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WHAT CAN WE DO ABOUT IT?

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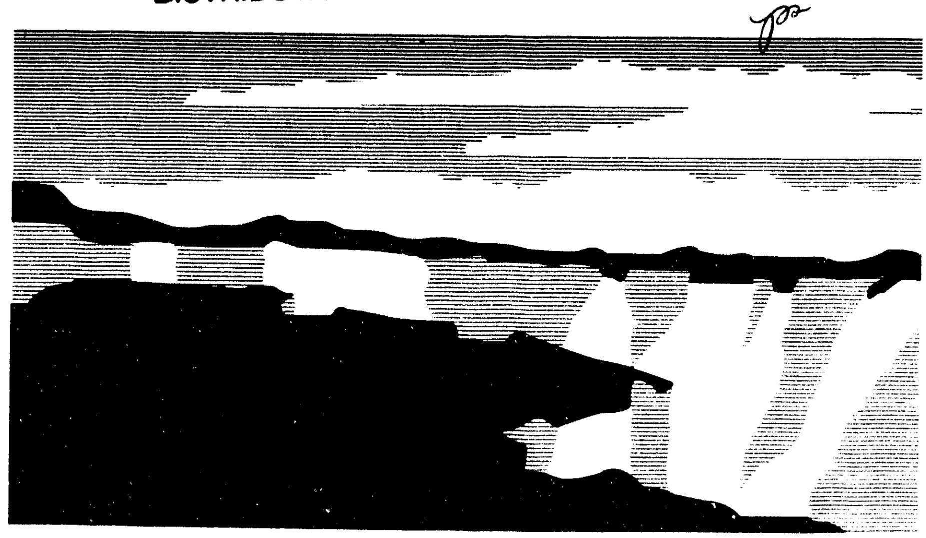

Los Alamos
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WHAT CAN WE DO ABOUT IT?

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The requirements for intercept have been defined. Most can be met with existing technology. There are significant uncertainties in coupling efficiency and fragmentation limits. The best approach depends on warning, NEO size and composition, and cost. Optimal defenses generally involve both detection and defense. They are effective to large diameters and justify expenditures on the order of $50-100M/yr. Flyby and landing precursor experiments are scientifically justified. Coupling and deflection experiments are also needed and feasible.

This talk discusses what can be done about Near-Earth Object (NEO) impacts. It is based on the Congressionally mandated, NASA Sponsored NEO Interception Workshop held at Los Alamos,[1] the Meeting on Hazards Due to Comets and Asteroids at the University of Arizona,[2] and the International Meeting on NEO Hazards in Erice. It covers the main issues in acquisition, track, and homing on NEOs; the astrodynamics of interception; intercept vehicles and payloads; energy delivery; and materials interaction. It summarizes what each technology could do about threatening NEOs and indicates appropriate directions for research to improve those capabilities. It also indicates the combinations of detection and deflection that are cost effective for NEOs detected on final approach or many orbits before impact.

Acquisition, Tracking, and Homing. The Interception Workshop assumed NEOs would be discovered by visible telescopic searches several orbits ahead of impact and then reacquired for tracking sensors prior to intercept. Radars could be quite valuable because they measure distances precisely out to ranges of a few tenths of an AU. Thus, they can make rapid and precise orbit determinations. However, radars only secure about 10% of current discoveries. Several large radars in the Northern and Southern hemispheres would be needed to handle the 1000 per month discovery rate expected from Spaceguard. Radar absorption measurements would complement visible reflectivity measurements and doppler imaging would also be useful for irregular or asymmetric bodies. Once the NEO is re-acquired, current telescopes and radars could track it to the point of handover to on-board sensors for rendezvous or impact. Homing could be done with modest optical or radar sensors, which could evolve from DoD programs. There are problems, e.g., coma could obscures a comet's nucleus until too late for closing maneuvers, which could require auxiliary probes.

