remo, 1994.

NEO fragmentation strengths

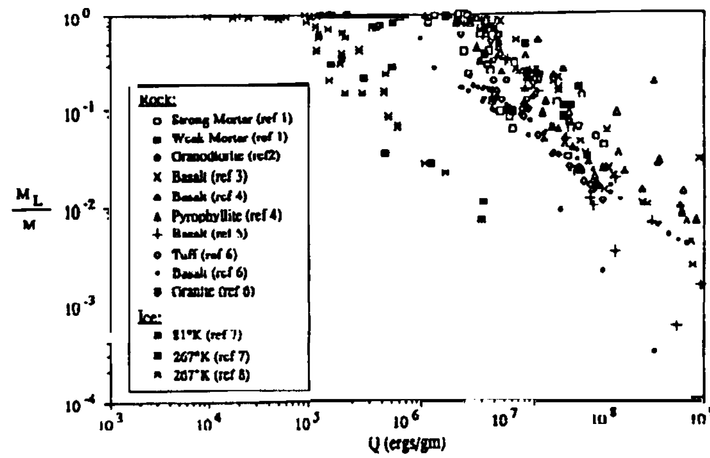
Table 1 contains an approximate listing of NEO material impact strength regimes (for basalt and ice only) as a function of M_l/M_t, the ratio of mass of the largest fragment to the original total mass, i.e., basically the net result to the target in terms of target mass dispersion. Catastrophic fragmentation can be defined here as the case where $M_l/M_t < 0.5$. Conversely, for $M_l/M_t > 0.5$ the target is still considered intact, but cratered.

Table 1. Experimental fragmentation strength regimes for rock and ice.

	Local crater		← Catastrophic Fragmentation →			
Target Material	E_p/M_t	M_l/M_t	E_p/M_t	M_l/M_t	E_p/M_t	M_l/M_t
Rock (basalt)	0.07	0.9	3	0.1	10	0.01
Ice	0.01	0.9	0.05	0.1	0.6	0.01

where: E_p/M_t=Projectile Energy/Target mass, J/gm; and M_l/M_t = Mass largest fragment produced/target mass

Other fragmentation strength data are shown in Fig. 2. It should be noted that the values in Table 1 are based on limited experimental data, and as such they should be considered only approximate, with large statistical variation in going from material sample to material sample. Nonetheless, these values suggest an upper limit on manageable energy deposition to rock and ice NEOs. Also, these values are considered conservative in that they could be high by an order of magnitude for a 1 km diameter body due to strain rate effects. At larger body sizes the strain-rate shock loading of the material is less (due to the effect of scale) and therefore the material failure level would be expected to be less. Materials are harder to fracture at higher strain rates, than the levels at which they fail for lower strain rates. Also, because of the general lack of obvious local inheterogeneities in the "pristine" laboratory samples (presumably unlike the case in nature) the target strength is considered "strength dominated" and, therefore, one would expect target fragmentation strength to be less in larger scale real materials. To first order, however, these data have direct application for estimating target responses for KE impacts, and perhaps for other high-rate energy deposition mitigation schemes as well.



Sources of Data. (1) Davis and Ryan (1988), (2) Cintala and Hörz (1984). (3) Fujiwara et al. (1977), (4) Takagi et al. (1984), (5) Fujiwara and Tsukamoto (1980), (6) Matsui et al. (1982), (7) Lange and Ahrens (1982), (8) Cintala et al. (1985)

Figure 2. Experimental rock and ice fragmentation strengths, $Q=E_p/M_t$ vs. M_l/M_t (Housen and Holsapple, 1990).

Modeling kinetic energy impacts

Ultimately it will be necessary to computationally model a kinetic energy intercept, that is an impactor striking a particular target NEO. It is impossible for us to expect to be able to test full-scale engagements on Earth, nor can we expect to do precursor impact experiments in space on many conceivable NEO bodies, if such missions are even conducted at all. Therefore some approach is needed to allow us to confidently predict (and assumably control) the full-scale outcome of such engagements. Much work has been done in empirically "curve-fitting" existing data sets, thereby resulting in a crude first-order approach which could be used to predict engagement outcomes. The danger in this approach is that the empirical model only applies over the range of parameters explored and assessed in its underlying experiments, and may not necessarily apply outside this parameter space, especially when "scaling-up" the engagement parameters many orders of magnitude in impactor and target body size (and mass) and perhaps up to an order of magnitude in velocity. The preferred approach would therefore be to use complex three-dimensional hydrocodes operating on high-speed computers to predict the outcome. Such an approach instills an increased level of confidence in the predicted outcome because these simulation codes are replete with the ability to model the complex temporal, three-dimensional, and physics-based aspects of this particular type of hypervelocity impact engagement. However, even hydrocodes need appropriate input data and should be validated against physics data and hopefully a representative engagement, i.e., a precursor mission.

