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A Comprehensive Program for Countermeasures Against Potentially Hazardous Objects (PHOs)

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Abstract. At the hundredth anniversary of the Tunguska event in Siberia it is appropriate to discuss measures to avoid such occurrences in the future. Recent discussions about detecting, tracking, cataloguing, and characterizing near-Earth objects (NEOs) center on objects larger than about 140 m in size. However, objects smaller than 100 m are more frequent and can cause significant regional destruction of civil infrastructures and population centers. The cosmic object responsible for the Tunguska event provides a graphic example: although it is thought to have been only about 50 to 60 m in size, it devastated an area of about 2000 km^2. Ongoing surveys aimed at early detection of a potentially hazardous object (PHO: asteroid or comet nucleus that approaches the Earth's orbit within 0.05 AU) are only a first step toward applying countermeasures to prevent an impact on Earth. Because "early" may mean only a few weeks or days in the case of a Tunguska-sized object or a long-period comet, deflecting the object by changing its orbit is beyond the means of current technology, and destruction and dispersal of its fragments may be the only reasonable solution. Highly capable countermeasures – always at the ready – are essential to defending against an object with such short warning time, and therefore short reaction time between discovery and impending impact. We present an outline for a comprehensive plan for countermeasures that includes smaller (Tunguska-sized) objects and long-period comets, focuses on short warning times, uses non-nuclear methods (e.g., hyper-velocity impactor devices and conventional explosives) whenever possible, uses nuclear munitions only when needed, and launches from the ground. The plan calls for international collaboration for action against a truly global threat.

1. Introduction.

A new search program to be initiated by NASA will identify, track, and catalog 90 % of potentially hazardous objects (PHOs: asteroids and comet nuclei that approach the Earth's orbit within 0.05 AU and could collide with Earth) larger than 140 m in size. However, just as objects less than 1 km in size were found in the first survey for objects larger than 1 km, so objects smaller than 140 m will be found in the new survey. More importantly, objects smaller than a few hundred meters are of significant interest because they are several 100 to 1000 times more numerous than kilometer-sized objects, are fainter and more difficult to detect, and will likely provide much shorter warning times between discovery and impact. Despite their size, even the smallest of these PHOs can have devastating effects, as the Tunguska event of 30 June 1908 has shown. In addition, threats from long-period comet nuclei, although relatively rare but large (sometimes tens of kilometers in size), cannot be accurately predicted because of their long orbital periods and rapid transit times through the inner solar system. As an example, Comet C/1983 H1 (IRAS-Araki-Alcock), which was discovered on 27 April 1983 and has an orbital period of 963.22 years, had a close encounter with the Earth only two weeks later, on 11 May 1983, at a distance of 0.0312 AU. Two other long-period comets came even closer to Earth: D/1770 L1 Lexell at 0.0151 AU and 55P/1366 U1 Tempel-Tuttle at 0.0229 AU.

Setting aside the societal implications of impacts, astronomers have argued that asteroids and comet nuclei are the remnants of planet formation (Marov, this conference; Shustov and Rykhlova, this conference) and have collided with planets throughout the history of our planetary system. The evidence is clear from the impact craters on the Moon, Mars, Mercury, and other moons in our solar system, as well as from over 160 identified impact craters on Earth. These impacts have occurred throughout the history of our planetary system and indeed still occur. The Tunguska event in Siberia and the collision of Comet Shoemaker-Levy 9 with Jupiter in 1994 are reminders and warning signals that we should take seriously. The extinction of the dinosaurs has been attributed to the impact of a large asteroid or comet nucleus on Earth (Bottke et al., 2007). Zaitsev (2006) has listed six objects that passed between Earth and the Moon since 1991. Two large asteroids, several hundred meters in size, 2004 MN4 = 99942 Apophis and 2004 VD17, will approach the Earth on 19 March 2029 and 4 May 2102, respectively. Besides the Tunguska event, there were several other notable, although smaller events in the last hundred years: On 13 August 1930 in Curuçá, Amazonas, Brazil; on 12 February 1947 in Sikhote-Alin, Russia; on 24 September 2002 in Vitim, Bodaybo, Russia; and on 15 September 2007 in Alta Plana, near Lake Titicaca in Peru. We must not ignore these warning shots!