Astrodynamics of Interception. The astrodynamics and guidance required for NEO interception is standard, but is complicated by the long ranges at which intercepts take place, the uncertain NEO orbits, the high inclinations involved—especially for long-period comets

(LPCs)—and the large velocity changes required for many intercepts. Each of these considerations put a premium on discovery many orbits before impact. For low-inclination NEOs, the intercept trajectory can approximate a minimum energy transfer, so the payload delivered can be substantial. For high-inclination NEOs and modest warning, it may be necessary to supply a large divert velocity. For 15 degree inclination, the divert would be about as large as that required to reach low-Earth orbit (LEO) in the first place. Larger diverts could be prohibitive even for small precursor packages. For such missions, more complex gravity assisted trajectories could be followed, if warning time permits.

Available Vehicles and Payloads. For precursor missions to determine NEO composition and strength, there are a number of capable, lightweight packages, such as the DoD Clementine passive and active visible and infrared sensor package, which can be flown on Pegasus, Scout, or MMII/III boosters for various missions. Such packages could support flyby missions within months to measure surface structure and rendezvous missions with about a year for the determination of internal composition and strength. However, that there are no payloads available for fast, highly inclined NEOs, which require packages with transponders and seismic sensors that weigh a few kilograms and last for decades. Intercept missions with either kinetic or explosive payloads would have to be carried on heavy lift vehicles. Titan IV can put about 20 tons and Energia about 100 ton in low-Earth orbit (LEO), which would support intercept payloads at low inclinations of perhaps 2 to 10 tons. While larger launch capacities would be useful, multiple launches could be used for larger NEOs without requiring assembly on orbit.

Energy Delivery and Materials Interaction. There is a range of interaction technologies available for deflecting or fracturing NEOs. Each has advantages and disadvantages. Starting with the lowest thrust, solar sails have the lowest power requirements, but require the longest times to accomplish deflection. Rocket thrusters are the most developed, but require the most mass for a given deflection. A mass driver, such as a railgun, eliminates the need to carry the expellant mass, but requires the interceptor to rendezvous with and soft land on the NEO to operate. Using the outgassing from the NEO itself eliminates mass and power, but may not be available on all NEOs.

Kinetic energy deflection operates by maneuvering the interceptor into a position where it is run over by the NEO. At a relative velocity of 30 km/s, its impact releases an energy density about 100 times that of high explosive (HE). That ejects a large amount of mass, whose reaction deflects the NEO in the opposite direction. This process can be efficient, but it is difficult to spread the delivered energy around smoothly, so irregular NEOs could be deflected in the wrong direction or fragmented into many pieces.

Nuclear explosives also deflect by ejecting mass, but have a specific energy density about a million times that of HE. Since the deflection velocity scales directly with this energy density, nuclear explosives can generate deflections about a million times larger than chemical thrust or 10,000 times larger than kinetic energy. That advantage can be very important for large NEOs, for which the energies and masses approach those that can be put into deep space. Nuclear explosives share kinetic energy's fragmentation and spall limitations. They have several modes of operation. They can be buried for maximum impulsive efficiency, although that requires penetrating unknown, structured NEOs. They can more easily be placed on the surface, although that involves a penalty in efficiency of about a factor of 10. They can standoff about a NEO radius. That produces more uniformly irradiation, but reduces coupling efficiency by about another factor of 10.

Which technology is best depends on the specific engagement and warning time, NEO size and composition, and the costs of various interception technologies, but a few trends are clear from the above discussion. Small objects and long warning permit deflection by kinetic energy, mass drivers, etc. Large objects and shorter warning times require large kinetic energy impactors or nuclear explosives.

Deflections. These trends can be made more quantitative by calculating how large a NEO each technology could deflect enough to miss the Earth, given a 5 ton payload in deep space. Figure 1 shows these maximum diameters for reaction times of days to centuries. For times greater than about 10 years, the curves merge into three groups. The top curve is for deflection with a subsurface nuclear explosion. With 100 years to react, it could deflect a ≈ 100 km NEO. With 10 years to react, it could deflect about a 30 km NEO. At about 10 years, the nuclear subsurface curve divides into two branches. The upper curve is for a rocket with a very high specific impulse. The lower curve is for the specific impulse of current chemical fuels. Higher specific energy fuels are useful for short warning times because they support deflection at longer ranges, which maximizes the deflection possible from a given interceptor mass. The next line down is for standoff nuclear explosives. It is about a factor of 3 below that for subsurface bursts because of the factor of ≈ 30 coupling efficiency reduction for standoff. However, given 10 years warning, standoff could still deflect a ≈ 10 km NEO.

