

DEFLECTION AND FRAGMENTATION OF NEAR-EARTH ASTEROIDS

THOMAS J. AHRENS

California Institute of Technology

and

ALAN W. HARRIS

Jet Propulsion Laboratory

Collisions by near-Earth asteroids or the nuclei of comets pose varying levels of threat to man. A relatively small object, ~ 100 m diameter, which might be found on an impact trajectory, could potentially be diverted from an Earth impacting trajectory by a rocket launched, 10^2 to 10^3 kg impactor, with a lead time of ~ 10 yr. For larger bodies or shorter lead times, the use of kinetic energy impactors appears impractical because of the larger mass requirement. For any size object, nuclear explosions appear to be more efficient, using either the prompt blow-off from neutron radiation, the impulse from ejecta of a near-surface explosion for deflection, or, least efficiently, as a fragmenting charge.

I. INTRODUCTION

Several hundred asteroids and short-period comet nuclei with diameters $> 10^2$ m, have been discovered in Earth-crossing orbits. Upon extrapolating this known population of near-Earth objects (NEOs) to those not yet discovered, it is estimated that $\sim 2 \times 10^3$ objects ≥ 1 km in diameter are present in a transient population (Shoemaker et al. 1990; see Chapter by Rabinowitz et al.).

Comets are brought into the swarm of NEOs by gravitational perturbation mainly by Jupiter from their orbits in the Kuiper belt or Oort cloud (Weissman 1990). Some objects currently classed as near-Earth asteroids may be devolatilized comets. In the case of asteroids, the source of NEOs is largely from the main asteroid belt. Earth- or near-Earth-crossing objects are removed from this population either via collision with a planet or by gravitational perturbation which causes them to be ejected into hyperbolic orbits. The largest Earth-crossing asteroids have diameters approaching 10 km. It is unlikely that any objects larger than ~ 5 km diameter remain undiscovered, but some 3 to 5 km objects are probably still to be found.

Scientific interest in NEOs is great because it appears that many of these

objects are mainbelt asteroids which have been perturbed into terrestrial planet-crossing orbits, and thus give rise to a large fraction of the impact flux on terrestrial planet surfaces (Binzel et al. 1992). NEOs as small as 5 to 10 m in diameter can occasionally be telescopically observed (Scotti et al. 1991; see Chapter by Carusi et al.). Meteorites are fragments of NEOs that have survived passage through the Earth's atmosphere. Because the number distribution of different meteorite classes correlates poorly with asteroid type, as inferred from reflectance spectra of mainbelt asteroids, it may be that the present terrestrial meteorite collection is a poor sample of the asteroid population. To further study asteroids, one or more unmanned flyby or rendezvous missions to near-Earth asteroids (NEAs) are currently being planned by NASA (Veveřka and Harris 1986; see Chapter by Cheng et al.). Finally, the composition of NEOs is of interest as these objects represent possible mineable resources which, in principle, could supply raw materials, including water, and hence, oxygen and hydrogen for extended space flights (see Chapter by Hartmann and Sokolov).

Earth-crossing asteroids have been recognized telescopically since 1932, when K. Reinmuth discovered 1862 Apollo. However, it was the American geologist, G. K. Gilbert whose work on Meteor Crater, Arizona, and many later workers, conclusively demonstrated that the impact of Earth-crossing asteroids and comets produce the ~120 known meteorite impact craters on the Earth and virtually all the craters on the Moon.

In 1980, a startling discovery was reported by Alvarez et al. (1980). They found a concentration of platinum group metals of 10^3 to 10^4 times normal crustal sedimentary abundances, and in approximately chondritic meteoritic proportions, at two sites in Europe, exactly at the Cretaceous-Tertiary (K/T) boundary. On this basis, they proposed that an asteroid or a comet, ~10 km in diameter, impacted the Earth 65 Myr ago and the prompt high speed projectile ejecta from this impact was lofted upward to the stratosphere and was dispersed worldwide. They further proposed that this dust layer gave rise to a temporary decrease in solar insolation and drastically, but temporarily, affected the world's climate, and hence the biotic food chain.

In the 13 yr since the publication of the Alvarez et al. hypothesis, probably the most significant discovery in paleontology in this century, the platinum-rich element layer has been uncovered at some 200 sites all over the Earth, in terrestrial sediments and shallow marine and deep marine sedimentary environments. The concentration of platinum-group elements in the impact ejecta varies such that it can be considered to consist of typically ~1% meteoritical material (Gubbio, Italy). In some localities it occurs up to ~10% concentration (Stevens Klint, Denmark). The platinum-rich element horizon is always found in sediments of exactly Cretaceous-Tertiary (65 Myr) age. In addition, the K/T ejecta layer contains mineral grains (quartz and feldspar) which bear distinctive shock-induced lamellae as well as spherules of impact-induced glass spheres. Such spherules have long been associated with impact craters both on the Earth and the Moon.

In 1992 good radiometric ages (Sharpton et al. 1992; Swisher et al. 1992) and stable isotope data associating the molten ejecta with a source terrane (Blum and Chamberlain 1992; Blum et al. 1993) have been obtained. The shocked mineral grains and shock-induced glasses are now believed to be part of ejecta from the ~250 km diameter Chicxulub Impact Crater located along the northwest coast of the Yucatan Peninsula in Mexico. The radiometric and stable isotope data reinforce the association of the Chicxulub Crater, which formed in shallow marine sediments, with the K/T boundary impact event. Previously Bourgeois et al. (1988) and Hildebrand et al. (1991) reported the occurrences of local, presumed tsunami-related, deposits directly underlying the platinum-rich element layer around the rim of the proto-Caribbean sea in Central America and in the Southeastern United States (see the Chapters by Smit and by Hills et al.). Such deposits were anticipated earlier, on a theoretical basis, by Ahrens and O'Keefe (1983).

The K/T boundary marks the end of the Mesozoic era and thus represents the demarcation between the age of reptiles (Mesozoic) and the age of mammals (Tertiary). Evidence that similar extinction-causing impacts occurred previously in Earth history is incomplete. The K/T event appears to be the most recent, and hence has the best preserved record, of five major extinction events which have been recognized by paleontologists to have occurred in the last 500 Myr of Earth history. Approximately 50% of all marine genera and probably 90% of all species became extinct at the K/T boundary. These included terrestrial, marine, micro- and macro-organisms, and the well-known groups of dinosaurs. An impact of such a large bolide on the Earth is believed to give rise to a large number of global physical (Gerstl and Zardecki 1982; O'Keefe and Ahrens 1982; Toon et al. 1982; Vickery and Melosh 1990) and chemical effects (O'Keefe and Ahrens 1989; Brett 1992; Sigurdsson et al. 1992) which are deleterious to life. However, the generation of environments which endanger the existence of a multitude of life forms and their detailed effect on the global environment are not yet thoroughly understood (Chapters by Sheehan and Russell and by Toon et al.).

As the Alvarez et al. hypothesis became more widely accepted in the 1990s scientists, and eventually governments, recognized that the Alvarez scenario bore many similarities to the post-nuclear winter environment (Covey et al. 1990; Crutzen and Birks 1982; Turco et al. 1990).

Sparked by public concern, the United States House of Representatives in 1991 requested the National Aeronautics and Space Administration to conduct studies of the asteroid-impact threat to the Earth's human population (Morrison 1992; Chapter by Morrison et al.) and possible measures which could be taken to prevent cosmically induced disasters with global consequences (Rather et al. 1992; Chapter by Canavan et al.). The recent Near-Earth Object Detection Workshop (Morrison 1992; Chapter by Morrison et al.) quantified the hazards to the world population from different sized Earth impactors based, in part, on the results of an earlier workshop (Shoemaker 1983) in 1981.

Using the estimated population of NEOs and their size distribution, objects with diameters of about 10 m impact the Earth almost annually, and although visible and audible for distances of 10^2 to 10^3 km, these objects largely break up and expend their typically 10 Kton (of TNT) energy in the atmosphere. Earth impact of NEOs of about 100 m diameter, e.g., the 1908 Tunguska event (energy ~ 10 Mton) has a frequency of about once every ~ 300 yr. Although the Tunguska bolide did not hit the Earth's surface, it nevertheless did great damage. These objects, although inducing local areas of devastation of $\sim 5 \times 10^3$ km², have an annual probability of leading to the death of a given individual of only $\sim 3 \times 10^{-8}$ yr⁻¹. Although less frequent, once every 0.5 Myr, Earth impactors of the ~ 1 km diameter size are inferred to be the minimum size which can induce global catastrophic effects ($\sim 25\%$ human mortality). Thus the annual individual death probability from such an event is of the order of 5×10^{-7} . This is comparable to the annual worldwide probability of an individual succumbing in a commercial airplane accident. (Chapter by Morrison et al.)

When viewed in this way, it appears to us that a balanced response for society to deal with the NEO impact problem might be an expenditure perhaps up to some sizeable fraction of the amount of funding committed to air safety and control. We believe this would be in the range of 10^7 to 10^8 dollars per annum worldwide. As was concluded by the Near-Earth Object Detection Workshop, funding at this level would vastly improve our knowledge of the population and distribution of near-Earth objects using groundbased and possibly space-borne telescopes. We consider it premature to conduct detailed engineering studies or construct prototype systems for deflection of NEOs for several reasons. It is unlikely that such a system will ever be needed. If a body exists on a collision course, it is likely that it can be detected with enough lead time to construct a deflection system after the discovery and characterization of the body and its orbit. With today's technology, a deflection system is bound to be vastly more costly than a thorough groundbased survey. Thus for the present, in the absence of a discovered threatening body, it appears more useful to direct resources to improved searching rather than deflection technology.

In this chapter we examine the orbit perturbation requirements to deflect objects from the Earth, which might be found to have Earth-impacting trajectories. We then examine several physical means for both deflecting and explosively fragmenting such objects. We consider NEOs in three size ranges: 0.1, 1, and 10 km in diameter. Their collision fluxes, on the total area of the Earth are respectively, 10^{-3} , 10^{-5} , and 10^{-8} per year. Objects significantly smaller than 100 m pose little threat, because they do not penetrate the atmosphere intact. Short duration responses, which might be considered for new comets, have recently been described by Solem (1991, 1992; Chapter by Solem and Snell). This study addresses the physical means of encountering NEOs with spacecraft-bearing energetic devices many years, or even decades, before projected Earth impact.

To quantify the present work especially with regard to nuclear explosive cratering in the low-gravity asteroid environment, we employ recent studies of cratering at varying gravities and atmospheric pressures (Housen et al. 1993; Schmidt et al. 1986) and impact ejecta scaling (Housen et al. 1983), which were not available to earlier studies (MIT Students 1968; Solem 1992).