Others have argued that there are many natural disasters such as hurricanes, typhoons, tornados, earthquakes, tsunamis, and volcanic eruptions that occur much more frequently than impacts of cosmic objects with the Earth. Thus it would behoove us to concentrate our attention on avoiding catastrophes from such events. Three facts undermine this argument. First and perhaps most important, it considers only the probability aspect of risk assessment. Risk assessment requires that likelihood and consequence be convolved. Because the potential consequence of PHOs is so great, consideration of probability alone is not appropriate (Chapman and Mulligan, 2002). Second, prevention of catastrophic loss from other natural events is based almost entirely on early warning systems. Similarly, such warning systems for PHO detection are in place and are being further improved to identify smaller objects, down to about 140 m in size. Third, there are no known or likely forceful countermeasures for other natural hazards. In sharp contrast *it is within our reach to develop countermeasures against the collision of a cosmic object with Earth.* All the elements of the technology to defend our planet are in hand; we need only tailor and deploy the technologies to meet the need. In the discussion that follows, we illustrate a comprehensive plan for countermeasures against collisions of asteroids and comet nuclei with Earth.

2. Collisions with a Small Asteroid or Comet Nucleus Can Devastate Civil Infrastructures and Population Centers.

The size distributions shown in Figs. 1 and 2 suggest that small objects will be encountered most frequently (a Tunguska-sized object about once in 200 to 1000 years). As these figures show, 50 m objects are at least 100 times more abundant than 1 km sized objects. Just as more objects less than 1 km in size were found in the first survey for objects larger than 1 km, even smaller objects less than 140 m in size will be found in the new survey for objects larger than 140 m. The vertical green lines indicate objects of 50 m and 140 m in size. The horizontal green lines are drawn where the vertical green lines intersect the dashed blue curve. Thus, 50 m objects are about ten times more abundant than 140 m objects. Since small objects tend to be very faint, they may be close to Earth when they are found and warning times for an impending collision may be very short.

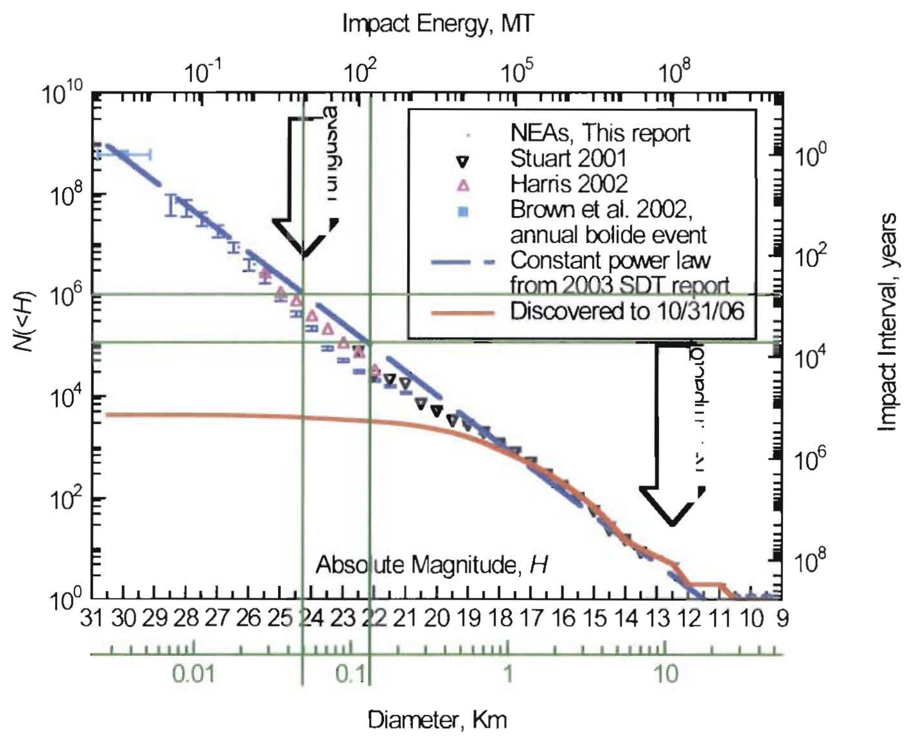

Fig. 1. Frequency of NEOs by size, impact energy, and magnitude. Attention is drawn on 140 m and Tunguska-sized objects. The size-frequency distribution dips substantially from a constant power law in the size range of about 100 m. This dip may be related to the transition from "rubble pile" to "monolithic" bodies. (Based on Harris, 2006, 2007).