The next line is for kinetic energy impact. It is about an order of magnitude below that for standoff nuclear for a warning time of a decade, where it could deflect a ≈ 2 km NEO. For shorter times, the high specific energy kinetic impact curve falls above that for standoff nuclear explosives on current boosters. The curve for current fuels lies several orders of magnitude below. The curve for mass drivers lies lower still. They could only deflect 100 m NEOs for warning times of a year, but could approach ≈ 1 km NEOs in a decade and ≈ 3 km in a century.

Uncertainties. There are significant uncertainties in each of the deflection technologies. For kinetic energy the main uncertainty is how to deliver energy usefully. That has three parts: how to deposit the energy deep enough to be useful, how to distribute it so the NEO will be deflected rather than fragmented, and how to deliver energy to the proper area so that the NEO will be deflected in the desired direction, which is particularly difficult for very asymmetric objects. While the coupling efficiency can probably be bounded by a factor of 2-4 uncertainty, the distribution and direction issues have yet to be bounded. For nuclear explosives, there are four issues. The first is whether it is possible to penetrate to the depth required for optimal expulsion in NEO material of unknown composition. The second is whether it is possible to penetrate to even the modest depths required for good coupling in chondritic and metallic NEOs. The third is the coupling efficiency for surface explosions, which is known only for the Earth's surface. The fourth is the actual coupling penalty for standoff explosions, which have been studied primarily in the short-warning, high-fluence limit, whereas most applications appear to lie in the long-warning, low-fluence region. Any of these effects might contribute an order of magnitude uncertainty to the overall coupling, which would lead to about a factor of two uncertainty in the NEO diameters shown in Fig. 1. There is an additional order of magnitude uncertainty due to questions about the maximum energy that can be delivered per explosion without fragmenting the NEO into a unmanageable swarm of smaller objects. However, such limits on the energy delivered per explosions could apparently be compensated for to some extent by using a larger number of smaller explosions with the same total yield.

What should we do? The previous sections discussed what could be done about threatening NEOs without consideration of whether the measures would be cost effective. To address that it is necessary to answer three more questions. The first is what the loss would be if nothing was done—which is also the benefit that would be gained by doing something. The second is what it would cost to do that something. The third is whether the marginal benefits of doing something are greater than the marginal costs of doing so.

Figure 2 shows the benefits of providing defenses as a function of NEO diameter. The benefits of defenses are estimated from the losses expected in their absence, i.e., the product of the collision frequency, the area damaged, and the value per unit area, summed over diameters. There are four main contributions. Below 50 m damage is done by small metallic NEOs that penetrate the atmosphere. The ≈ $10M/yr losses shown correspond to current interpretations of Spacewatch data. Earlier Spacewatch data indicated losses an order of magnitude higher; lunar crater data indicate losses an order of magnitude lower; data from defense sensors are intermediate. From 50 to 250 m losses are dominated by stony asteroids. They total to about those from the metallics. The ≈ $100M/yr losses from 250 m to 2 km NEOs are dominated by tsunamis from impacts in the ocean; losses from impacts on land are about an order of magnitude lower. Above 1-2 km the losses are potentially global and catastrophic. The ≈ $500M/yr losses there are estimated from the cost of evacuating those in the impact region and providing supplies for the decades that might be required for the return of habitability in the absence of defenses.

Determining what it would cost to provide defenses involves several steps. The first is estimating the cost of detection as a function of the range at which it is performed and differentiating it to determine the marginal cost of detection. The second is parameterizing the cost of deflection versus range and differentiating it to determine the marginal cost of deflection. The third is equating the marginal costs of detection and deflection to determine the optimal combination for each NEO diameter and the marginal cost of the combination.