II. NEAR EARTH ASTEROID ORBIT DEFLECTION CONSIDERATIONS

A. Short Time-Scale Deflection

On a time scale short compared to the orbit period P , the displacement δ achieved by a velocity change Δv is the same as for rectilinear motion:

$$\delta = \Delta v \cdot t \quad (1)$$

in either transverse or along the track of the orbital motion. For $t \lesssim P/2\pi$, to perturb a body $1 R_{\oplus}$ in time t requires

$$\Delta v \sim \frac{R_{\oplus}}{t} \sim \frac{75 \text{ m s}^{-1}}{t, \text{ days}} \quad (2)$$

where R_{\oplus} is an Earth radius.

B. Long Time-Scale Deflection

On a longer time scale, a transverse increment of velocity perpendicular to the orbital plane results in a change of inclination. If the Δv is applied as shown in Fig. 1a, the maximum displacement of the NEO, δ_{\max} , occurs at 90° from the place in the orbit that the perturbation was applied. The semimajor axis remains unchanged. Then

$$\delta_{\max} \cong \Delta v P / 2\pi. \quad (3)$$

Thus, the perturbed NEO changes only its inclination.

If a perturbation Δv is applied radially as shown in Fig. 1b, the maximum radial displacement occurs 90° around and is the same as given by Eq. (3). However, as the body moves closer to the Sun, it moves faster, so that 180° around in its new orbit it is displaced along the orbit track by a distance

$$\delta_{\max} \cong 2\Delta v P / \pi. \quad (4)$$

In the second half of the orbit, the displacement motion is reversed, so that the particle returns to the point of application of Δv at the same time as the unperturbed reference point, because the semimajor axis, and hence the orbit period was unchanged.

A velocity increment applied along the track of motion of an object produces a change of orbital semimajor axis, and hence orbital period, in

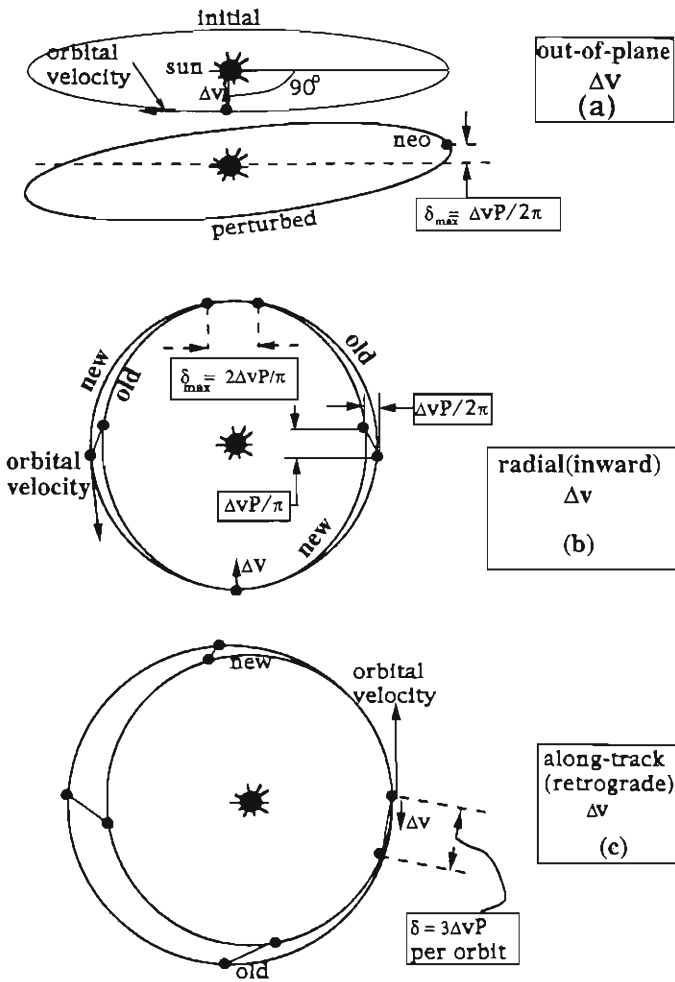


Figure 1. Sketch of the effect on the orbit of an NEO upon perturbing its velocity by Δv : (a) perpendicular to its orbital plane; (b) radially in its orbital plane; and (c) tangentially to its orbit, in its orbital plane.

addition to a change of eccentricity. Thus, the resultant displacement from the original motion consists of an oscillatory component, but also a secular drift, which continues to grow with successive orbits. The mean rate of drift can be derived from the equation for the energy of orbital motion:

$$E = -\frac{GM_s}{2a} = -\frac{GM_s}{r} + \frac{1}{2}v^2 \tag{5}$$

where G is the universal constant of gravitation, M_s is the mass of the Sun, a is the orbital semimajor axis, r is the distance from the Sun at the point in the

orbit where the velocity increment is to be applied, and v is the heliocentric velocity at that point in the orbit. After applying a velocity increment Δv along the time of motion, the energy of the new orbit is

$$E' = -\frac{GM_s}{2(a + \Delta a)} = -\frac{GM_s}{r} + \frac{1}{2}(v + \Delta v)^2 \quad (6)$$

where Δa is the change in orbital semimajor axis. After expanding the above expression in terms of the small quantities, and differencing from the initial energy, we can obtain:

$$\frac{\Delta a}{a} \approx \frac{2\Delta v}{v_0} \sqrt{\frac{2a}{r} - 1} \quad (7)$$

where $v_0 = \sqrt{GM_s/a}$ is the mean orbital velocity. From Kepler's third law, we have $P^2 \propto a^3$, and hence $\Delta a/a = (2/3)(\Delta P/P)$. The mean position in the new orbit diverges by a distance $-2\pi a \Delta P/P$ from the position in the original orbit, so the mean velocity of divergence is

$$\Delta v' = -\frac{2\pi a}{P} \frac{\Delta P}{P} = -v_0 \frac{\Delta P}{P} \quad (8)$$

and thus

$$\Delta v' = -3\Delta v \sqrt{\frac{2a}{r} - 1}. \quad (9)$$

For a circular orbit, $a = r$, and the above expression reduces to

$$\Delta v' = -3\Delta v. \quad (10)$$

After one orbit, the maximum deflection for a nearly circular orbit is (Fig. 1c)

$$\delta \simeq -3\Delta v P. \quad (11)$$

Thus, over a time t long compared to P , an increment Δv applied parallel to v produces a deflection of

$$\delta \simeq 3\Delta v t. \quad (12)$$

It can be seen that for an eccentric orbit, the greatest effect is achieved by applying Δv at the perihelion. For example, for an orbit of eccentricity 0.5, $r = 0.5a$ at perihelion and $\Delta v' = -3\sqrt{3}\Delta v \approx -5\Delta v$. At aphelion of the same orbit, $r = 1.5a$ and $\Delta v' = -\sqrt{3}\Delta v \approx -1.7\Delta v$. Thus for typical NEO orbits, the circular orbit value, $\Delta v' \sim 3\Delta v$ is accurate within a factor of 2 or so. In order to achieve a deflection distance of one Earth radius in a time $t(>P)$, the velocity increment required is:

$$\Delta v \approx \frac{R_{\oplus}}{3t} \approx \frac{0.07 \text{ m s}^{-1}}{t \text{ yr}}. \quad (13)$$

Thus it appears that if a time of the order of a decade is available to achieve deflection, a velocity increment of $\sim 1 \text{ cm s}^{-1}$ is sufficient.

III. IMPLEMENTATION OF ORBITAL DIVERSION

Several scenarios are considered, including deflection via kinetic energy impactor, mass driver systems, as well as nuclear explosive radiation and blow-off, and ejecta impulse from cratering explosions (see also the Chapter by Melosh et al.).

A. Direct Impact Deflection

It is feasible to deflect a small ($\sim 10^2 \text{ m}$ diameter) NEO via direct impact because:

1. The kinetic energy delivered for even a modest encounter velocity ($\sim 12 \text{ km s}^{-1}$) of an upper stage launched spacecraft is much more efficiently coupled (70 to 80%) to the asteroid (Smither and Ahrens 1992) than surface explosions. The energy density at 12 km s^{-1} is $70 \times 10^{10} \text{ erg}$ per g of impactor. This is much greater than typical chemical explosive energies ($4 \times 10^{10} \text{ erg g}^{-1}$), and as demonstrated below the ejecta throw-off from such an impact will suitably perturb the NEO.
2. Although cratering efficiency on a small (100 m diameter) NEO (escape velocity 5 cm s^{-1}) is unmeasured, extrapolating small-scale studies (at high and low gravities) suggests that the cratering efficiency may be $\sim 10^4$ times (Holsapple 1993; Housen et al. 1993) the earthly value of 2.8 tons of rock per ton of equivalent explosive yield (Cooper 1977). For impact of an Earth-launched projectile into an NEO, two regimes of cratering mechanics need to be considered. At small scales (tens to perhaps hundreds of m), the strength of the target asteroid or comet needs to be considered as affecting, and perhaps even controlling impact cratering mechanics whereas for larger impact craters local gravity controls the cratering process.

Strength Regime. Housen et al. (1983) observed, on the basis of the experiments of Gault et al. (1963), that upon impact into basalt (here assumed to be typical of NEO materials), where the strength of the target controls the size of the crater, the cumulative mass of ejecta, $M(>v)$ traveling faster than v is given by

$$M(>v) = 0.05 R_c^3 \rho \left(\frac{Y}{\rho v^2} \right) \quad (14)$$

where ρ and Y are the target density and material strength, respectively, and R_c is the radius of the crater produced. In the strength-controlled regime, the size of the crater is determined by the scale to which elastic deformation exceeds the yield strength of the target material, which in turn dictates the minimum speed with which broken fragments are ejected. We can derive the minimum speed v_{\min} by equating the mass $M(>v_{\min})$ with the total mass M_{ej}

evacuated from the crater. Assuming the crater is a half-oblate spheroid of radius R_c , and depth $\sim 0.4R_c$ (see, e.g., Pike (1980), we can relate the total mass excavated to the crater radius approximately:

$$R_c^3 \approx 1.2 \frac{M_{ej}}{\rho}. \quad (15)$$

Inserting Eq. (15) into Eq. (14), and equation $M(>v_{\min}) = M_{ej}$, we can rearrange the resulting expression to obtain the following for the minimum ejecta velocity:

$$v_{\min} \approx \sqrt{0.06 \frac{Y}{\rho}} \approx 0.24 \sqrt{\frac{Y}{\rho}}. \quad (16)$$

Thus expression (14) is valid for $v \geq v_{\min}$. Note that the elastic energy density per unit mass stored in a material when stressed to its yield point Y is $\sim YS/(2\rho)$, where S is the yield strain. Thus v_{\min} is related dimensionally to the "rebound velocity" of the material, assuming a constant value of the yield strain for materials of various strengths. We note also that v_{\min} is much greater than the escape velocity from a small asteroid, e.g., for a very weak material, $Y = 10^7$ dyne cm^{-2} , $v_{\min} \approx 5$ m s^{-1} ; for a 1 km diameter asteroid, the escape velocity is $v_{\text{esc}} \approx 0.5$ m s^{-1} .