The results from the Spaceguard Survey <http://neo.jpl.nasa.gov/stats>, as of July 16, 2008, are as follows: 5472 Near-Earth Asteroids (NEAs) and 65 Near-Earth Comets (NECs) have been identified for a total of 5537 Near-Earth Objects (NEOs). Of these only 746 NEAs are believed to be larger than about 1 km, i.e., have brightness H < 17.75. Again, the majority (more than 86%) of the objects found by the Spaceguard survey were smaller than 1 km.

Section 321 of the NASA Authorization Act of 2005 (U. S. Public Law No. 109-155) directed the NASA Administrator to (1) carry out a survey program of NEOs, including ground-based and space-based alternatives with technical descriptions, (2) recommend options and propose a budget to carry out the survey program pursuant to the recommended options, and (3) provide an analysis of possible alternatives that NASA could employ to divert an object on a likely collision course with Earth.

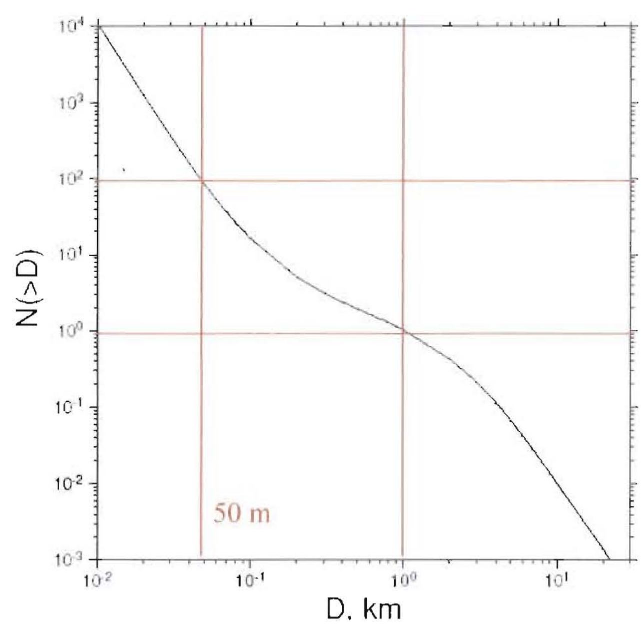

Fig. 2. Cumulative size–frequency distribution derived from lunar crater distribution. The curve is normalized to a frequency $N = 1$ for a diameter $D = 1$ km. We have added the vertical line at about 50 m to indicate a Tunguska-sized object and a horizontal line where the vertical line intersects the curve. (Based on Werner et al., 2002).

In response, the NASA White Paper to the U. S. Congress "The Near-Earth Object Survey and Deflection Analysis of Alternatives," dated March 2007, lists the following key findings for diverting a potentially hazardous object (for details see http://www.nasa.gov/pdf/171331main_NEO_report_march07.pdf):

1. Nuclear standoff explosions are assessed to be 10 - 100 times more effective (for required delivery energy) than non-nuclear alternatives.
2. Surface or subsurface nuclear explosives may be more efficient, but they run an increased risk of fracturing the NEO. They also carry higher development and operations risks.
3. Non-nuclear kinetic impactors are the most mature approach and could be used in some deflection or mitigation scenarios, especially for NEOs that consist of a single small, solid body.

4. "Slow push" mitigation techniques are (in general) the most expensive, have the lowest level of technical readiness, and their ability to both travel to and divert a threatening NEO would be limited unless mission durations of many years to decades are possible.
5. In the aggregate, an estimated 30 – 80% of PHOs are in orbits that are beyond the capability of current or planned launch systems (for rendezvous for "slow push" mitigation). Therefore, planetary gravity assist swing-by trajectories or on-orbit assembly of modular propulsion systems may be needed to augment launch vehicle performance, if these objects need to be deflected. We add that development and use of nuclear propulsion may be a desirable if not necessary means to rendezvous and stay with a PHO for a long part of its orbit for a "slow push" deflection.

The report lists mitigation options as shown in Table 1.

Table 1. Deflection and Mitigation Options

Impulsive Technique	Description
Conventional Explosive (surface)	Detonate on impact
Conventional Explosive (subsurface)	Drive explosive device into PHO and detonate
Nuclear Explosive (standoff)	Detonate on flyby via proximity fuse
Nuclear Explosive (surface)	Impact, detonate via contact fuse
Nuclear Explosive (delayed)	Land on surface, detonate at optimal time
Nuclear Explosive (subsurface)	Drive explosive device into PHO, detonate
Kinetic Impact	High velocity impact

Although the suggested procedures place the program for countermeasures in the USA in the domain of an inter-agency effort with responsibilities for the Department of Defense (DOD) and the Department of Energy (DOE), realistically, any such mission would also require international cooperation and execution.