These marginal benefits and costs are shown on Fig. 3. The down-sloping squares are the marginal benefits obtained by differentiating the curve on Fig. 2, which highlights the four major contributions. The solid lines are the costs of optimized defenses for four estimates that differ by factors of 10. The bottom curve is for nominal costs. It intersects the marginal benefit curve at about 8 km, which means that for nominal parameters, defenses would be effective for NEOs up to about the size of the K-T impactor. The integral of the marginal cost up to the intersection gives ≈ \$50-100M/yr as the amount that could be spent effectively on such defenses. If costs were a factor of 10 higher, defenses would still be effective for NEOs with diameters up to about 3 km. Another factor of 10 increase in costs would make defenses ineffective for all but the small metallic asteroids, for which the integrated costs only justify a program of ≈ \$10M/yr.

Detection on prior orbits. The previous section discussed defenses against NEOs detected on final approach. That analysis can be extended to systems that detect and deflect NEOs many orbits before impact. The first step is to paramaterize the search system detection radius and volume. The second is to use that radius to derive the NEO's probability of detection per orbit. The third is to compound that probability to determine the probability that a NEO will impact without detection as a function of radius. The forth is to differentiate that result with respect to radius to determine the expected marginal losses. Equating those marginal losses to the marginal benefits determines an optimal search radius of ≈ 1.5 AU, which is about that proposed for Spaceguard. It also indicates that the net benefits of such a system would increase rapidly in about 10-30 NEO orbits, or about 40-120 years, which indicates that both detection and interception should be developed in the next few decades to properly support such a defense.

Directions for Research are indicated by the uncertainties discussed above. They include the integrated design of precursor and intercept missions, better models of and information on NEOs, and calculations with real NEO material properties. There is also a need for experiments, which should involve flyby and rendezvous precursor experiments. Before requirements can be defined to better than an order of magnitude, it will also be necessary to perform coupling and deflection experiments in space. There is a recognition that many intercepts require nuclear explosives, but there is a reluctance to propose such experiments in space. It appears that kinetic energy coupling and deflection experiments could both resolve the uncertainties for kinetic deflection and provide valuable interim information on nuclear deflection.

Summary and conclusions. The requirements for intercepting NEOs have been defined roughly. Acquisition, tracking, and homing can be treated by standard telescopes and radars and that astrodynamics and guidance are standard, apart from long ranges and inclined orbits, which put a premium on early detection. Vehicles and payloads are available for most precursor and intercept missions. There is a range of technologies for energy delivery and materials interaction, which is the most uncertain area. The best approach depends on NEO size, composition, warning, and cost. There are significant uncertainties in coupling efficiency and fragmentation limits that apply to all impulsive concepts including kinetic and nuclear energy.

Optimal combinations of detection and deflection for NEOs on final approach are not sensitive to cost and performance parameters. Defenses are effective to diameters of 4-8 km and justify expenditures on the order of $50-100M/yr. Defenses that detect NEOs many orbits prior to impact are cost effective for large NEOs, justify similar expenses, and would be appropriate within decades. There are a number of uncertainties that need to be resolved before requirements could be defined to better than an order of magnitude. Some involve theory or laboratory experiments; others involve experiments in space. Flyby and landing precursors are scientifically justified. Coupling and deflection experiments are needed; kinetic energy experiments could arguably provide much needed interim data.

References

1. G. Canavan, J. Solem, and J. Rather, *Proceedings of the NEO Interception Workshop* , Los Alamos National Laboratory report LA-12476-C, February 1993.