Impact experiments

Impact experiments are necessary to provide both detailed material property data for predictive models, and also full-scale data to validate and verify the models against. Very little direct experimentation has been done in support of the planetary defense mission. Some material property (Furnish and Boslough, 1994), fragmentation (Hartmann, 1977; Fugiwara et al., 1978; and Davis and Ryan, 1990) and momentum deposition (Tedeschi et al., 1994) data have been collected. But these data are certainly incomplete for this application, and much more data are required. Much related work has been done which could serve as the basis for our initial understanding of using KE to deflect or disrupt NEOs. Examples are many in the area of planetary sciences: asteroid belt collisions/evolution, planetary impacts, ice and rock cratering and fragmentation, and the recent comet Shoemaker Levy-9 fragment impacts of Jupiter. The military arena has also done much work, e.g., in shielding, penetration, and cratering, and in the development of complex three-dimensional hydrocodes, e.g., Eulerian, Arbitrary Lagrangian Eulerian (ALE), and Smooth Particle Hydrodynamics (SPH).

Momentum deposition uncertainties

Current analytical and semi-empirical impulse deposition models may be underestimating high velocity impact effects, resulting in underestimated predicted momentum deposition values. Figure 3 shows a comparison of several analytically calculated normalized impulse parameters, I* (Shafer et al., 1994), for different impact velocities compared against some world-unique momentum deposition experimental data for rock, ice, and iron samples (Tedeschi et al., 1994). Observe that the experimental data are up to a factor of four higher than the calculations at the given impact velocity. It is interesting to note the monotonic trend that the lower density materials have higher I* values. This trend is probably due to the effect of target material phase change, especially in the vapor and ionized plasma states where secondary chemical reactions may even be possibly occurring on sufficiently short timescales to be increasing the apparent momentum deposition to the target due to more energetic mass blow-off effects. Obviously these speculations are preliminary and more research and analysis are required to provide a conclusive basis for this hypothesis. It is also interesting to note that the iron data point identically compares with two of the more realistic analytical momentum deposition models. This is probably so because the two models were formulated and benchmarked against data from low velocity impact tests against metal targets, where massive target-response phase changes did not take place, i.e., solid to liquid or solid to vapor. The analytical models in Fig. 3 most likely have limitations when extrapolated to higher impact velocities beyond which they were validated, and certainly beyond the point of significant phase-change effects in the target material.

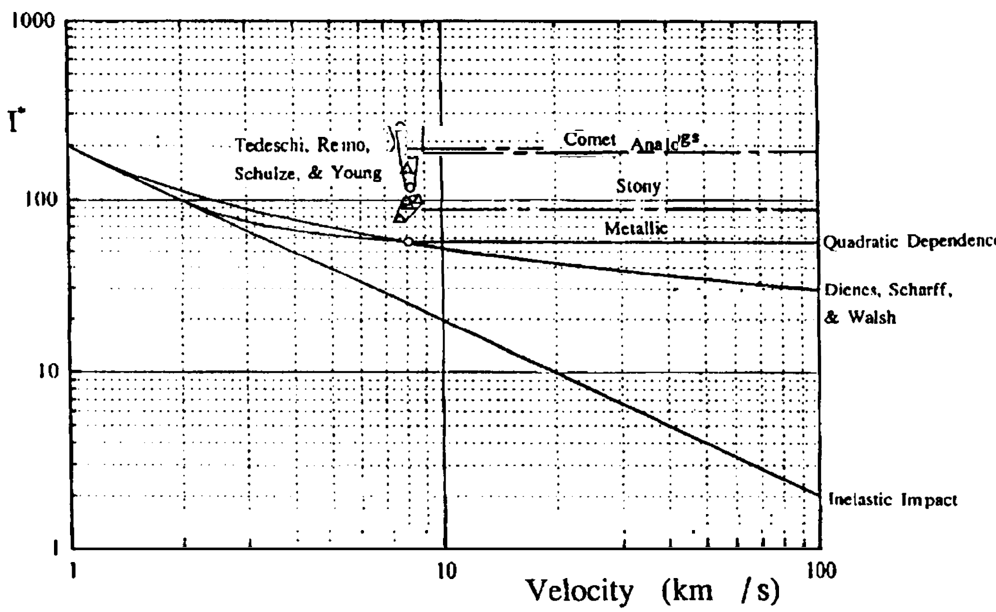


Figure 3. Comparison of analytical non-dimensional momentum deposition values, I* (Shafer et al., 1994), vs. world-unique experimental data (Tedeschi et al., 1994) for kinetic energy impacts into NEO analog materials.