The NASA White Paper does *not* address a number of important classes of objects that drive the overall risk to planet Earth. These include (1) PHOs smaller than 140 m in size, (2) long-period comets, and (3) short warning-time objects. Examples of such objects include the asteroid or comet nucleus that caused the Tunguska event in which 2000 km^2 were devastated in Siberia on 30 June, 1908 and the long-period Comets C/1983 H1 (IRAS-Araki-Alcock), D/1770 L1 Lexell, and 55P/1366 U1 Tempel-Tuttle. Long-period comets typically are larger (tens of kilometers in size) than short-period comets. Approximate sizes of short-period comet nuclei that have been investigated by spacecraft are 1P/Halley: 15.5×8.5×8 km, 19P/Borrelly: 16×8×8 km, 81P/Wild 2: 5.5×4.0×3.3 km, and 9P/Tempel 1: 6.2×4.6 km (third dimension not known). Since long-period comets come from the outer solar system they have high speeds and short transition times in the inner solar system. Furthermore, they are not confined to be in the ecliptic plane; indeed, they can even be in retrograde orbits. Their large mass and high relative speed with respect to the Earth make them particularly dangerous, short warning-time objects. Previous considerations have largely disregarded the threat from such objects, either because the probability of a comet impact was deemed relatively small compared to the asteroid impact threat or the warning time would simply be too short to allow effective reaction. We are not so fatalistic in the plans presented here.

3. Our Short-Term Objectives for Countermeasures.

Our recommended program would begin with implementation of the recommendations in the NASA White Paper to the U. S. Congress. While intact deflection of a PHO is our highest priority, destruction of a PHO and dispersion of its pieces must also be considered. In addition, we consider five other objectives for countermeasures against PHOs:

1. Expand the recommendations to include smaller, more frequently occurring (i.e., Tunguska-sized) objects.
2. Include countermeasures against the long-period comet threat.
3. Enhance the focus on short warning-time (hence short available reaction-time) events. It is the short warning time that we emphasize initially, but the procedures we propose for short reaction times work also when time for reaction is long. Thus they can also act as a back-up process in case a "slow push" procedure fails.
4. Use non-nuclear methods (e.g., conventional explosives or hyper-velocity impactor devices) whenever possible.
5. Use nuclear munitions only when essential because of immediacy and magnitude of the threat, and keep them on the ground to launch them only when needed.

The advantages of ground-launched preventive measures include much easier maintenance of essential systems; flexibility to use hyper-velocity impactors, conventional explosives, nuclear explosives, or a combination of these; readiness on short notice; and overall lower cost of developing, maintaining, and upgrading capabilities. Launching from a space platform may reduce the time for engaging a cosmic object with countermeasures, but maintenance and upgrading would likely require frequent high-cost return visits making it economically untenable. In addition, launching from the ground is politically less threatening than space-based systems.

Our objectives are not to negate or eliminate work on "slow push" methods such as pulsed lasers, the asteroid tugboat, the gravity tractor, the enhanced Yarkovsky effect, mass drivers, or focused solar deflectors. Rather, our recommended approach *complements* the use of "slow push" methods that may be viable when greater reaction time (years to decades) is available. Collaboration and co-operation with teams that propose using of "slow push" methods is welcomed, because it will move toward a more integrated solution to addressing the overall risk presented by cosmic objects of all sizes. The rapid response methods we discuss can also be used as a backup if a "slow push" method that depends on years of successful operation should fail for any reason.

At the end of an initial period of about three years for preliminary scientific and technologic investigations of the engagement space, we propose an international conference. This conference would summarize the findings, present the results, make detailed long-range plans, and invite the international scientific community to participate in this wide-ranging preparation for the defense of our planet.

4. The Engagement Space.

The engagement space involves a list of available countermeasures from which the appropriate choices can be made to maximize their effectiveness depending on the type of threat encountered. Thus the engagement space is multidimensional. It depends on the length of warning time, the size of the object, the composition of the object (e.g., Fe-Ni, stony, carbonaceous, ice-dust), the structure of the object (e.g., monolithic, fractured, rubble pile), the spin state, and the shape of the object.