Using the compilation of Holsapple and Schmidt (1982) of cratering experiments conducted in vacuum, for impacts into metals, the mass M_{ej} of material excavated as a function of impactor mass M_i , density ρ_i and impact speed v_i is given by

$$M_{ej} \approx 0.458 M_i \left(\frac{\rho}{\rho_i} \right) \left(\frac{\rho v_i^2}{Y} \right)^{0.709}. \quad (17)$$

The differential form of Eq. (14) can be written

$$dM = \frac{2v_{\min}^2 M_{ej}}{v^3} dv \quad (18)$$

with v_{\min} given by Eq. (16) and M_{ej} given by Eq. (17). The momentum impulse imparted to the NEO is thus

$$p = \int_{v_{\min}}^{\infty} v \cos \theta dM = \int_{v_{\min}}^{\infty} \frac{2v_{\min}^2 M_{ej} \cos \theta}{v^2} dv = 2v_{\min} M_{ej} \cos \theta \quad (19)$$

where θ is the angle from vertical of the ejecta spray, which we take to be $\sim 45^\circ$. Thus

$$p \approx \sqrt{2} v_{\min} M_{ej}. \quad (20)$$

By conservation of momentum, we obtain the recoil deflection velocity of an NEO of mass M_{NEO} which results from the impact:

$$\Delta v \approx \frac{M_i v_i + p}{M_{\text{NEO}} - M_{ej}} \approx \frac{M_i v_i + \sqrt{2} v_{\min} M_{ej}}{M_{\text{NEO}} - M_{ej}}. \quad (21)$$

By substituting expression (17) for M_{ej} and (16) for v_{min} , and neglecting M_{ej} compared to M_{NEO} , we can rewrite the above to obtain an expression for the ratio M_i/M_{NEO} :

$$\frac{M_i}{M_{NEO}} \approx \frac{\Delta v}{v_i} \left/ \left[1 + 0.16 \left(\frac{\rho}{\rho_i} \right) \left(\frac{\rho v_i^2}{Y} \right)^{0.209} \right] \right. \quad (22)$$

In the above expression, the numerator without the denominator gives the recoil which would result from an inelastic collision. The denominator is the "enhancement factor" which results from the added recoil from ejecta.

In Table I we list the masses required, impacting at 12 and 40 km s⁻¹, to produce a Δv of 1 cm s⁻¹ in NEOs of diameters 0.1 and 1 km diameter, and yield strengths of 10⁷ (soft rock or ice) and 10⁹ (hard rock) erg cm⁻³, respectively. We have taken $\rho = \rho_i = 2 \text{ g cm}^{-3}$ to compute these results.

TABLE I
NEO Deflection via Impact, Strength Regime for 1 cm s⁻¹ Perturbation

v_i (km s ⁻¹)	Y (dyne cm ⁻²)	M_i/M_{NEO}	M_i ($D = 100 \text{ m}$)	M_i ($D = 1 \text{ km}$)
12	10 ⁷	2.0×10^{-7}	250 kg	250 T
40	10 ⁷	4.5×10^{-8}	50 kg	50 T
12	10 ⁹	3.1×10^{-7}	450 kg	450 T
40	10 ⁹	7.6×10^{-8}	100 kg	100 T

From the above table, it is clear that the impactor mass required to deflect a 100 m NEO with a decade lead time is modest, less than 1/2 metric ton over a plausible range of strengths and impact velocities. However to deflect a 1 km NEO requires a very large impacting mass, generally hundreds of tons. As will be seen shortly, nuclear blasts offer a more economic solution for all but very small NEOs.

B. Gravity Regime

As an outgrowth of a program led by Robert Schmidt at Boeing Corporation (Seattle, WA) to study the scaling via variable gravity (centrifuge experiments) on gravity controlled impact and explosion craters, the cratering efficiency of these craters is better understood (see, e.g., Schmidt and Housen 1987; Holsapple and Schmidt 1980, 1982; Housen et al. 1983; and Holsapple 1993). They obtain the following empirical expression for the ejecta velocity distribution from impact craters where gravity dominates material strength:

$$M(>v) = 0.32 \rho R_c^3 \left(\frac{\sqrt{gR_c}}{v} \right)^{1.22} \quad (23)$$

As before, we can relate the total mass evacuated to the radius of the crater from Eq. (15). Equating $M(>v_{min})$ to M_{ej} , we can solve for v_{min} in the gravity regime:

$$v_{min} \approx 0.5 \sqrt{gR_c} \quad (24)$$

Note that this velocity is about that necessary to "hop" out of the crater from its center, and thus is in all cases less than the escape velocity from the asteroid. Because ejecta traveling at speeds less than the escape velocity will fall back on to the asteroid and not contribute to the momentum impulse, the integral analogous to Eq. (19) should be taken from a lower limit of v_{esc} , rather than v_{min} :

$$v_{\text{esc}} = \sqrt{\frac{2GM_{\text{NEO}}}{R_{\text{NEO}}}}. \quad (25)$$

Schmidt and his co-workers (see references above) also derive empirical relations for the total volume of material evacuated by impacts into various materials. For dry sand under gravity scaling, they obtain:

$$M_{\text{ej}} = 0.132M_i \left(\frac{v_i^2}{R_i g} \right)^{0.51}. \quad (26)$$

By combining Eqs. (26) and (15) into Eq. (23), we can arrive at an approximate expression for $M(>v)$ as a function of impactor mass M_i and impactor velocity, v_i :

$$M(>v) \approx 0.047 \left(\frac{\rho_i}{\rho} \right)^{0.203} M_i \left(\frac{v_i}{v} \right)^{1.22}. \quad (27)$$

The differential form of this, neglecting the factor $(\rho_i/\rho)^{0.203}$, is:

$$dM = 0.057M_i \frac{v_i^{1.22} dv}{v^{2.22}}. \quad (28)$$

The momentum impulse from the ejecta is thus:

$$p = \int_{v_{\text{esc}}}^{\infty} v \cos \theta dM = \int_{v_{\text{esc}}}^{\infty} 0.057M_i \frac{v_i^{1.22}}{v^{1.22}} \cos \theta dv = 0.26M_i \frac{v_i^{1.22}}{v_{\text{esc}}^{0.22}} \cos \theta. \quad (29)$$

Because the above integral involves velocities down to v_{esc} , the trajectories of ejecta at such low velocities are distorted, and the velocity after escape is less than that at the surface. We have numerically integrated the function with these corrections, and find for $\theta = 45^\circ$,

$$p \approx 0.16M_i \frac{v_i^{1.22}}{v_{\text{esc}}^{0.22}}. \quad (30)$$

By conservation of momentum, the recoil velocity of the asteroid is:

$$\Delta v \approx \frac{M_i v_i + p}{M_{\text{NEO}} - M_{\text{ej}}} \approx \frac{M_i v_i + 0.16M_i \frac{v_i^{1.22}}{v_{\text{esc}}^{0.22}}}{M_{\text{NEO}} - M_{\text{ej}}}. \quad (31)$$

As before, we can neglect M_{ej} compared to M_{NEO} , and rearrange Eq. (31) to obtain the ratio of impactor mass to asteroid mass to achieve a deflection velocity Δv :

$$\frac{M_i}{M_{NEO}} \approx \frac{\Delta v}{v_i} \left/ \left[1 + 0.16 \left(\frac{v_i}{v_{esc}} \right)^{0.22} \right] \right. \quad (32)$$

As with Eq. (22), the denominator is the "enhancement factor" due to recoil from ejecta.

In Table II we list the masses required, impacting at 12 and 40 km s⁻¹, to produce a Δv of 1 cm s⁻¹ in NEOs of diameters 0.1 and 1 km diameter. We have taken $\rho = 2$ to compute these results.

TABLE II
NEO Deflection via Impact, Gravity Regime for 1 cm s⁻¹ Perturbation

v_i (km s ⁻¹)	Diameter (km)	M_i/M_{NEO}	M_i
12	0.1	2.4×10^{-7}	240 kg
40	0.1	6.0×10^{-8}	60 kg
12	1.0	3.4×10^{-7}	340 T
40	1.0	8.6×10^{-8}	86 T

As with the strength regime, it is feasible to deflect a 100 m NEO by a few cm s⁻¹ with a kinetic impactor, but the masses required to deflect a 1 km object are prohibitive, compared to deflection by nuclear explosion.

B. Mass Drivers for Deflection

As a long-term response, one might imagine employing a mass driver system which is in operation for many years. For a lead time of three decades prior to Earth encounter, and assuming a constant deflecting thrust over the entire time interval, a $\Delta v \sim 0.4$ cm s⁻¹ would be required. (For a continuous acceleration, $\delta = 1/2at^2 = 1/2(at)t = 1/2\Delta v t$. Hence from Eq. (12), $\delta \sim 3\Delta v t/2$.) It might be technically feasible to deliver a reaction engine or "mass driver" to an asteroid which will launch ejecta mined from part of the asteroid. Such a device operating on a small asteroid over a decade time scale, provides the needed Δv . For an ejection velocity of ~ 0.3 km s⁻¹, the ejected mass necessary to produce a recoil of 0.4 cm s⁻¹ is

$$\Delta m \sim \frac{0.4 \text{ cm s}^{-1}}{0.3 \text{ km s}^{-1}} m_a \quad (33)$$

where m_a is the NEO mass. For a 1 km diameter, 2 g cm⁻³ density NEO, the ejected mass is 14 Ktons. Although such a system might be technically feasible, it will become clear from what follows that nuclear energy offers a much less expensive solution.

C. Momentum Transfer from a Stand-Off Nuclear Blast

One means of coupling the energy of a nuclear explosion to an asteroid to deliver a momentum impulse to the asteroid is to use a neutron (and penetrative X-ray)-rich nuclear device in the stand-off mode (Hyde 1984). Specifically, we assume that neutrons from such a device penetrate a characteristic distance $t_0 \approx 20$ cm (for a mean atomic weight of 25 and an assumed NEO density of 2 g cm^{-3}) along the line of travel in the process of being absorbed. This results from simply considering the absorption cross section of nuclei compared to their lattice spacing in typical mineral crystals. The absorption length is along the line of travel of the neutrons, thus for neutrons striking the surface at an oblique angle, the vertical depth of penetration is reduced by the cosine of the angle of incidence.