Kinetic energy versus nuclear energy

It may be possible to at least study and model the effectiveness of higher-rate energy deposition nuclear mitigation technologies (see Fig. 4) using KE impact phenomenology to partially benchmark complex hydrocode models in higher energy state and phase change regimes. Of course, such models also have the ability to model other types of energy deposition schemes as well, e.g., lasers, microwaves, and concentrated solar energy. Both KE impact and nuclear explosive energy deposition schemes generate high-pressure shock waves in the target material. However, there are differences which need to be examined and understood. For example, a KE impact (of a "chunk" of mass) would appear to the body as a quasi-pointsource of deposited energy just below the surface, from which shock waves would than propagate radially outward from the source region into the body. Nuclear explosives, on the other hand, could be applied in two ways, i.e., stand-off explosion and sub-surface penetration or burial. The stand-off explosion would generate area shock-loading to the target body, while the sub-surface charge would appear as a quasi-pointsource of energy deposition, like the KE impact case. Therefore, kinetic energy should be pursued because of its apparent dual-benefit in modeling other rapid energy deposition schemes. Also, KE does not have to be a point source energy release within the target body, it has the marked advantage of being tailorable in its application to the target body. For example, it is possible for the mass of the interceptor to be spread out into a large area (i.e., a sheet of mass) to generate what would then appear to the target body as an area impulse, like that from a stand-off nuclear explosive irradiation. Issues to be resolved include:

1. What are the energy coupling efficiencies of KE and nuclear explosives?

2. How much of a dynamic stress state is imparted to the body during the energy coupling phase?

3. How will the dynamic stress state interact with the target body during the target response phase?

4. How will the target ultimately respond? Will it remain intact, or will it fragment to some degree?

These issues can only be resolved through a combined modeling and experimentation research program.

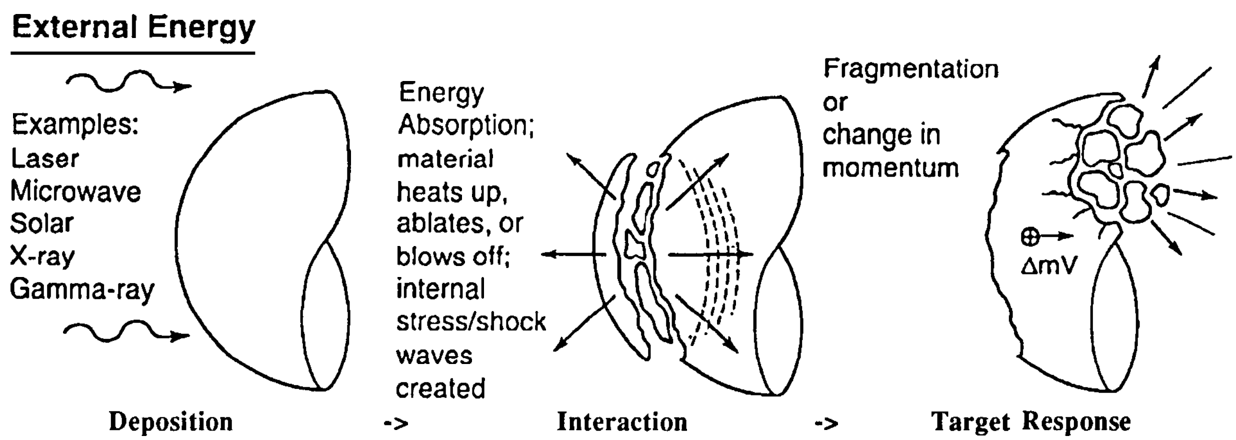


Figure 4. High energy nuclear mitigation technology examples; specifically: x-ray and gamma-ray deposition (neutron deposition is not shown).

KE mitigation strategy

In order to maximize the predictability and ultimately the controllability of a planetary defense KE impact mission someday, the following strategy is recommended (in order of priority):

1) Deflect the threatening NEO away from Earth through impact cratering, without breaking up the body.