Short warning times require aggressive procedures. Destruction of the object and dispersal of its fragments may be the only solution for short warning times. Deflection is the preferred method of action if there is sufficient time to react and "slow push" methods should be considered in such cases.

Both destruction and deflection are relatively easier for smaller objects than for larger ones. Large objects may require multiple missions and complex sequencing of the countermeasures, in addition to appropriate timing of them, to achieve the desired mission objectives.

The composition of the object also influences the decision process in important ways. In a compact object, an impulsive procedure (e.g., use of a projectile or an explosive charge) may generate shock waves that travel through the object and spall the opposite side. The spalled material may fly off with high speed, carrying most of the imparted momentum away, leaving the motion of the main part of the body virtually unaltered; and the major portion of the object may remain intact. As a result the threatened impact with Earth may not be diminished significantly. In a fractured or a rubble pile object, spalling is less likely, but the rubble around the impact zone would absorb significant energy by crushing and compacting the material rather than ablating it. In this case, a significant portion of the object would remain in the original configuration and the potential risk of collision with Earth may not be reduced significantly. Use of explosives has an added advantage over an impactor only device (Walker and Chocron, 2007). Detonation of explosives in the subsurface would eject part of the fragmented materials out of the PHO, forming a crater and imparting additional momentum to the remaining PHO body to deflect it from the original path. The momentum transfer would depend on the composition and shape of the PHO, as well as the amount of ejecta from the resulting crater, number of such explosive charges, and the sequence of their detonation. Placement of explosive charges must consider the shape, size, and composition of the PHO. The shape and size will determine how many sites are available to place explosives, which is important to both destruction and deflection of an object. Because the PHO will be spinning, care must be taken not to cause spin-induced fission. Clearly, "slow push" methods might avoid many of these complications, but they require long reaction times, typically many years and possibly decades.

Decision-making procedures must be prepared well in advance to make the correct choice. The unknown composition and structure of the threatening object will complicate the decision. All remote sensing observations of asteroids and many spacecraft investigations deal only with surface properties, which are usually obscured by regolith and altered by space weathering. We know very little about the interior properties (i.e., the geophysical and geological properties) of asteroids and comet nuclei. In the event of engaging a PHO, it will be desirable to have a monitoring spacecraft perform damage assessment.

Among the choices of countermeasures, decisions have to be made when to use hyper-velocity impactors with or without explosives, when to use conventional explosives for destruction (subsurface explosions) and for deflection (surface explosions), when to use nuclear explosives for destruction (surface or subsurface explosions) and for deflection (stand-off explosions).

5. International Collaboration and Co-ordination.

PHOs are clearly a worldwide threat and any impact could affect the territory of multiple nations. Countermeasures will require international collaboration, coordination, and agreements. Although the United Nation Committee on the Peaceful Uses of Outer Space and its NEO working group can facilitate coordination at a high level, work at a more technical level must also be coordinated. We can make use of the Permanent Monitoring Panel for Cosmic Objects (PMPCO), which meets annually at the Seminars on World Emergencies. The World Federation of Scientists sponsors these seminars. Participants of the PMPCO currently include representatives from Europe, Japan, Russia, and the USA.

We also have set up task groups through the auspices of the International Astronomical Union Commission 15 (Physical Studies of Comets and Minor Planets) to describe and unify definitions for critically needed data for asteroids and comets and to assemble geophysical and geological data for these bodies. As an illustration of the international nature of these collaborations, we can mention (1) the Task Group on Asteroid Magnitudes with team leaders from the USA and Argentina, (2) the Task Group for Albedo – Polarimetric Albedo Calibration for asteroids with team leaders from Italy and Argentina, (3) the Task Group on Comet Magnitudes with team leaders from Uruguay and Japan, and (4) the Task Group on Geophysical and Geological Properties of Asteroids and Comet Nuclei with team leaders from Finland, Argentina, and Japan. Each of these task groups has an international membership that is even wider than that indicated by the team leaders.

6. Long-Term Plans.

Long-term objectives for developing and implementing a comprehensive program for PHO countermeasures include:

1. Evaluating the technical readiness of the program elements.

2. Conducting laboratory experiments and tests of program-element effectiveness using appropriate PHO-simulating materials.
3. Artificially activating seismic measurements on asteroids and conducting radio-tomography on comet nuclei to determine geophysical and geological properties.
4. Developing a geophysical and geological database of asteroids and comet nuclei.
5. Constructing and testing modular systems for countermeasures.
6. Developing science packages with instrumentation to determine effects of countermeasures observed from companion spacecraft.