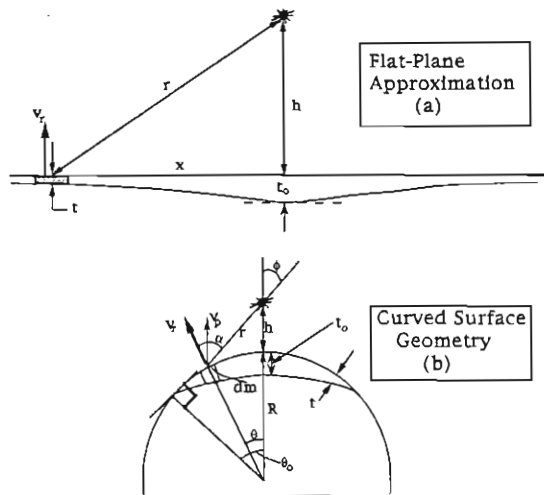


Figure 2. Geometry of deposition of nuclear explosive radiation on (a) a half-space, and (b) a spherical NEO.

From Ahrens and Harris (1992), Eqs. (9) and (10), the vertical velocity of the layer spalled off the asteroid (Fig. 3) is

$$\Delta v_r = \frac{\gamma \Delta E}{c_p} \quad (34)$$

where γ is the thermodynamic Grüneisen ratio, assumed to be near unity, ΔE is the absorbed energy density, per mass, and c_p is the sound speed in the asteroid material, typically $\sim 2 \text{ km s}^{-1}$ for rocky regolith. To evaluate the integrated momentum impulse, we need to evaluate ΔE and the depth of penetration t as a function of distance away from the sub-blast point. Consider first the flat-plane approximation, where the ratio of stand-off distance h to

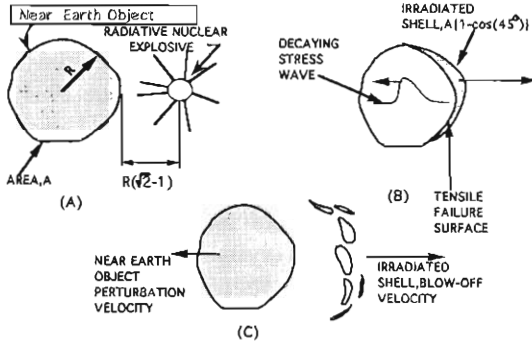


Figure 3. Sketch of the use of nuclear explosive radiation to induce a ($\sim 1 \text{ cm s}^{-1}$) velocity perturbation in a NEO. (a) Nuclear explosive designed to provide a substantial fraction of its yield as energetic neutrons and gamma rays is detonated at an optimum height $(\sqrt{2} - 1)R$, above an asteroid (see Appendix), (b) Irradiated to a depth of $\sim 20 \text{ cm}$, surface material subsequently expands and spalls away from the NEO, inducing a several kilobar stress wave in the NEO. (c) Blow-off of the irradiated shell induces a cm s^{-1} velocity perturbation in the NEO.

asteroid radius R is small, thus the surface of the asteroid can be regarded as a flat plane (see Fig. 2a).

In a ring of mass dm which lies a distance x from the sub-blast point, of width dx and thickness t , the characteristic depth of penetration of the neutrons is

$$t = t_0 \cos \phi \tag{35}$$

The angular area of the ring as seen from point of explosion is

$$dA = \frac{dx \cos \phi}{r} \cdot \frac{2\pi x}{r} \tag{36}$$

where the first term is the radial angular length and the second term is the circumferential angular length. The energy absorbed is thus

$$de = dA \cdot y / (4\pi) \tag{37}$$

where y is the neutron yield of the explosion. The mass contained in this ring is

$$dm = 2\pi \rho x t dx = 2\pi \rho x t_0 \cos \phi dx \tag{38}$$

where ρ is the density of the asteroid material, ~ 2 to 3 g cm^{-3} . The energy per unit mass in the annular volume is therefore

$$\Delta E = de / dm. \tag{39}$$

Hence,

$$\Delta E = \frac{y \cos \phi}{4\pi r^2 t_0} = \frac{y}{4\pi r^2 t_0 \rho}. \tag{40}$$

Thus the ring of matter will be ejected upward from the asteroid surface at a velocity

$$\Delta v_r = \frac{\gamma y}{4\pi r^2 t_0 \rho c_p} = \frac{\gamma y \cos^2 \phi}{4\pi h^2 t_0 \rho c_p}. \quad (41)$$

The increment of momentum impulse to the asteroid is thus $dp = dm \cdot \Delta v_r$:

$$dp = \frac{\gamma y}{2h^2 c_p} x \cos^3 \phi dx. \quad (42)$$

We can substitute $\cos \phi = h/\sqrt{h^2 + x^2}$ in the above and integrate to obtain the total momentum transfer:

$$p = \frac{\gamma y h}{2c_p} \int_0^\infty \frac{x dx}{(h^2 + x^2)^{3/2}} = \frac{\gamma y}{2c_p}. \quad (43)$$

Interestingly, almost all of the physical parameters (h , ρ , t_0) disappear from the final result. One must be careful, however, to scrutinize the resulting absolute values of the energy density ΔE and the ejection velocity, Δv_r , implied by the chosen yield and stand-off distances. In particular, ΔE should not be so large that the surface material is melted or evaporated, nor should Δv_r be less than the escape velocity from the asteroid surface.

Now consider the more general case of a stand-off distance where $h/R \sim 1$, that is, where the curvature of the asteroid surface is important (see Fig. 2b). The depth of penetration of the neutrons becomes

$$t = t_0 \cos \alpha \quad (44)$$

and the mass in a ring on the surface an angle θ away from the sub-blast point is

$$dm = 2\pi \rho t R \sin \theta R d\theta = 2\pi \rho t_0 R^2 \cos \alpha \sin \theta d\theta. \quad (45)$$

The expressions for ΔE and Δv_r remain the same as above, but with r related to h , R , and ϕ as shown in Fig. 2b. In the spherical case, the mass increment is ejected radially, but only the component of velocity Δv_p parallel to the line from the center of the asteroid to the center of the explosion will contribute recoil momentum, thus $\Delta v_p = \Delta v_r \cos \theta$. The increment of momentum becomes

$$dp = dm \cdot \Delta v_p = \frac{\gamma y}{2c_p} \left(\frac{R}{r}\right)^2 \cos \alpha \sin \theta \cos \theta d\theta. \quad (46)$$

To obtain the total momentum, this must be integrated over the entire surface exposed to radiation. Because the integration is with respect to θ , the upper limit, where $\alpha = 90^\circ$, is

$$\cos \theta_0 = \frac{1}{1 + h/R}. \quad (47)$$

We can state the result in terms of the flat plane approximation, as follows:

$$p = A \frac{\gamma y}{2c_p} \quad (48)$$

where A is a constant that tends to 1 in the limit of $h/R \rightarrow 0$:

$$A = \left(\frac{R}{R+h} \right)^2 \int_0^{\theta_0} \frac{\sin^2 \alpha \cos \alpha \cos \theta}{\sin \theta} d\theta. \quad (49)$$

Note that we have made use of the sine law of triangles to eliminate r , i.e., $r/\sin \theta = (R+h)/\sin \alpha$. We have numerically evaluated the above integral to obtain the plot of A vs h/R in Fig. 4.

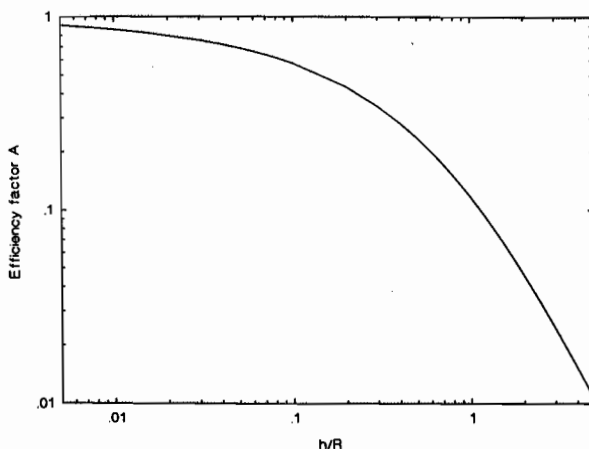


Figure 4. Geometrical efficiency factor A (Eq. 49) vs normalized elevation h/R .

We now express the neutron yield y as

$$y = nW \quad (50)$$

where W is the total explosive yield. The momentum impulse p is related to the recoil velocity of the asteroid by dividing by the mass of the asteroid:

$$\delta v = \frac{p}{\frac{4}{3}\pi\rho R^3} \approx 0.1 \frac{nAW}{D^3}. \quad (51)$$

In the approximate expression, we have inserted nominal values of the constants as mentioned above, and converted units for convenience, to asteroid diameter in km, total explosive yield W in Kt, ($1 \text{ Kt} = 4 \times 10^{19} \text{ erg}$), and δv in cm s^{-1} . For most cases of interest, the requirement that Δv_r be greater than the escape velocity from the surface is not an important limitation, nor is the

requirement that the surface not be melted. Thus one can generally employ a stand-off distance of $h/R \sim 0.4$ as suggested by Ahrens and Harris (1992) (see also the Appendix at the end of this chapter), whence $A \sim 0.3$ (Fig. 4). Therefore, to obtain a δv of $\sim 1 \text{ cm s}^{-1}$ requires $\sim 30 \text{ Kt}$ of neutron energy yield for a 1 km diameter asteroid. If the efficiency of producing neutrons n lies between 0.03 and 0.3 as suggested by Ahrens and Harris (1992), then the required total explosive yield is 0.1 to 1 Kt, 100 Kt to 1 Mt and 100 Mt to 1 Gt, to deflect 0.1, 1, and 10 km asteroids by 1 cm s^{-1} .

D. Deflection by Surface Nuclear Explosive

Another approach to the use of nuclear explosives is to use a surface charge to induce cratering on the NEO. The thrown-off ejecta effectively induces a velocity change in the NEO and the ejecta is highly dispersed and is not expected to be a hazard when it is encountered by the Earth. This method suffers the disadvantage in that the NEO may be inadvertently broken into large fragments which may represent a hazard to the Earth. For 0.1, 1, and 10 km diameter, we examine the nuclear explosive surface charge required to perturb the NEO. Again we consider explosive cratering in the cases for strength and gravity controlled cratering.