2) Disrupt the threatening NEO by diverting as much mass as possible away from an Earth impact.

Deflection is the preferred approach because the outcome(s) of smaller-sized KE impactors on the target body would be more predictable and observable. This can work only if the warning time is adequate to allow us to marshal enough KE impactors (rockets with smart terminal maneuvering payloads) to deflect the NEO with an acceptable change in velocity to have the remaining body miss the Earth by a comfortable margin. However, if the amount of warning time is not adequate and there are no other viable mitigation technologies available, then disruption is the only logical course of action. It would be highly desirable to deflect as much mass as possible away from the Earth than to hope for an uncomfortable near-miss or adjusted benign Earth impact location. Of course, for the larger kilometer-class NEOs, kinetic energy will not be feasible without decades of warning time and therefore some other mitigation technology would be required.

Disruption capabilities against small NEOs

If a threatening NEO is small enough, i.e., on the order of 100's meters in size, KE impacts possibly could be used to predictably disrupt the body - literally independent of the amount of warning time. In this case, the bodies fragmentation due to the impact would be so complete that the resultant debris cloud would pose little or no danger to Earth, even if all the debris were still to impact the Earth. Existing experimental data (see Table 1) scaled up to full-scale engagements provides a means to assess to first order the approximate target body size regimes where KE impacts might play a role in disrupting small NEOs. Two upper bounding mass delivery systems were considered: 1) the Russian Energia and 2) the old American Saturn V rocket, capable of delivering 30,000 kg and 50,000 kg, respectively, in Earth escape trajectories (Isakowitz, 1991), although the largest demonstrated trans-Earth delivery was <6220 kg by the USSR Phobos mission (Wilson, 1994). It was assumed for calculational purposes that the impact velocity is 30 km/sec, mostly reflecting an approximate average approach velocity for a threatening NEO. Both rock and ice targets were examined for two different values of fragmentation strength, with the resultant mass of the largest post-impact fragment, i.e., M_l/M_t, as the metric of success for the hypothetical engagement. The results of the analysis are shown in Fig. 5.

Target/Frag. Strength Largest allowable frag.	Energia Largest NEO Target	Energia Largest Fragment	Saturn V Largest NEO Target	Saturn V Largest Fragment
Basalt/ E_p/M_t = 3 J/gm M_l/M_t = 0.1	128 m	60 m	152 m	71 m
Ice/ E_p/M_t = 0.05 J/gm M_l/M_t = 0.1	725 m	336 m	860 m	400 m
Basalt/ E_p/M_t = 10 J/gm M_l/M_t = 0.01	86 m	40 m	102 m	47 m
Ice/ E_p/M_t = 0.6 J/gm M_l/M_t = 0.01	316 m	147 m	376 m	174 m

Figure 5. Fragmentation capabilities of KE impacts against small NEOs as a function of impactor mass; target material, size, and fragmentation strength; and size of the largest post-impact target fragment generated.

The results clearly show the ability of KE impacts to suitably disrupt rock NEOs up to about 100 m in size and ice NEOs up to about 300 m in size, where the largest resultant debris fragment would pose a far less serious impact hazard to Earth, if it were to even hit Earth. Once disrupted, fragments from the NEO target body would disperse radially outward with some induced delta-velocity. Although typically the trend is for the larger fragments to have lower induced velocities, it is conceivable that provided enough warning time exists, the largest fragment might even miss the Earth, or, if need be, it could even be intercepted by another KE impactor and then rendered harmless. Fragment dispersion velocities are not so well understood, due mainly to very limited fragment velocity data (Davis and Ryan, 1990; Barge and Pellat, 1993; and Hartmann, 1985) and the relative inability to model such phenomena (Tedeschi, et al., 1992). Debris cloud fragment size and mass distributions are somewhat better understood, and can be modeled to first order (Tedeschi et al., 1994 and Tedeschi, et al., 1992). Given the fact that we do not now know or have an effective way of knowing the interior structure of a large NEO and its response to energy deposition, it would seem prudent to consider a precursor KE impact mission to provide data to address these issues.

