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*Proceedings of the Near-Earth-Object
Interception Workshop*

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MASTER

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Outline of Near-Earth Object Interception Workshop Proceedings

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Preface

The following pages present a detailed summary of the results of the Near-Earth-Object Interception Workshop, hosted by the Los Alamos National Laboratory (LANL) on January 14-16, 1992 at Los Alamos, New Mexico. This document is the second of two reports resulting from the direction of the United States House of Representatives' NASA Multiyear Authorization Act of 1990 (26 September 1990). The National Aeronautics and Space Administration (NASA) was directed to undertake two workshop studies to evaluate the threat to the Earth of asteroid and comet impacts and to explore remedial actions that would prevent such disasters. The first workshop sought to define the spectrum of threats and proposed a detection system to greatly expand the knowledge base of these objects. The second workshop, reported here, investigated the range of technologies and response options that may be applicable if an object poses an actual threat to the Earth. The official NASA reports on both workshops were submitted to Congress in brief form in March 1992. The detailed report of the first workshop is available from NASA's Office of Space Science and Applications under the title "The Spaceguard Survey: Report of the NASA-International Near-Earth-Object Detection Workshop."

Since much of the required expertise for intercepting and deflecting near-Earth objects resides in technical communities outside the civilian space program, NASA accepted the offer of the U.S. Department of Energy's Los Alamos National Laboratory to collaborate in conducting the second workshop and preparing the final report. The meeting was chaired by John Rather of NASA's Office of Aeronautics and Space Technology, with Jurgen Rahe of NASA's Office of Space Science and Applications as co-chair and Gregory Canavan of the LANL senior technical staff as official host.

The present document seeks to elucidate the key findings of the Interception workshop in a manner understandable to nontechnical readers. A technical discussion, Proceedings of the NEO Interception Workshop, containing individual scientific contributions by workshop participants is available as a separate Los Alamos National Laboratory document edited by Gregory Canavan.

Since the 94 invitees represented many different viewpoints and diverse technical backgrounds, a few words are in order to clarify how the results of the Interception workshop evolved and were edited to form this report. After two and one-half days of technical presentations and discussions in plenary sessions, the members of the workshop divided into seven topical working groups to discuss key areas and issues. These groups subsequently reconvened to discuss summary oral reports in plenary assembly. Written summaries were then provided by the chairmen of each working group to serve as the basis for this final report. Each chapter heading bears the name of the working group which provided the source material. The goal and the challenge was then to merge the diversity of opinions and topics from the working groups and the participants at large to give a balanced representation of the overall findings.

The consolidated document, including the Executive Summary, was edited by John Rather with detailed review by members of the Steering Committee. Thus, members of each working group bear responsibility only for the materials treated within their assigned topical areas as submitted for the final edit. The reader should be aware that the materials reported in Chapters 2 through 7 therefore reflect the opinions of the associated working groups and not an integrated position for the entire workshop.

An exception to the latter rule is Chapter 1, the Introduction and Systems Overview, where the editor and Steering Committee melded the report of the Systems Analysis working group with an overall consolidation of opinions and technical results. This was deemed appropriate to avoid unnecessary repetition and to provide an opening chapter that shows the full scope of the deliberations, results, and opinions. Hence, the editor and Steering Committee share responsibility for the opening chapter with the chairman of the Systems Analysis working group. The final draft of this report, dated May 26, 1992, was sent for final review by all workshop participants. The large number of detailed criticisms received were then carefully factored into the present version of the final report. While it was impossible to achieve unanimous agreement on all topics, we have sought to ensure that the resulting synthesis represents the majority consensus of the workshop correctly and comprehensively. A questionnaire was provided to all participants to poll the overall approval/disapproval of the final report and of the individual working group members/chapters. The results were 89 percent favorable. Two members strongly dissented and requested removal of their names from the report.

The Steering Committee



NICK DOWNES

"Take all six, and I'll throw in the giant asteroid."