Strength Regime. There is relatively little data for mass of the ejected volume of nuclear craters in the strength regime and there are virtually no calibration experiments. Schmidt et al. (1986, p. 190) give a value of $\sim 10 \text{ kg}$ mass of excavated "dry soft rock" per kg equivalent yield of high explosive. We take "soft rock" to imply a yield strength of $\sim 10^8 \text{ dyne cm}^{-2}$. To estimate the recoil impulse of the ejecta from a surface nuclear explosion, we replace Eq. (17) by:

$$M_{ej} \approx 10 W. \quad (52)$$

Equations (14), (16), (18), and (19) are all valid for this case, changing only the above expression for M_{ej} . In Eq. (16), we use $Y = 10^8 \text{ dyne cm}^{-2}$ to evaluate $v_{\min} \approx 17 \text{ m s}^{-1}$. Because for a nuclear explosive, the "impactor mass" is negligible, the momentum Eq. (21) consists only of the recoil momentum. Neglecting the mass of the ejecta compared to that of the NEO, we obtain

$$\Delta v \approx \frac{p}{M_{\text{NEO}}} \approx \frac{\sqrt{2} \cdot 10 \cdot v \cdot W}{M_{\text{NEO}}} \quad (53)$$

and thus,

$$W \approx 4 \times 10^{-5} \Delta v M_{\text{NEO}} \quad (54)$$

where Δv is in cm s^{-1} . Hence to deflect asteroids of 0.1, 1, or 10 km diameter by 1 cm s^{-1} , explosive yields of 40 t, 40 Kt, or 40 Mt are required, respectively.

Gravity Regime. Although a large number of large-scale surface explosion experiments have been conducted in air at Earth's gravity, the effects of both reduced (and increased) gravity and reduced (from atmospheric) and increased atmospheric pressure on cratering has been studied from surface

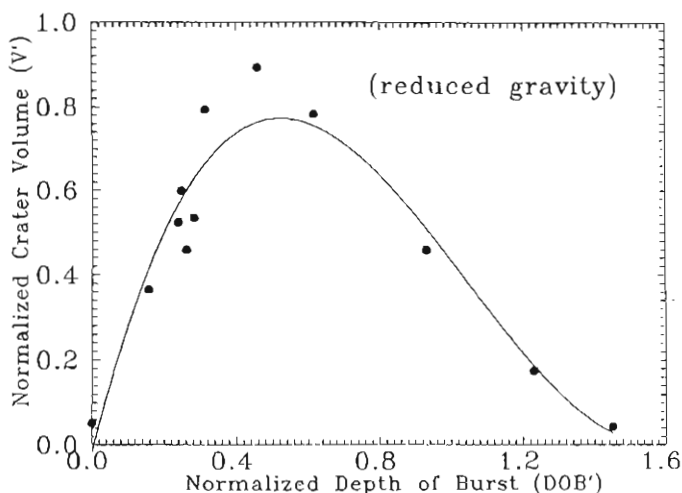


Figure 5. Normalized crater volume (Eq. [62]) vs normalized depth of burst (Eq. [60]) for 1.7 g cm^{-3} sand. Data taken by Johnson et al. (1969) at varying gravities 167, 373, 981 and 2453 cm s^{-2} . Polynomial is fit to data.

and buried explosive charges only in the laboratory. Johnson et al. (1969) first studied these effects using several gram charges and igniters at gravities varying from 167 to 2450 cm s^{-2} (Fig. 5).

Although the initial packing density of Johnson's et al.'s 1969 samples are reported as 1.7 g cm^{-3} , it appears possible that this density may have decreased substantially during the period that the test apparatus was subjected to reduced gravity. (These experiments were conducted within an aircraft flying a reduced gravity trajectory.) Moreover, the greater excavation efficiency of the propellant igniters vs detonators used in later experiments may account for the larger normalized crater volume vs depth of burst, as compared to later studies. Lower, but still highly variable, normalized crater volume cratering experiments are reported by Herr (1971) (Fig. 6). Herr conducted an extensive series of cratering tests on quartz sand and granulated carbonate material studied at variable atmospheric pressure and depth of burial.

The most extensive study of the effects of charge size, placement with respect to the free-surface, explosive type, soil density and atmospheric pressure on explosive (and impact cratering) have been conducted by Schmidt et al. (1986) and Housen et al. (1993). These data are also used to describe the effect of charge burial in the next section. On the basis of close modeling of nuclear explosion craters with small scale high explosive tests, we employ the formalism of explosive crater scaling of Holsapple and Schmidt (1980,1982) in which they define the cratering efficiency for gravity scaled cratering as:

$$\pi_v \equiv \rho V_e / W = a \pi_2^b \quad (55)$$

where a and b are constants which depend on charge type and placement, ρ

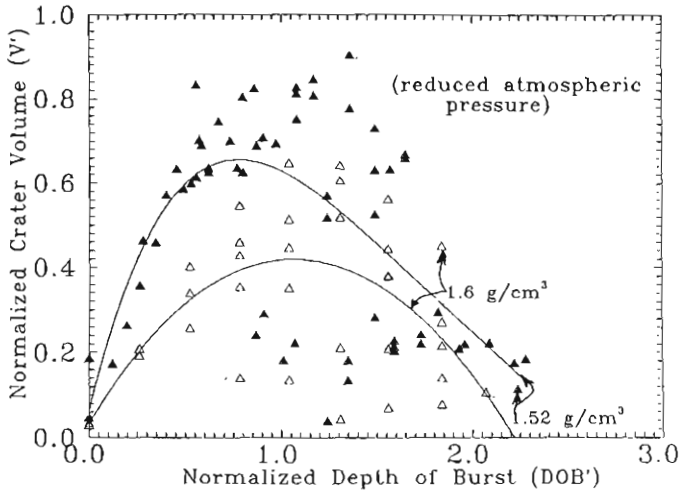


Figure 6. Herr's (1971) data for experiments in 1.52 and 1.60 g cm^{-3} granular media for varying depths of burst and atmospheric pressures. Polynomial is fit to data. Coordinates are the same as in Fig. 5.

is the mass density of the media, V_e is the crater volume, and W is explosive equivalent mass, usually of TNT. The product

$$\rho V_e = M_{ej} \quad (56)$$

is the same quantity as in Eqs. 17 and 26. Here π_2 is the gravity scaling parameter and is defined as

$$\pi_2 \equiv \frac{g}{Q} \left(\frac{W}{\delta} \right)^{1/3} \quad (57)$$

where Q is the energy content per mass of TNT, $4.2 \times 10^{10} \text{ erg g}^{-1}$, and δ is the mass density of the explosive charge.

For surface nuclear charges with high radiative outputs, the parameters a and b of Eq. 55 in the gravity regime are given by the curve of Schmidt et al. (1986, p. 192) as $a = 0.008$ and $b = -0.49$. Using Eq. (23) for the mass of ejecta traveling at velocities greater than v_{esc} , Eq. (15) and Eq. (55) in the integral analogous to that of Eq. (29) we find

$$p = \int_{v_{esc}}^{\infty} v \cos \theta dM = \cos \theta M_{ej}^{1.203} / (0.22 v_{esc}^{0.22}) \quad (58)$$

where M_{ej} is taken from Eq. 56.

Again in analogy to Eq. (31), we find

$$\Delta v = p / (M_{NEO} - M_{ej}). \quad (59)$$

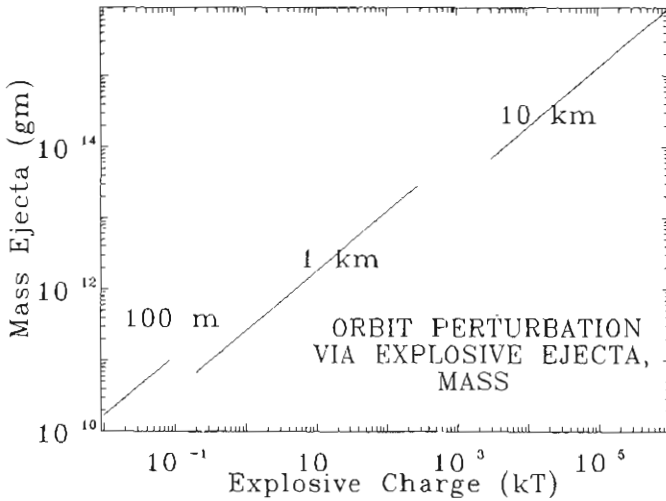


Figure 7. Mass ejecta accelerated to greater than escape velocity for cratering explosive charges on surface of 0.1, 1, and 10 km diameter NEO as a function of explosive yield.

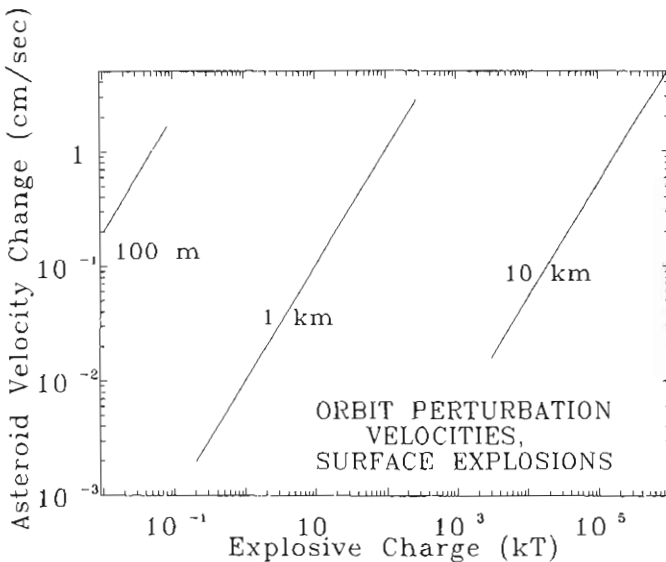


Figure 8. Resultant NEO velocity change resulting from momentum conservation vs surface charge for 0.1, 1 and 10 km objects.

The mass of ejecta and the velocity imparted to the NEO vs nuclear yield is plotted in Fig. 7 and Fig. 8. For a Δv of 1 cm s^{-1} for 0.1, 1, and 10 km NEOs require surface charges of 500 kg, 90 Kt and 0.2 Gt. These values are comparable to the yields calculated for 1 cm/sec velocity deflection via radiative stand-off explosions.

The extrapolation of cratering efficiency to the low gravity (0.003 cm s^{-2}) for a 0.1 km NEO should be regarded with caution. Moreover, whether cratering on asteroids is gravity or strength dominated may also depend on asteroid type.

Thus, surface explosions appear to be not substantially better than radiative stand-off explosions, in deflecting NEOs. However, it is clear that the knowledge requirements for surface cratering, especially with regard to material properties, for large NEO masses, are subject to greater uncertainty.

IV. DISPERSAL AND EXPLOSIVE FRAGMENTATION

Gravity Regime. By burial of a nuclear charge in a NEO, cratering efficiency can be drastically increased. There is good reason for desiring some nuclear charge burial, as surface exploded nuclear charges couple only a small fraction of their energy to rock (0.2 to 1.8%) for radiative and hydrodynamic coupling (Housen et al. 1993), whereas the large fraction of the energy of a deeply buried charge is coupled into rock. This approach can be employed with two objectives: the ejecta mass will increase down to some burial depth—however, its velocity will in general be lower and less momentum per unit of ejecta will be imparted to the NEO; secondly, the buried charge may be used to fragment and disperse the NEO.