Conducting a KE mitigation mission

Someday the need will arise to protect the Earth against a threatening NEO impact. A KE impact defense mission would involve the delivery of an appropriate amount of mass (and momentum and energy) to the approaching NEO either to gently deflect the body or to disruptively disperse all or a significant amount of the body's original mass away from an Earth impact. Related deep-space and defense missions have been successfully conducted in the past. They are complex, and they take time, resources, and great effort. Activities involved would include: threat detection, warning, and verification; tracking; authority to proceed; mission planning and end-game analysis; logistics and launch preparations; safety and security; delivery and survival in space of the mitigation technology; terminal homing and "intercepting" the target; assessing the result and trying again as necessary. Some level of mitigation planning now seems prudent to help ensure a timely future response, especially in light of our current inability to provide significant warning time in some particular cases, i.e., the smaller impactors (<100 m class) and long period comets. Such planning could include laboratory research and experimentation, as well as precursor impact experiments in space. Others have proposed geopolitical constructs for future planning purposes (Tedeschi and Teller, 1994).

The need for precursor KE impact missions

Precursor mitigation missions may be warranted if our ability to mitigate threatening NEOs with KE someday in the future is significantly hampered without them. However, the burden of proof for such a need rests clearly on the planetary defense community. A precursor mission would improve our understanding of: carrying massive smart spacecraft payloads long distances through the hostile environments of space, final approach and terminal homing with the target, target impact, the interaction of the KE impactor with the NEO to deflect or fragment it, the response of a NEO to an impact, long range tracking and control, modeling and planning assumptions, and scaling-up energy coupling experiments and analysis performed on Earth, among others. Doing precursor missions would allow smarter choices to be made in times of emergency. Others have either proposed NEO rendezvous missions (Nozette, 1995 and Tedeschi and Allahdadi, 1995) or are actively planning upcoming related missions, i.e., NASA/NEAR and ESA/Rosetta.

Future research opportunities

An effective KE impact NEO protection scheme for use against an approaching object would ideally require extensive study and research *a priori* to determine the best way to safely deliver and couple a given amount of mass, momentum, and energy into an approaching body to either fragment or deflect it. Experimentation might include not only laboratory experiments and simulations, but also the study of actual deflection or disruption of NEOs in non-menacing orbits. Doing so would provide an increased level of confidence in the effectiveness of KE against some future NEO impactor. Extensive modeling and analysis then would be required to explore the full parameter space for using KE against different NEO materials and dynamic states.

Knowing how kinetic energy couples into various target materials serves as the basis for predicting the effectiveness a kinetic energy impact defensive action. This can be done only through carefully controlled experimentation and modeling, whereby various target materials are probed and characterized experimentally and analytically by a number of kinetic energy fluences. The target material response is observed, measured, and quantified, and then scaled up in terms of it's effectiveness at imparting momentum to or physically fragmenting a larger body composed of this material. Figure 6 shows an experimental set-up for world-unique momentum deposition experiments conducted in 1994, as an example of how experimental testing (and analysis) can be conducted at low cost. While some experimental data are available, much more material property data and energy coupling experimentation are required (Remo, 1994; Shafer et al., 1994; and Tedeschi et al., 1994). Table 2 summarizes the types of research opportunities which exist to better understand and predict KE impact physics. Needless to say, laboratory experimentation and modeling are very cost effective options which should be pursued.

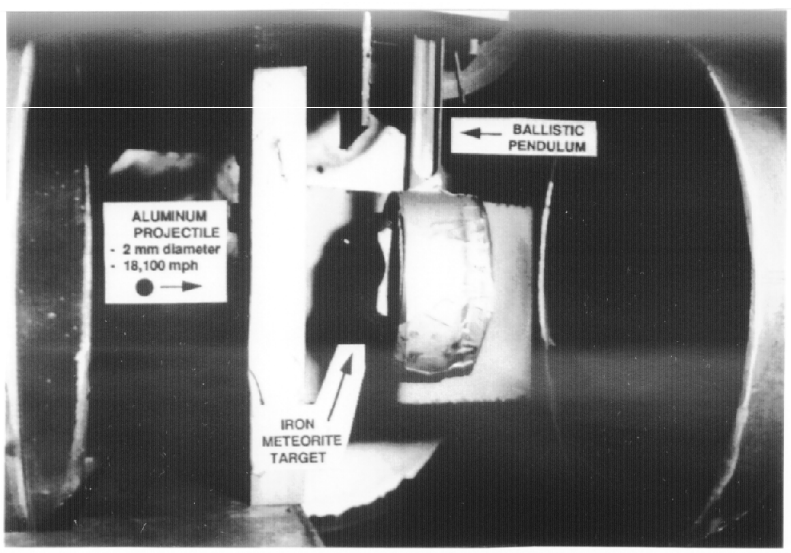


Figure 6. Experimental set-up at the U.S. Air Force AEDC impact range for measuring KE impact momentum deposition to an iron meteorite target mounted on a specially designed ballistic pendulum (Tedeschi et al., 1994).