**PROCEEDINGS OF THE
NEAR-EARTH OBJECT INTERCEPTION WORKSHOP
Los Alamos National Laboratory
Los Alamos, New Mexico
January 14-16, 1992**

ABSTRACT

The National Aeronautics and Space Administration Headquarters sponsored the Near-Earth-Object Interception Workshop hosted by the Los Alamos National Laboratory on January 14-16, 1992 at the J. Robert Oppenheimer Study Center in Los Alamos, New Mexico. The Workshop evaluated the issues involved in intercepting celestial objects that could hit the Earth. It covered the technologies for acquiring, tracking, and homing, as well as those for sending interceptors to inspect, rendezvous with, land on, irradiate, deflect, or destroy them. This report records the presentations and technical options reviewed.

Working Agenda/Topics
 NASA Near-Earth-Object Interception Workshop
 January 14 - 16, 1992
 Los Alamos National Laboratory

Tuesday, January 14

<u>Time</u>	<u>Session</u>	<u>Topic</u>	<u>Speaker/Presider</u>
0830-0845		Opening Remarks	<i>J. D. G. Rather</i> NASA HQ
0845- 0930	A	Review of the NASA Near-Earth-Object (NEO) Detection Workshop, San Juan Capistrano, July, 1991	<i>D. Morrison</i> NASA Ames
0930-1200	B	Threat Characterization for NEO Interception	
0930-1000	B1	<i>Physical Properties: State of the Data</i>	<i>E. Shoemaker</i> U.S.G.S.
1000-1030	B2	<i>Orbits: State of the Data</i>	<i>B. Marsden</i> Smithsonian Astro- physical Observatory
1030-1045	B3	<i>The Spacewatch CCD Search</i>	<i>Tom Gehrels</i> U. of Arizona
1045-1100	B4	<i>The Palomar photographic search</i>	<i>Eleanor Helin</i> NASA/JPL
1100-1115	B5	<i>Automated Photographic Scanning</i>	<i>Duncan Steel</i> Anglo-Australian Observatory
1115-1130	B6	<i>Lowell Observatory Sky Search: population statistics</i>	<i>Ted Bowell</i> Lowell Observatory
1130-1150	B7	<i>International Asteroid Watch</i>	<i>Don Yeomans</i> NASA/JPL
1200-1300		Lunch, LANL Cafeteria	
1300-1600	C	Tutorials and Technology Summaries	
1300-1330	C1	<i>Tutorial on Dynamics of Interception</i> 1. Parameterization of the Interception Problem 2. Required energy to perturb? disrupt? capture? 3. Required parameters for successful interaction: warning time as function of flyout time, NEO mass, interaction energy transfer, etc. 4. Explain technical challenge of workshop	<i>C. Phipps</i> LANL
1330-1400	C2	<i>Tutorial on Physics of deflection and disruption</i> 1. Deflection by explosive interaction 2. Deflection by kinetic energy impact	<i>J. Solem</i> LANL

Time	Session	Topic	Presenter
1400-1430	C3	<i>Summary of Available Interception Technologies</i> Rockets, Explosives, Kinetic Vehicles, and Ultralite Spacecraft	<i>Lt Col P. Kustan</i> <i>SDIO</i>
1430-1500	C4	<i>Required Decision Tree</i> How to relate threat range to course of action	<i>E. Tagliaferi</i> <i>SRA Corporation</i>
1500-1600	C5	<i>A creative look at Match between Threats and Technologies</i>	<i>Speakers TBD</i> <i>LLNL</i>
1600-1700	D	Required Acquisition and Tracking System Performance 1. Range (signal to noise) 2. Resolution/error 3. Spatial Coverage ($\Omega/4\pi$) 4. Temporal Coverage 5. Technologies and Methods, current & future 6. Synergistic effects	<i>G. Canavan</i> <i>LANL,</i> <i>et al.</i>
1700-1900		Reception	
Wednesday, January 15			
0830-1030	E	Materials interactions in NEO interception 1. Composition 2. Strength of materials 3. Material base 4. Crater physics on asteroids	<i>J. Remo</i> <i>Quantametrics</i> <i>et al.</i>
1030-1230	F	Candidate technology alternatives 1. Conventionally-powered interceptors 2. Nuclear-powered interceptors 3. Laser deflection 4. Laser-powered interceptors 5. Ion thrusters on asteroids 6. Mass drivers on asteroids	<i>J. Powell</i> <i>Brookhaven Nat-</i> <i>ional Lab, et al.</i>
1230-1330		Lunch, LANL Cafeteria	
Afternoon		Working groups 1. Astrodynamics of Interactions 2. Acquisition, tracking and homing 3. Vehicles and payloads 4. Energy delivery/materials interactions 5. State of technologies: current/future 6. Systems analysis } these groups wander & interact 7. Program options } with groups 1-5, who stay fixed	Cafeteria side- rooms
1800 on		Evening banquet with Dr. Edward Teller as distinguished speaker	