2. T. Gehrels ed, *Hazards Due to Comets and Asteroids,* in press.

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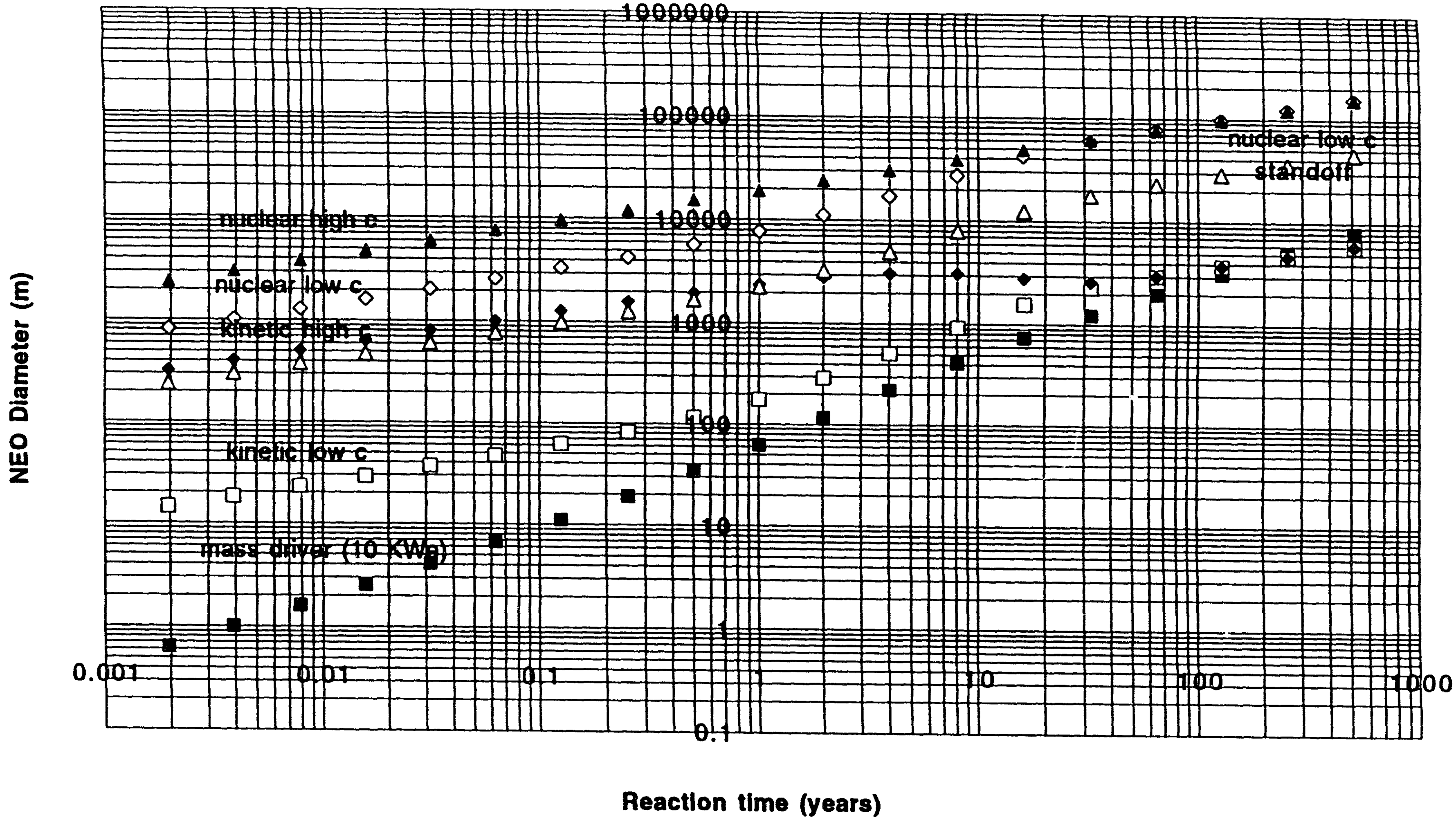
Fig. 1.