In this section we use, as suggested by Housen et al. 1993, the normalized depth of burst, DOB' which is defined as

$$DOB' \equiv \frac{DOB}{a} \pi_2^{\alpha/3} \{1 + 0.9[P \pi_2^{\alpha/3}/(\rho g a)]^{0.7}\}^{\chi} \quad (60)$$

where DOB is the actual depth of burst, a is the radius of the equivalent sphere of TNT chemical explosive, P is the atmospheric pressure and the empirical parameter, $\alpha = 0.581$. Because nuclear explosives, in general, couple their yield less effectively than chemical explosives into Earth media we reduce nuclear yields by a factor of 1.6 when correlating to chemical explosive data. The exponent χ , is given as

$$\chi = \alpha/[0.7(3 - \alpha)]. \quad (61)$$

Similarly the normalized excavated volume V' is defined as

$$V' = \pi_v \pi_2^{\alpha} \{1 + 0.14[P \pi_2^{\alpha/3}/(\rho g a)]^{1/3}\}^y \quad (62)$$

where y is given as:

$$y = 9\alpha/(3 - \alpha). \quad (63)$$

Scaled results for small scale tests in quartz sand (1.8 g cm^{-3}), at normal and variable gravity up to $5 \times 10^5 \text{ cm s}^{-2}$ and variable atmospheric pressure, tests using a high density magnetite-bearing sand (3.08 g cm^{-3}), data from

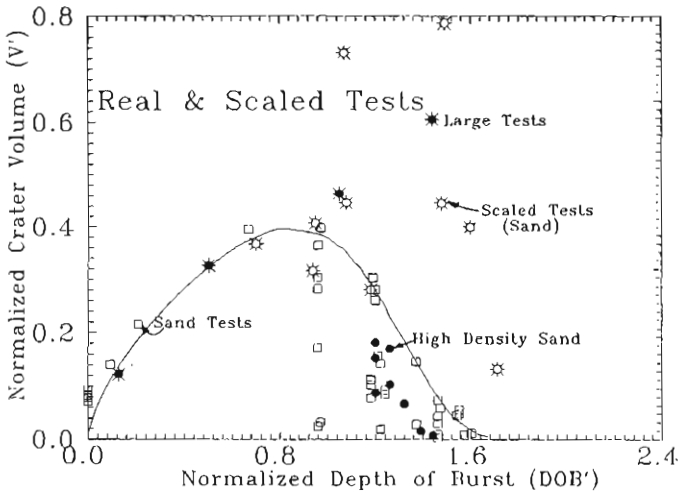


Figure 9. Housen et al.'s (1993) data for experiments in 1.8 g cm^{-3} sand, 3.1 g cm^{-3} sand, scaled laboratory (alluvium) and large scale nuclear and explosive tests. Coordinates are the same as in Figs. 5 and 6. Equation (64) is fit to these data.

large chemical (0.5 Kt-TNT) and nuclear (up to 100 Kt) explosions are shown in Fig. 9. These have been fit by Housen et al. to:

$$V' = 0.64 \log_{10} DOB' + 0.2884 - 9.7757 \times 10^{-3} / (0.6959 - \log_{10} DOB')^{7.1805}. \quad (64)$$

Figure 10 shows the equivalent radius of the mass of ejecta yielded, vs the DOB values, calculated from Eqs. (60) through (64). The peak values of each curve are those which result in "complete excavation," that is, the radius of the mass of the ejecta equals the radius of the NEO. The yield values required for an excavating charge are less by a factor of 3×10^3 to 5 in going from 0.1 to a 10 km NEO, than those calculated for fragmentation below. These charges are 800 kg for a 100 m NEO, 22 Kt for a 1 km NEO, and 0.6 Gt for a 10 km diameter NEO. The effect of gravity on the radius of excavated volumes is seen to be substantial. Notably, the optimum (largest radius of excavated volume) depth of charge decreases with increasing NEO size and surface gravity. Figure 10 also shows the radius of excavated volumes between craters on the Earth and a 10 km NEO differ by a factor of up to 5 in going from the gravity of a 10 km diameter object, 0.3 cm s^{-2} to that of the Earth (982 cm s^{-2}). Also shown is the curve of normalized charge depth vs radius of excavated volume when the slight effect of the Earth's atmosphere is taken into account.

Strength Regime. Small-scale fragmentation experiments on solid rocks demonstrate that the bulk of the fragments of a collisional disruption have velocities of $\sim 10 \text{ m s}^{-1}$. However, the "core" or largest fragment has been

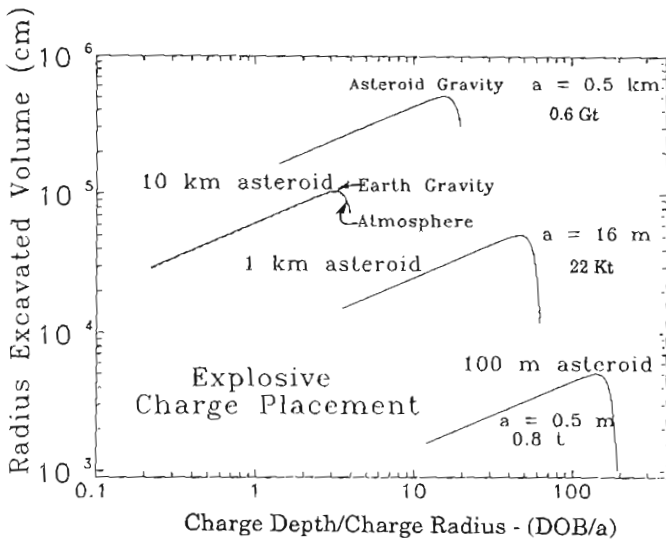


Figure 10. Radius of excavated sphere of asteroidal material for 0.1, 1, and 10 km NEO vs normalized charge depth. Effect of nominal yield explosive for each size NEO is indicated. The effect of gravity is demonstrated by the curve labeled "Earth Gravity" which gives the excavated crater volume assuming terrestrial rather than asteroidal gravity for the 10 km asteroidal case, where a 0.6 Gt explosive charge yields a radius of excavated volume of crater corresponding to spheres of 5 and 1 normalized radius on the asteroid and Earth, respectively. When the Earth's atmosphere is taken into account, the minor decrease in crater volume is indicated.

demonstrated to have a differential velocity of no more than $\sim 1 \text{ m s}^{-1}$ (see, e.g., Nakamura and Fujiwara 1991). From Eq. (2), if the body is fragmented ~ 75 days before Earth encounter then most of the $\geq 10 \text{ m}$ fragments will still impact the Earth. For a small object (0.1 to 1 km), dispersal of the bulk of the fragments into the Earth's atmosphere may be sufficient, as long as no fragments $\geq 10 \text{ m}$ are allowed. For a really large object ($> 1 \text{ km}$) fragmentation would need to be conducted one or more orbits before intersection with the Earth to assure that most fragments miss the Earth. In general, the debris cloud would spread along the orbit according to Eq. (11) and in the transverse direction according to Eqs. (3) or (4). For a characteristic velocity of ejecta of 10 m s^{-1} , the debris cloud would be $\sim 10 R_{\oplus}$ in radius (with some oscillation about the orbit) and grow in length by $\sim 200 R_{\oplus}$ per orbit period. Thus, if the NEO were destroyed one orbit before encounter, the Earth might encounter as little as 0.1% of the debris. But more conservatively, if many large fragments with $\Delta v \lesssim 1 \text{ m s}^{-1}$ remained, as much as 10% of that mass might be intercepted. Thus fragmentation is likely to be a safe choice only for long lead-time response (decades) or for relatively small bodies where the fragments may be allowed to hit the Earth.

"Catastrophic disruption" is generally defined as fragmentation where

the largest fragment is $\lesssim 1/2$ the total mass. The energy density to accomplish this decreases with increasing size of body, and becomes rather uncertain when extrapolated to 1 to 10 km size bodies (see, e.g., Housen and Holsapple 1990). However, for the present purpose, we are interested in the energy density necessary to break up a NEO so that all fragments are $\lesssim 10$ m in size. This is obviously a higher energy density than that required to just "break it in two," and we suggest that it should be of the order of the energy density needed to "break in two" a 10 m object $E_{\text{frac.}} \sim 10^7 \text{ erg g}^{-1}$.

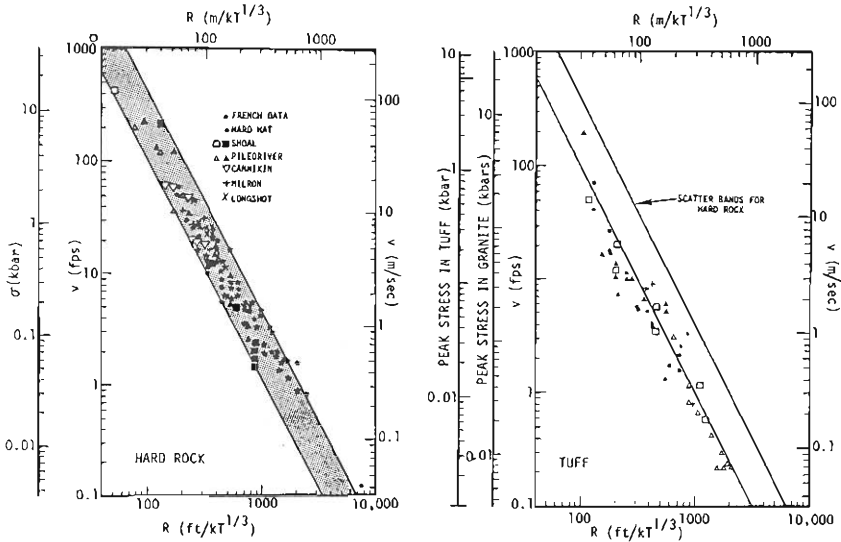


Figure 11. Particle velocity from contained explosion vs scaled radius. *Left*: hard rock; *Right*: tuff, representative of soft rock.