Table 2. Future research opportunities in KE impact hazard mitigation physics.

Material Properties: Composition, micro- and macro-structure, rate dependencies.
- Exam ne and test Earth-analog materials and recovered meteorite samples, and collect & test samples in situ on comets and asteroids.

Equation of State: High-pressure loading conditions.
- Test samples and developEOS models.

Computational Modeling: Better understand and simulate impact physics.
- Modify and expand existing capabilities to handle complex materials, structures, phase-changes, and late-time structural responses.

Early-Time (Local) Impact Physics: Crater Formation
- Conduct carefullv designed tests at full scales and velocities, conduct modeling simulations and make improvements. Do space experiments.

Late-Time (Global) Impact Physics: Momentum Deposition or Fragmentation
- Conduct carefully designed tests at full scales and velocities, conduct modeling simulations and make improvements. Do space experiments.

ESAs unsuccessful attempt to impact a comet

Earth's only attempt at impacting a NEO with KE came in 1992 when the European Space Agency (ESA) tried to ram comet P/Grigg-Skjellerup with the Giotto spacecraft (Burnham, 1993; Grensemann and Schwehm, 1993; and Wilson, 1994). Giotto wasn't even close - it missed by some 200 km! But, nevertheless, valuable insights can be derived from this first of its kind encounter based on an examination of the facts. After its successful fast flyby of Halleys comet in 1986, Giotto went into hibernation for nearly four years in the hard vacuum and cold of deep space. It was reactivated in early 1992 to attempt not a flyby of comet P/Grigg-Skjellerup, but to actually impact the comet in July 1992 using ground-control directed guidance. Particulars of the interesting encounter are given in Fig. 7 and Table 3

Giotto Spacecraft　　　　Encounter Geometry

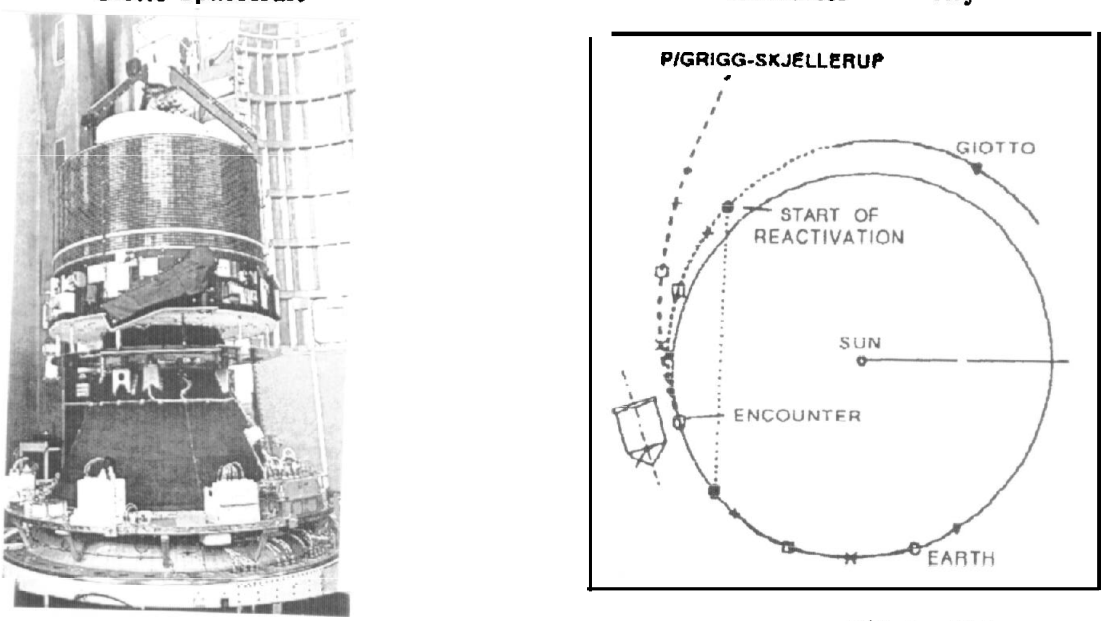


Figure 7. The Giotto spacecraft and encounter geometry with comet P/Grigg-Skjellerup.