7. Geophysical and Geological Properties of PHOs.

Geophysical and geological data for asteroids and comet nuclei are important for developing effective countermeasure technologies. Such data can be obtained by various means. Many techniques are possible using only small spacecraft missions. Seismological exploration is an important tool for probing the interior structure and composition of asteroids and radio tomography is important for obtaining data for structure and composition of comet nuclei.

Asteroid seismology can be accomplished using arrays of miniaturized (micro-electro-mechanical systems: MEMS) seismometers distributed over the surface of an asteroid. Seismic activity can be induced artificially using explosives or a kinetic impactor. A challenging part of such experiments is to design and test techniques for delivery and anchoring of the seismometers in an environment with no gravity, no atmosphere, and a regolith-covered surface. The seismic measurements will be transmitted to the ground for analysis. We will define such a mission that is also of great scientific interest.

Radio-tomography is part of the European Rosetta mission to Comet 67P/Churyumov-Gerasimenko. The estimated diameter of its nucleus is about 4 km and its orbital period is about 6.57 years. Other very useful investigations of the nucleus material properties will be carried out by the MUPUS instrument suite as part of the Lander of the Rosetta mission. The Rosetta spacecraft will arrive at the comet in 2014, when the comet is still at a large heliocentric distance before the coma fully develops. Landing on the nucleus is scheduled for August 2014.

The framework for the database to accommodate these data was decided at an international conference and has been set up at http://neodata.space.swri.edu. It contains observational data of asteroids and comet nuclei and data from simulated materials where real data from asteroids and comet nuclei is not available. The data are divided into two major categories: Static data for "slow push" deflection purposes and impulse data for deflection and destruction using explosives or kinetic impactors.

8. Existing Tools and Facilities.

Southwest Research Institute and Los Alamos National Laboratory have state-of-the-art computational tools that are required to model various forms of countermeasures. Relatively simple modeling might be sufficient for "slow push" deflection techniques.

The requirements increase for impulsive techniques. For example, the strength of materials must be taken into account in the energy and momentum transfer calculations of deflection or disruption by kinetic impactors. The requirements increase further when explosives are involved. Fortunately, many models already exist which can be used as a basis from which to work. Modeling of explosive countermeasures requires consideration of not only the strength of materials, but cratering and shock propagation as well. Shock propagation can lead to a loss of momentum transfer through spallation of material off the opposite side of the object. Nuclear methods require the most complicated modeling techniques. These models must include radiation transfer, opacities, equations of state (EOS), and neutron absorption cross sections. Opacity plays an important role in energy deposition and subsequent ablation. The EOS and opacity will depend on the detailed composition of the PHO. Minor constituents can have large photon absorption cross sections (e.g., molecular bands vs. atomic lines) and the composition, including its phases (solid particles, liquid droplets, gas, and plasma) changes as a function of temperature and density. Considering the composition of meteoritic materials (Jarosewich, 1990) hundreds of new molecules can form as the temperature and density of the materials change. In such calculations it is important to conserve the elemental composition of the mixture as phases change with temperature and density. Such details must be taken into account even for calculations assuming local thermodynamic equilibrium (LTE; see, e.g., Sharp and Huebner, 1990). One of the questions is whether LTE is a sufficiently accurate approximation. If it is insufficient, then chemical kinetics and possibly heterogeneous chemical kinetics has to be invoked.

A hyper-velocity test facility is available at Southwest Research Institute to test the effectiveness of kinetic impactors on various materials and structures (see Figs. 3). Speeds that are relevant for PHO deflections by kinetic impactors can be reached in this facility (see Figs. 4 and 5). Walker et al., (1995) provide more complete descriptions of experiments with impact speeds above 10 km/s. Explosives test facilities exist at Southwest Research Institute and Los Alamos National Laboratory.

Fig. 3. Two views of the NASA-funded inhibited shaped charge launcher located at Southwest Research Institute in San Antonio, Texas. The evacuated flight and target chamber is the main component. The large cables are attached to the x-ray heads used for in-flight diagnostics. The conical charge liner completes the vacuum seal; in the left image it has been placed on the blast shield for reference.