Time	Session	Topic	President
Thursday, January 16			
0830-1030	G	Working group reports (20 minutes each, groups 1-5 only)	<i>J. D. G. Rather</i> NASA
1030-1230	H	Integration of Workshop Findings (Incorporates reports from groups 6 & 7)	<i>C. B. Tarter</i> LLNL
1230-1330		Lunch, LANL Cafeteria	
1330-1530		Program options	<i>S. Nozette</i> DoE
1530-1600		Concluding remarks	<i>J. D. G. Rather</i>

The workshop greatly benefited from the wisdom of Edward Teller, who fully and enthusiastically participated in all of our sessions, including those held on his 84th birthday. In honor of that event, Eleanor Helin and Brian Marsden went to considerable lengths to quickly obtain official designation of minor planet #5006 as "Teller." The announcement of this honor was made at the workshop banquet, with special accolades delivered by another distinguished participant, Prof. Fred Reines, the discoverer of the neutrino. Dr. Teller's citation follows:

**5006 TELLER
(1989 GL5)**

Discovered 1989 April 5 by E. Helin at Palomar.

Named in honor of the distinguished Hungarian-born, U.S. physicist Edward Teller. Known for his seminal work in physics and astrophysics, notably on the Gamow-Teller relationship that is of fundamental importance to our knowledge of the weak interaction and its roles in astrophysics. He has also made significant contributions in chemical physics, molecular physics, and quantum theory. He served as professor of physics at George Washington University, the University of Chicago, and the University of California. He inspired the creation of the Lawrence Livermore National Laboratory, has served as its Director, and now serves as Director Emeritus to the present time. Since 1975 he has been Senior Research Fellow at the Hoover Institute, Stanford University. He has been highly effective in promoting open international science free of secrecy. Having entered the world a few months before the 1908 Tunguska event, Teller was honored by the naming of this minor planet at his 84th birthday celebration, 1992 January 15, during his participation in the NASA Workshop on procedures for the interception of threatening near-earth asteroids and comets.

Announced at Los Alamos National Laboratory on the occasion of the Near-Earth-Object Interception Workshop.

LOS ALAMOS NEWSBULLETIN

Los Alamos National Laboratory

Vol. 12 No. 2, January 24, 1992



A jubilant Edward Teller celebrated his 84th birthday at a banquet held in his honor at the Otowi Cafeteria Jan. 13. What do you give a renowned scientist? Something heavenly, of course. And that's just what Eleanor Helin of the National Aeronautics and Space Administration's Jet Propulsion Laboratory did. She announced at the banquet that she had named one of the asteroids she discovered after Teller. Asteroid 5006 Teller is as wide as the San Francisco Bay and orbits in the main asteroid belt between Mars and Jupiter. Teller was in Los Alamos attending a NASA workshop at the Laboratory that addressed strategies for intercepting and deflecting asteroids and other objects on a collision course with Earth. Photo by LeRoy H. Swanson

NASA workshop on asteroids held at Laboratory

Los Alamos-developed strategies will be presented to Congress

Los Alamos-developed strategies for intercepting and deflecting asteroids or other objects on a collision course with Earth will form part of a NASA presentation to Congress later this year.

The strategies were presented last week at a National Aeronautics and Space Administration workshop hosted by the Laboratory and involving 80 participants from a number of institutions.

The workshop coincided with Edward Teller's 84th birthday. At a banquet in Teller's honor held at Otowi Cafeteria, Eleanor Helin of NASA's Jet Propulsion Laboratory honored Teller by announcing that she had named one of the asteroids she had discovered after him.