Because of the large energy requirements to fracture a well consolidated NEO, only nuclear explosives are considered. In order to relate the energy density as a function of radius r for a completely coupled (buried) nuclear charge of yield W , we employ the empirical relations of shock-induced particle velocity v vs energy scaled radius $r' \equiv r/(W)^{1/3}$ of Cooper (1977) (Fig. 11). For hard (mainly igneous) terrestrial rocks Cooper's compilation can be fit by

$$v \text{ (cm s}^{-1}\text{)} = 5.72 \times 10^{10} r'^{-2}. \quad (65)$$

Similarly, for soft rocks, Cooper's compilation can be fit with

$$v \text{ (cm s}^{-1}\text{)} = 2.90 \times 10^{10} r'^{-2}. \quad (66)$$

The shock wave internal energy per unit mass is equal to $v^2/2$:

$$E = v^2/2 \quad (67)$$

where v^2 can be specified by Eq. (65) or (66) and thus, $E = E_{\text{frac}} = 10^7 \text{ erg g}^{-1}$. Upon substituting Eq. (66) into Eq. (67) for 1 Kt, we find $r = 36$ m. Thus, a 1 Kt explosive is expected to fragment a 36 m radius sphere of soft rock, if the explosive is placed well within the NEO. Also, a 1 Mt charge of explosive will fragment 360 m radii of soft rock and 1 Gt of explosive will fragment 3.6 km of soft rock. In contrast, for hard rock (Eq. [65]), which describes less attenuative rock, gives a radius of fracture of 70 m for 1 Kt explosion. From Eq. (66), to deliver 10^7 erg g^{-1} to 0.1, 1, and 10 km diameter NEOs, similar to soft rock, requires 1 Kt, 1 Mt, and 1 Gt, centrally placed. For NEOs similar to hard rock 0.1, 1, and 10 km diameter require 3 Kt, 3 Mt and 3 Gt, of explosive, respectively.

The above discussion is based on the premise that the charge is buried to sufficient depth so as to obtain optimum fragmentation. Dispersal seems to require about the same energy as deflection, and also is benefited by charge burial. Hence, NEO deflection rather than destruction via fragmentation, appears to be the favorable choice.

V. MAXIMUM Δv ACHIEVABLE IN A SINGLE IMPULSE

Most of the deflection methods discussed above operate impulsively, by impacts or explosions. It is implicit in such methods that the impulse is applied unevenly throughout the NEO. Thus in the case of an incoherent NEO, various parts of the NEO will receive unequal increments of the velocity impulse; indeed the dispersion in Δv among various parts of the NEO is likely to be of the order of Δv itself. Thus the various parts of the NEO will have relative velocities with respect to the center of mass of the order of Δv . If Δv exceeds the NEO surface escape velocity, then the result of the impulse will be to disperse the various pieces of the NEO, rather than to move it coherently as a single body. If Δv is less than the surface escape velocity, then the separate pieces will not escape from one another, and deflection may occur coherently.

In the case of an initially coherent NEO, i.e., a solid rock, the shock wave propagating through the body as a result of a surface explosion or stand-off nuclear blast is likely to fracture the NEO at least into large pieces. Note that the energies calculated for comminution and dispersal of an asteroid by explosion are only about an order of magnitude greater than required to divert it by 1 cm s^{-1} . Hence even an impulsive Δv of only $\sim 10 \text{ cm s}^{-1}$ would cause major fracturing of the NEO, so that in terms of its response to such an impulse, it should behave the same as an incoherent NEO, even if it were a single coherent rock before the impulse. We can appeal to terrestrial experience in this matter. Major earthquakes can deliver an impulsive Δv of the order of 1 m s^{-1} on a time scale of 10^1 to 10^2 s, and such impulses do indeed cause 100 m objects (large buildings) to fracture and even fragment.

Thus it appears that for NEOs ≥ 100 m in diameter, the maximum single impulsive Δv that can be applied without danger of dispersing the NEO into large fragments is of the order of its surface escape velocity. This is $\sim 1 \text{ m s}^{-1}$

for a 1 km diameter NEO, and is directly proportional to diameter, i.e., ~ 10 cm s^{-1} for a 100 m NEO and ~ 10 m s^{-1} for a 10 km NEO. One can imagine that it would be desirable, indeed probably necessary, to apply several small velocity impulses to an object in order to divert it accurately. However there are limits to the number of impulses that could be economically employed, perhaps of order 10. It therefore appears reasonable to take $\sim 10v_{\text{esc}}$ as a practical limit to the Δv which can be applied for diverting a NEO of a given size.

VI. CONCLUSIONS

We have examined the velocity criteria for perturbation of the orbits of Earth-crossing objects (asteroids and comets) so as to cause objects that have trajectories which intersect the Earth to be deflected. For objects discovered only as they approach on a collision course, the velocity perturbations required are tens to hundreds of m s^{-1} . Energy levels are prohibitive for larger bodies, and the required perturbation impulse would disrupt the body as discussed above.

We also note that perturbation of an object is most effective by applying a change in velocity Δv along its original orbit and thereby inducing a change in orbital period. An impulse Δv along the line of motion provides a larger deflection δ , after time t , of the order of $3\Delta vt$.

For a ~ 100 m diameter NEO, the kinetic energy of $\sim 10^2$ to $\sim 10^3$ kg impactors, intercepting at 12 km s^{-1} will provide enough energy to crater and launch ejecta in the low gravity environment of these objects to induce velocity perturbations of in the order of 1 cm s^{-1} . For larger diameter NEOs, deflection via this method appears impractical because of the large mass of impactors required. Mass drivers require launching $\sim 10^3$ to 10^4 tons of NEO material over an interval of 30 yr prior to encounter in order to deflect a 1 km NEO from Earth impact. Nuclear explosive irradiation may be used to blow-off a surface layer from one side of the asteroid, to produce a recoil deflection velocity. Charges of 0.1 to 1 Kt, 100 Kt to 1 Mt and 100 Mt to 1 Gt of nuclear explosives are required in order to blow off a shell sufficient to perturb the velocity of 0.1, 1, and 10 km NEOs by 1 cm s^{-1} . The ranges of explosives required correspond to a radiative efficiency range 0.3 to 0.03 assumed for the nuclear explosives. Surface charges of 500 Kg, 90 Kt and 200 Mt may be used to eject crater material to greater than local escape velocity, and hence, perturb 0.1, 1, and 10 km diameter NEOs by a velocity increment of ~ 1 cm s^{-1} . These estimates are based on using radiative nuclear charges and extreme extrapolation of the effect of gravity on gravity-dependent cratering. Burial of nuclear charges to induce fragmentation and dispersal requires *in-situ* drilling which is difficult on a low gravity object or technically challenging if dynamic penetration methods are to be employed. Optimally buried cratering charges required to excavate completely (working only against local gravity) 0.1, 1, and 10 km diameter NEOs require nuclear yields of 800 kg, 22 Kt and 0.6 Gt, respectively.

Upon examining the deflection or fragmentation options, deflection appears to be the most promising goal because charge burial is not required or desirable. For a small (100 m) NEO, the kinetic energy impact deflection method is both technically feasible and does not involve the politically complex issue of placing nuclear explosives on a spacecraft. For the 1 to 10 km diameter NEO, which includes the largest Earth-crossing objects, only the nuclear option is practical. For this task, deflection via nuclear explosive radiation appears to be the simplest method. This would appear to require less detailed knowledge of the physical characteristics of an Earth-crossing object, and the development of the charges required to deflect large Earth-crossing objects appear to be technically feasible.

Finally, we should note that while further study of the feasibility of diverting NEOs may be warranted, we do not believe it is appropriate now to conduct engineering designs of systems because of: (1) the low Earth impact probability of hazardous NEOs; (2) the high cost compared to low probability; and (3) the rapid changes in defense systems technology.

Acknowledgments. Research was supported at Caltech and JPL by NASA. We appreciate the helpful comments of the reviewers. TJA benefited from the technical discussions held at the LANL/NASA Workshop on Near Earth Object Interception, January 14–16, 1992, Los Alamos National Laboratory and we both benefited from attendance at the Tucson Conference, January 5–9, 1993, on the subject of this book, and the Erice Asteroid Hazard Workshop, 28 April–4 May, 1993. We thank R. Schmidt, K. Holsapple, K. Housen, and J. C. Solem for their preprints.

REFERENCES

- Ahrens, T. J., and Harris, A. W. 1992. Deflection and fragmentation of near-Earth asteroids. *Nature* 360:429–433.
- Ahrens, T. J., and O'Keefe, J. D. 1983. Impact of an asteroid or comet in the ocean and extinction of terrestrial life. *Proc. Lunar Planet. Sci. Conf. 13, J. Geophys. Res. Suppl.* 88:799–806.
- Alvarez, L. W., Alvarez, W., Asaro, F., and Michel, H. V. 1980. Extra-terrestrial cause for the Cretaceous-Tertiary extinction. *Science* 208:1095–1108.
- Binzl, R. P., Xu, S., Bus, S. J., and Bowell, E. 1992. Origins for the near-Earth asteroids. *Science* 257:779–782.
- Blum, J. D., and Chamberlain, C. P. 1992. Oxygen isotope constraints on the origin of impact glasses from the Cretaceous-Tertiary boundary. *Science* 257:1104–1107.
- Blum, J. D., Chamberlain, C. P., Hingston, M. P., Koeberl, C., Marin, L. E., Schuraytz, B. C., and Sharpton, V. L. 1993. Isotopic composition of K/T boundary impact glass with melt rock from Chicxulub and Manson impact structure. *Nature* 364:325–327.
- Bourgeois, J., Hansen, T. A., Wiberg, P. L., and Kauffman, E. G. 1988. A tsunami deposit at the Cretaceous-Tertiary boundary in Texas. *Science* 241:561–570.
- Brett, R. 1992. The Cretaceous-Tertiary extinction—A new fatal mechanism involving anhydrite target rocks. *Geochim. Cosmochim. Acta* 56:3603–3606.