Fig. 4. Image of a test with the inhibited shaped charge launcher facility. The facility launches one-gram aluminum fragments at speeds in excess of 11 km/s into the evacuated chamber. The launcher was used to characterize the micrometeoroid and space debris shielding used on the International Space Station.

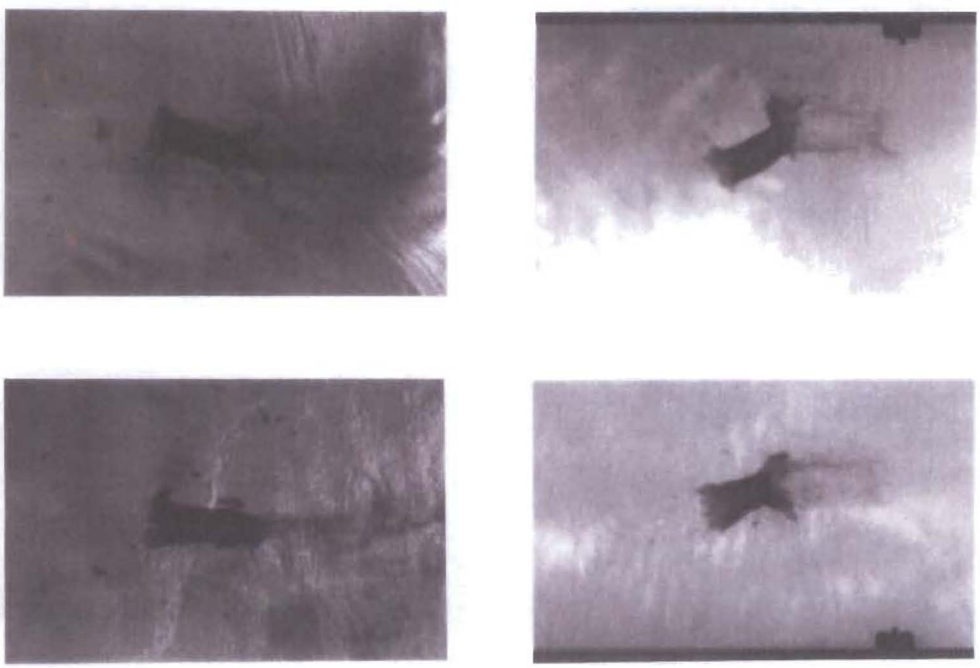

Fig. 5. X-ray images of aluminum projectiles from two independent launches (left and right panels) by the inhibited charge launcher. The upper and lower images are top and side views of the projectiles moving from left to right in near vacuum at speeds exceeding 11 km/s.

9. Launch Capabilities.

Collaboration with the aerospace industry will examine launch capabilities and requirements. This may involve modifications to existing launch vehicles and facilities or it may require some new launch vehicles and launch facilities. The launch vehicles must be reliable, ready for rapid launch, and provide substantial payload performance for high-energy missions into interplanetary orbits.

An important aspect of the aerospace industry collaborations is consideration of different requirements for different countermeasure scenarios. For example, there will be less stringent requirements for non-nuclear launches. Thus, it may be desirable to have different launch vehicles and different launch facilities for nuclear and non-nuclear options.

10. Summary.

In summary

1. The US Congress has requested an analysis of how to counter a threatening collision of an asteroid or comet nucleus with Earth. The basic technologies and expertise are available; we are developing specific proposals to evaluate and implement these.
2. Although the recommendations in the NASA report to Congress must be acted on in a timely manner, there is a compelling case for addressing additional concerns, including
   a. defense against smaller but more numerous and therefore more frequently encountered (Tunguska-sized) objects
   b. long-period comet nuclei with high kinetic energy.

   This broader perspective has a stronger risk basis, because it encompasses the most frequent and most energetic (and the technically most challenging) short warning-time (hence short available reaction-time) events. Countermeasures against short warning-time objects will also work against objects with long warning times.
3. Non-nuclear methods would be used whenever possible, because they are easier to deploy and politically less threatening.
4. Ground-based launch systems would be used in all cases, because of the relative ease of deploying, maintaining, and upgrading such systems.
5. Finally, international co-ordination of countermeasure processes is important to successful development and deployment.

The threat of an asteroid or comet nucleus collision with Earth is an international problem. For this reason we actively seek opportunities to co-operate and co-ordinate with international efforts to develop countermeasures against Earth-threatening asteroids and comet nuclei.

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