Table 3. Particulars of the attempted impact of comet P/Grigg-Skjellerup by the Giotto spacecraft.

Encounter date: 10 Jul 1992
Last course correction: 8 Jul 1992
Spacecraft status: Many subsystems still operational after comet Halley fly-by
Spacecraft mass: 529 kg
Nucleus size: 2 km (est.) dia.
Relative approach velocity: 14 km/sec
Comet position uncertainty: < 650 km
Distance from Earth: 1.2 AU
One-way light time: 12 minutes
Dust coma encountered: 17,000 km range
Large dust particles encountered: near nucleus
Passed by: Dark (tail) side
Closest approach: < 200 +/- 100km (est.)

As can be seen in Fig. 7, the Giotto spacecraft basically tried to get in front of the fast moving comet and let it impact the spacecraft with a relative impact velocity of 14 km/sec. Because the encounter was controlled from Earth, which was 1.2 AU in range at the time, several problems were encountered which ultimately lead to the failure of Giotto to impact the comet. The position of the comet was not known accurately, therefore it was difficult to know exactly where to aim the spacecraft for the intended intercept. The spacecraft was 12 minutes away from command guidance instructions from Earth on what to do. Conditions obviously changed quickly in the final 12 minutes, especially upon final approach to the comet shrouded somewhere inside the dusty coma. It should be clear that future encounters, if they are to have a reasonable chance to succeed, should allow the interceptor spacecraft to autonomously acquire, track, and home in on the target to intercept. The homing spacecraft must also have a healthy divert capability to make final course corrections just before intercept or closest approach, probably on the order of 1-2 km/sec in velocity increment. A slower terminal approach velocity is also desirable, if practical, in that it provides more time to do final maneuvering and intercept.

It's also instructive in this case to ask the question of what would have happened had the 529 kg Giotto spacecraft impacted the comet. The answer is not much. While the impact energy would have been a respectful 5.17×10^{10} J, or 12 tons of TNT equivalent energy release, the E_p/M_t ratio was only 1.6×10^{-5} J/gm, where the target (comet) mass was estimated at a massive 3.14×10^{15} gm. This value is nowhere near the threshold value of ≈ 0.5 J/gm which would have been required to fragment the comet, therefore the encounter result would have been the creation of an impact crater and momentum deposition to the comet. There certainly would have been a large impact flash and significant expulsion of cometary material, both of which may have been visible from Earth-based sensors. Assuming a momentum deposition value of 5 (based on Tedeschi et al., 1994), the calculated induced velocity would have been a mere 0.012 mm/sec - far too small to have been measured from Earth. It should not be assumed that we know how to mitigate NEOs with kinetic energy by spacecraft impact. We have seen that not only do we not understand the impact physics of high speed NEO impacts, nor the composition, structure, and resultant response of such bodies, but we also failed to intercept a comet using modern spacecraft technology in this situation. We should perhaps not have to feel a little too uncomfortable about this, but rather we should resolve to seriously study this issue and generate viable options to protect Earth from the NEO impact hazard.

Summary

Kinetic energy is a viable mitigation technique to protect Earth from the NEO impact hazard under certain circumstances by either deflecting or disrupting an approaching body. However, for us to have confidence in the effectiveness of kinetic energy as a defensive capability, we must seriously consider the conduct of laboratory experimentation and analysis, and of precursor intercept missions, to allow us to better understand and model the delivery and deposition of kinetic energy into NEO targets and the resultant response, i.e., the dynamic induced stress state and the ultimate global structural response. Conducting low-cost experimentation and analysis now will allow timely and effective defensive responses in the future.

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References

Alvarez, L., Alvarez, W., Assaro, F., and Michel, H., "Extraterrestrial Cause for the Cretaceous-Tertiary Mass Extinction," *Science*, **208**, 1095-1108, (1980).

Andersen, C., "An Overview of the Theory of Hydrocodes," *Int. J. Impact Engng*, **5**, 33-59 (1987).

Barge, P. and Pellat, R., "Mass Spectrum and Velocity Dispersions during Planetesimal Accumulation. II. Fragmentation," *Icarus* **104**, 79-96 (1993).

Burnham, D., "Journey to Grigg-Skjellerup," *Spaceflight*, **35**, 110-115, 1993.

Canavan, G., Solem, J., and Rather, J. eds., *Proceedings of the Near-Earth-Object Interception Workshop*, Univ. of California Report, Los Alamos (1992).