1000000
100000
10000
1000
100
10
1
0.1
0.001
0.01
0.1
1
10
100
1000
nuclear high c
nuclear low c
kinetic high c
kinetic low c
mass driver (10 KWe)
nuclear low c
standoff
NEO Diameter (m)
Reaction time (years)

F.8 C-B integral losses all NEO

Fig, 2

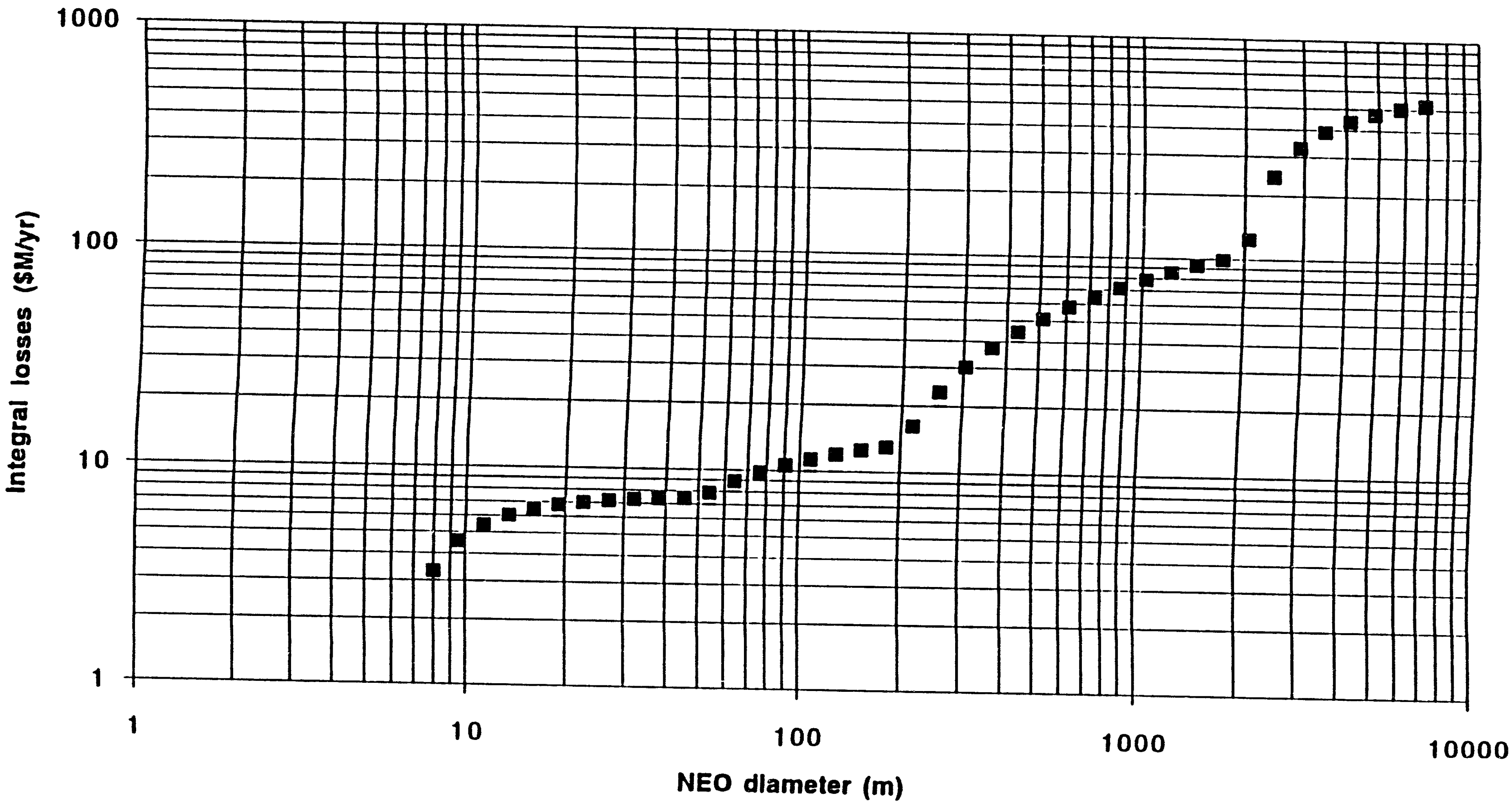
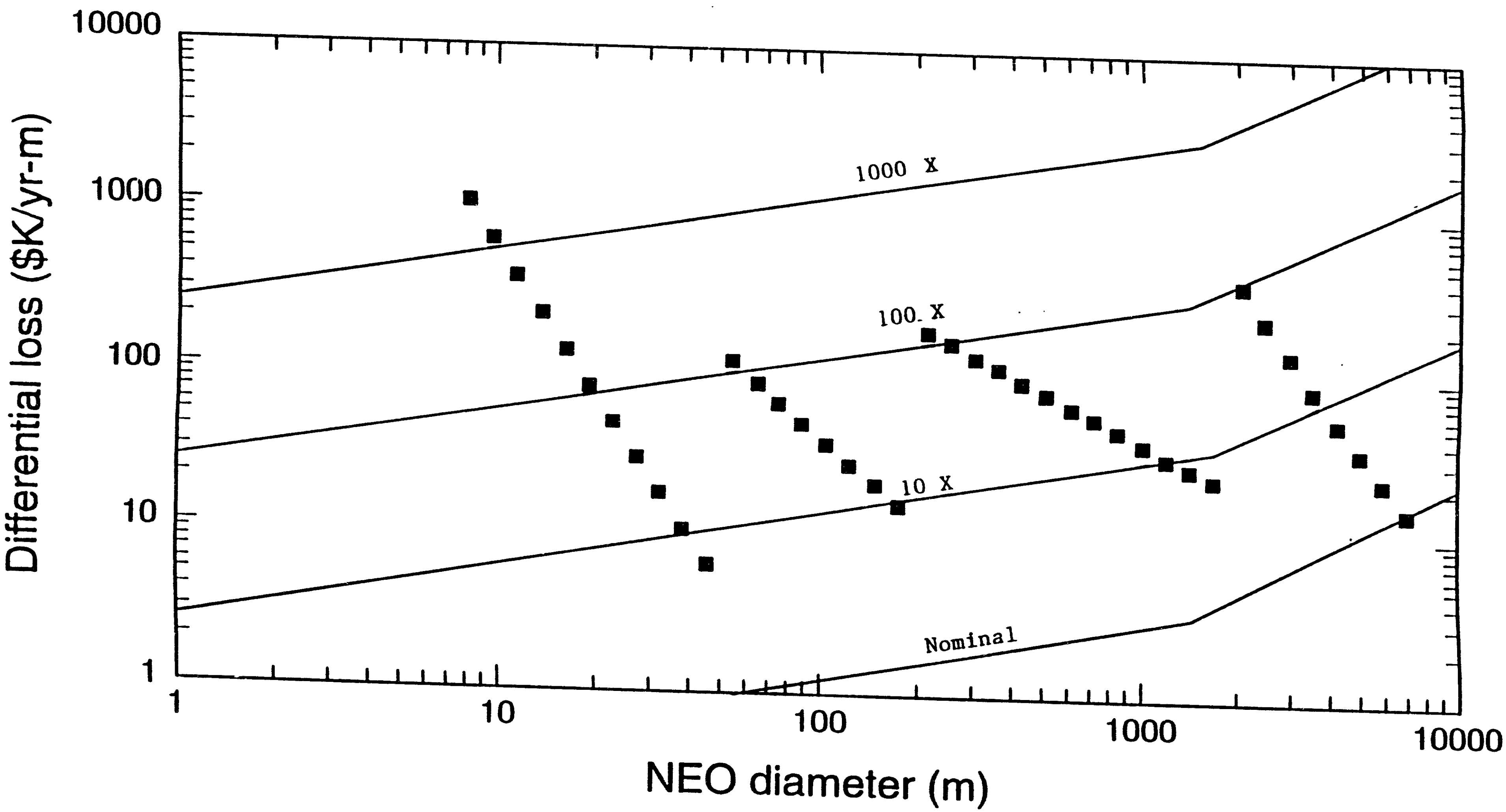


Fig. 3


Differential loss ($K/yr-m)
10000
1000
100
10
1
1000 X
100. X
10 X
Nominal
1
10
100
1000
10000
NEO diameter (m)

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