- Cooper, H. F., Jr. 1977. A summary of explosion cratering phenomena relevant to meteor impact events. In *Impact and Explosion Cratering*, eds. D. J. Roddy, R. O. Pepin and R. B. Merrill (New York: Pergamon Press), pp. 11–44.
- Covey, C., Ghan, S. J., Walton, J. J., and Weissman, P. R. 1990. Global environmental effects of impact-generated aerosols; Results from a general circulation model. In *Global Catastrophes in Earth History*, eds. V. L. Sharpton and P. D. Ward, Geological Soc. of America Special Paper 247 (Boulder: Geological Soc. of America), pp. 263–270.
- Crutzen, P. J., and Birks, J. W. 1982. The atmosphere after nuclear war: Twilight at noon. *Ambio* 11:115–125.
- Gault, D. E., Shoemaker, E. M., and Moore, H. J. 1963. *Spray Ejected from the Lunar Surface by Meteoroid Impact*, NASA TN-D-1767.
- Gerstl, S. A. W., and Zardecki, A. 1982. Reduction of photosynthetically active radiation under extreme stratospheric aerosol loading. In *Geological Implications of Impacts of Large Asteroids and Comets on the Earth*, eds. L. T. Silver and P. H. Schultz, Geological Soc. of America Special Paper 190 (Boulder: Geological Soc. of America), pp. 201–210.
- Herr, R. W. 1971. *Atmospheric-Lithostatic Pressure Ratio on Explosive Craters in Dry Soil*, NASA TR-R-366.
- Hildebrand, A. R., Penfield, G. T., Kring, D. A., Pilkington, M., Camargo, A. Z., Jacobsen, S. B., and Boynton, W. V. 1991. Chicxulub crater: A possible Cretaceous-Tertiary boundary impact crater on the Yucatan Peninsula, Mexico. *Geology* 19:867–871.
- Holsapple, K. A. 1993. The scaling of impact processes in planetary sciences. *Ann. Rev. Earth Planet. Sci.* 21:333–373.
- Holsapple, K. A., and Schmidt, R. M. 1980. On the scaling of crater dimensions, I: Explosive processes. *J. Geophys. Res.* 85:7247–7256.
- Holsapple, K. A., and Schmidt, R. M. 1982. On the scaling of crater dimensions, II: Impact processes. *J. Geophys. Res.* 87:1849–1870.
- Housen, K. R., and Holsapple, K. A. 1990. On the fragmentation of asteroids and planetary satellites. *Icarus* 84:226–253.
- Housen, K. R., Schmidt, R. M., and Holsapple, K. A. 1983. Crater ejecta scaling laws: Fundamental forms based on dimensional analysis. *J. Geophys. Res.* 88:2485–2499.
- Housen, K. R., Schmidt, R. M., Voss, M. E., and Watson, H. E. 1993. D. O. B. Scaling and Critical Depth of Burst for Cratering (Seattle: Boeing Corp.), DNA-TR-92-024.
- Hyde, R. A. 1984. Cosmic Bombardment. Lawrence Livermore National Lab Internal Rept. UCID-20062.
- Johnson, S. W., Smith, J. A., Franklin, E. G., Moracki, L. K., and Teal, D. J. 1969. Gravity and atmospheric pressure effects on crater formation in sand. *J. Geophys. Res.* 74:4838–4850.
- MIT Students. 1968. *Project Icarus* (Cambridge, Mass.: The MIT Press).
- Morrison, D., ed. 1992. *The Spaceguard Survey: Report of the NASA International Near-Earth-Object Detection Workshop* (Pasadena: Jet Propulsion Laboratory).
- Nakamura, A., and Fujiwara, A. 1991. Velocity distribution of fragments formed in a simulated collisional disruption. *Icarus* 92:132–146.
- O'Keefe, J. D., and Ahrens, T. J. 1982. Cometary and meteorite swarm impact on planetary surfaces. *J. Geophys. Res.* 87:6668–6680.
- O'Keefe, J. D., and Ahrens, T. J. 1989. Impact production of CO₂ by K-T extinction bolide and the resultant heating of the Earth. *Nature* 338:247–249.
- Pike, R. J. 1980. Control of crater morphology by gravity and target type: Mars, Earth, Moon. *Proc. Lunar Planet. Sci. Conf.* 11:2159–2189.

- Rather, J. D. G., Rahe, J. H., and Canavan, G., eds. 1992. *Summary Report of the Near-Earth-Object Interception Workshop* (Washington, D. C.: NASA).
- Schmidt, R. M., and Housen, K. R. 1987. Some recent advances in the scaling of impact and explosion cratering. *Intl. J. Impact Eng.* 5:543-560.
- Schmidt, R. M., Holsapple, K. A., and Housen, K. R. 1986. Gravity effects in cratering. In *Pacific Enewetak Atoll Crater Exploration (PEACE) Program Enewetak Atoll, Republic of the Marshall Islands* (Seattle: Boeing Corp. and Defense Nuclear Agency), DNA-TR-86-182.
- Scotti, J. V., Rabinowitz, D. L., and Marsden, B. G. 1991. Near miss of the Earth by a small asteroid. *Nature* 354:287-289.
- Sharpton, V. L., Dalrymple, G. B., Marin, L. E., Ryder, G., Schuraytz, B. C., and Urrutia-Fucugauchi, J. 1992. New links between the Chicxulub impact structure and the Cretaceous-Tertiary boundary. *Nature* 359:819-821.
- Shoemaker, E. M. 1983. Talk presented at Collision of Asteroids and Comets with the Earth: Physical and Human Consequences, July 13-16, Snowmass, Colo.
- Shoemaker, E. M., Wolfe, R. F., and Shoemaker, C. S. 1990. Asteroid and comet flux in the neighborhood of Earth. In *Global Catastrophes in Earth History*, eds. V. L. Sharpton and P. D. Ward, Geological Soc. of America Special Paper 247 (Boulder: Geological Soc. of America), pp. 155-170.
- Sigurdsson, H., D'Hondt, S., and Carey, S. 1992. The impact of the Cretaceous/Tertiary bolide on evaporite terrane and generation of major sulfuric acid aerosol. *Earth Planet. Sci. Lett.* 109:543-559.
- Smither, C. L., and Ahrens, T. J. 1992. Melting, vaporization, and energy partitioning for impacts on asteroidal and planetary objects. In *Asteroids, Comets, and Meteors 1991*, eds. A. W. Harris and E. Bowell (Houston: Lunar and Planetary Inst.), pp. 561-564.
- Solem, J. C. 1991. Nuclear Explosive Propelled Interceptor for Deflecting Comets and Asteroids on a Potentially Catastrophic Collision Course with Earth. Los Alamos National Lab Rept. LA-UR-91-3765.
- Solem, J. C. 1992. Interception of Comets and Asteroids on Collision Course with Earth. Los Alamos National Lab Rept. LA-UR-231.
- Swisher, C. C., III, Grajales-Nishimura, J. M., Montanari, A., Margolis, S. V., Claeys, P., Alvarez, W., Renne, P., Cedillo-Pardo, E., Maurrasse, F. J.-M. R., Curtis, G. H., Smit, J., and McWilliams, M. O. 1992. Coeval $^{40}\text{Ar}/^{39}\text{Ar}$ ages of 65.0 million years ago from Chicxulub crater melt rock and Cretaceous-Tertiary boundary tektites. *Science* 257:954-958.
- Toon, O. B., Pollack, J. B., Ackerman, T. P., Turco, R. P., McKay, C. P., and Liu, M. S. 1982. Evolution of an impact-generated dust cloud and its effects on the atmosphere. In *Geological Implications of Impacts of Large Asteroids and Comets on the Earth*, eds. L. T. Silver and P. H. Schultz, Geological Soc. of America Special Paper 190 (Boulder: Geological Soc. of America), pp. 187-200.
- Turco, R. P., Toon, O. B., Ackerman, T. P., Pollack, J. B., and Sagan, C. 1990. Climate and smoke: An appraisal of nuclear winter. *Science* 247:166-176.
- Veverka, J., and Harris, A. W. 1986. Near Earth Asteroid Rendezvous (NEAR) Science Working Group Report. (Pasadena: Jet Propulsion Laboratory), JPL-86-7.
- Vickery, A. M., and Melosh, H. J. 1990. Atmospheric erosion and impactor retention in large impacts, with application to mass extinctions. In *Global Catastrophes in Earth History*, eds. V. L. Sharpton and P. D. Ward, Geological Soc. of America Special Paper 247 (Boulder: Geological Soc. of America), pp. 289-300.
- Weissman, P. R. 1990. The cometary impactor flux at the earth. In *Global Catastrophes in Earth History*, eds. V. L. Sharpton and P. D. Ward, Geological Soc. of America Special Paper 247 (Boulder: Geological Soc. of America), pp. 171-180.

APPENDIX

Analytic Derivation of "Optimum Stand-Off Distance" h

The solid angle subtended by a cone of apex half-angle θ is $2\pi(1 - \cos \theta)$, or in units of the total unit sphere, $(1 - \cos \theta)/2$ (Fig. 12). Thus the fraction of the NEO surface which is irradiated by a nuclear explosion at a stand-off distance h is

$$F = \frac{1}{2}(1 - \cos \theta). \quad (\text{A1})$$

Similarly, the fraction of the radiative yield that intercepts the NEO surface is

$$f = \frac{1}{2}(1 - \cos \phi) = \frac{1}{2}(1 - \sin \theta). \quad (\text{A2})$$

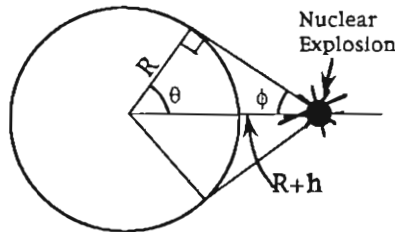


Figure 12. Geometry for calculating the optimum stand-off height h to deflect an NEO of radius R using the scheme shown in Fig. 3.

One criterion for an "optimum stand-off distance" h might be the distance at which the product $F \cdot f$ is maximum. Hence

$$\frac{d}{d\theta}(fF) = \frac{df}{d\theta}F + f \frac{dF}{d\theta} = 0. \quad (\text{A3})$$

This reduces to the following equation:

$$\sin \theta - \sin^2 \theta = \cos \theta - \cos^2 \theta. \quad (\text{A4})$$

The solution of interest is $\theta = 45^\circ$, when $f = F = (1 - \cos 45^\circ)/2 = 0.146$ and $h = (\sqrt{2} - 1)R$, or $h/R = 0.414$. In Fig. 13, we show f , F , and the product $F \cdot f$ vs the stand-off distance ration h/R . It should be noted that the above criterion is not a rigorous condition. For example, to deflect a very small asteroid, it is likely that the explosive yield required would be small, but the Δv required may be close to the limit that would fracture and disperse the asteroid, thus it may be better to use a larger explosive yield at a larger stand-off distance in order to push as gently as possible on the largest possible

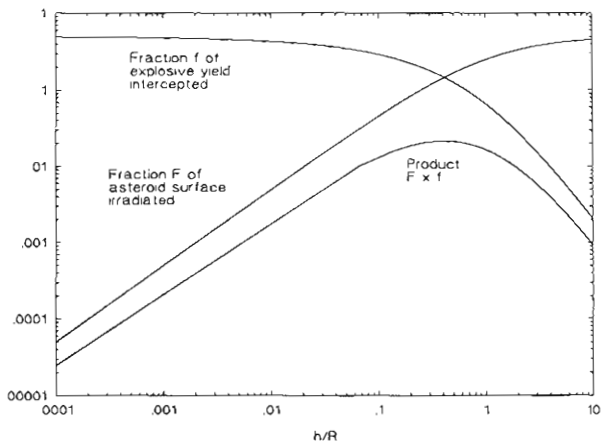


Figure 13. Fraction f and F of the explosive yield intercepted by an NEO and of the NEO surface irradiated, vs normalized height h/R . Also shown is the product $f \times F$ vs h/R .

fraction of the asteroid's surface. Conversely, for a very large asteroid, it is more likely that the required Δv would be only a small fraction of that which would disrupt the body, but the total yield required would be large. Thus, in this case, it may be more efficient to use a lower stand-off distance to achieve a higher fraction of the yield intercepted by the asteroid.