Davis, D. and Ryan, E., "On Collisional Disruption: Experimental Results and Scaling Laws," *Icarus* **83**, 156-182 (1990).

Fujiwara, A., Kamimoto, G., and Tsukamoto, A., "Destruction of Basaltic Bodies by High-Velocity Impact," *Icarus*, **31**, 277-288 (1977).

Furnish, M. and Boslough, M., "Dynamical Properties Measurements for Asteroid, Comet and Meteorite Material Applicable to Impact Modeling and Mitigation Calculations," *Proceedings 1994 Hypervelocity Impact Symposium*, Santa Fe, NM (1994).

Grensemann, M. and Schwehm, G., "Giotto's Second Encounter: The Mission to Comet P/Grigg-Skjellerup," *J. Geophys. Res.*, 98(A12), 20907-20910, 1993.

Halliday, D. and Resnick, R., *Fundamentals of Physics*, (John Wiley & Sons, New York, 1974).

Hartmann, W., "Planet Formation: Mechanism of Early Growth," *Icarus*, **33**, 50-61 (1978).

Hartmann, W., "Impact Experiments: 1. Ejecta Velocity Distributions and Related Results from Regolith Targets," *Icarus* **63**, 69-98 (1985).

Housen, K. and Holsapple, K., "On the Fragmentation of Asteroids and Planetary Satellites," *Icarus*, **84**, 226-253 (1990).

Isakowitz, S., *International Reference Guide to Space Launch Systems*, (AIAA, Washington, D.C., 1991).

Kawakami, S., Mizutani, H., Takagi, Y., and Kumazawa, M., "Impact Experiments on Ice," *Journal of Geophysical Research*, **88**(B7), 5806-5814 (1983).

McKnight, D., "Determination of Breakup Initial Conditions," *J. Spacecraft and Rockets*, **28**(4), 1991.

Morrison, D., *The Spaceguard Survey: Report of the NASA International Near-Earth-Object Detection Workshop*, Jet Propulsion Lab/Cal Tech Report, Pasadena (1992).

Nozette, S., "Clementine II", *Proceedings of Planetary Defense Workshop*, Livermore, CA (1995).

Remo, J., "Classifying and Modeling NEO Material Properties and Interactions," *Hazards Due to Comets and Asteroids*, (Univ. of Arizona Press, Tucson, 1994).

Scotti, J., Rabinowitz, D., and Marsden, B., "Near Miss of the Earth by a Small Asteroid," *Nature*, **354**, 287-289 (1991).

Shafer, B., Managan, R., Remo, J., Rosenkilde, C., Scammon, R., Snell, C., and Stellingwerf, R., "The Coupling of Energy to Asteroids and Comets," *Hazards Due to Comets and Asteroids* (Univ. of Arizona Press, Tucson, 1994).

Sharpton, V. and Ward, P. eds., *Global Catastrophes in Earth History: An Interdisciplinary Conference on Impacts, Volcanism, and Mass Mortality*, Geological Society of America, **247**, 1-98 & 417-606 (1990).

Tedeschi, W., Allahdadi, F., Connell, J., Hogg, D., Hunt, R., McKnight, D., and Reinhardt, A., "Determining the Effects of Space Debris Impacts on Spacecraft Structures," *Acta Astronautica*, **26**(7), 501-512 (1992).

Tedeschi, W., Remo, J., Schulze, J., and Young, R., "Experimental Hypervelocity Impact Effects on Simulated Planetesimal Materials," *Proceedings 1994 Hypervelocity Impact Symposium*, Santa Fe, NM (1994).

Tedeschi, W., "Protecting Earth from Comet/Asteroid Impacts through International Cooperation: Issues & Current Status," *19th International Symposium on Space Technology and Science Proceedings*, Yokohama, Japan (1994).

Tedeschi, W. and Teller, E., "A Plan for Worldwide Protection Against Asteroid Impacts," *Space Policy*, **10** (3), 183-184 (1994).

Tedeschi, W. and Allahdadi, F., "Near Earth Asteroid Rendezvous Mission," *Proceedings of Planetary Defense Workshop*, Livermore, CA (1995).

Wilson, A. ed., *Jane's Space Directory*, (Jane's Info. Grp. Ltd., Surrey, UK, 1994).

Wood, L., Ishikawa, M., Teller, E., and Hyde, R., "Cosmic Bombardment V: Threat Object Dispersing Approaches to Active Planetary De fense," *Proceedings of Planetary Defense Workshop*, Livermore (1995).