Asteroid 5006 Teller, as wide as the San Francisco Bay, orbits in the

main asteroid belt between Mars and Jupiter. Teller invited banquet participants to visit him there on his 100th birthday — in astral form.

If an asteroid as big as 5006 Teller were to strike Earth, it would be equivalent to an explosion of many thousands of megatons of TNT. Many scientists think a similar event caused the extinction of the dinosaurs. Thus, even though such collisions might be rare — happening only every 100 million years or so — they could cause worldwide catastrophes.

"At this moment in time, Homo sapiens possesses the capability to detect and deal with such cosmic casualties," said John Dale Solem of the Theoretical Division (T) and one of the workshop's technical hosts. "It seems an auspicious time to get serious about working on the problem."

Solem also said one could argue on moral grounds that humans have a responsibility to protect the other species on Earth from such catastrophe.

Asteroids smaller than 5006 Teller strike Earth more frequently. Countless grain-sized bits of debris intercept Earth daily, appearing as shooting stars at night.

Every few days, an object 20 meters or so in diameter passes as close to Earth as the moon, every hundred years or so, such an object collides with Earth. In 1908, an object of that size generated a shock wave that flattened the forest in northern Siberia for thousands of square miles, even though the object broke up before it reached the ground.

Larger objects would create more extensive damage, and could loft sufficient debris into the air to create global climate changes severe enough to decimate entire species or ecosystems.

Given the potential for damage from a collision with a mountain from space, why not give serious thought to ways of avoiding catastrophes? Solem said that a New Concepts Forum held last year (see Newsbulletin, Oct. 11, 1991) "stirred up quite a bit of interest in the problem."

Solem and Greg Canavan of the Physics Division (P), also a technical host for the workshop, recommended to NASA that the Laboratory host the meeting. It was the second of two NASA workshops organized in response to a Congressional mandate to look into the danger of collision — with near-Earth objects and what could be done about such collisions.

The first NASA workshop, held last July, focused on methods for detecting near-Earth objects. The workshop at Los Alamos examined ways to deal with such objects.

NASA later this year will present findings from the two workshops to the House Committee on Science and Technology.

—John R. Gustafson

Preface

This report presents the technical papers presented and a summary of the issues addressed at the Near-Earth-Object (NEO) Interception Workshop hosted by the Los Alamos National Laboratory (LANL) on January 14-16, 1992. It is the second of two reports resulting from the direction of the United States House of Representatives' National Aeronautics and Space Administration (NASA) Multiyear Authorization Act of 1990 of 26 September 1990, which directed NASA to undertake two Workshop studies to evaluate the threat to the Earth of asteroid and comet impacts and to explore remedial actions to prevent such disasters. The first Workshop sought to define the spectrum of threats and proposed a detection system to expand our knowledge about them. The second Workshop investigated the range of technologies and response options that may be applicable if an object poses an actual threat to the Earth. The attached official NASA reports on both Workshops were submitted to Congress in March 1992.

Since much of the required expertise for intercepting and deflecting near-Earth objects resides in technical communities outside the civilian space program, NASA accepted the assistance of the U.S. Department of Energy's (DoE) Los Alamos National Laboratory on conducting the workshop and preparing this report. The meeting was chaired by John Rather of NASA's Office of Aeronautics and Space Technology, with Jurgen Rahe of NASA's Office of Space Science and Applications as cochair and Gregory Canavan of Los Alamos as host.

Because the ninety-four invitees represented many different viewpoints and diverse technical backgrounds, it is appropriate to indicate how the results of the Interception Workshop evolved and were edited to form this report. After 2 1/2 days of technical presentations and plenary sessions, Workshop members divided into seven topical working groups to discuss key areas and issues. They subsequently summarized their conclusions orally in a plenary assembly, in which the chairman of each working group also provided a written summary.

Since there was not time to form an overall consensus, working group members bear responsibility only for the materials treated in their assigned areas. They are not responsible for the final version of those sections, which were submitted to a final rewrite. The section headings, which bear the names of the working groups that provided source material, contain both the submitted technical papers and the area summaries. The goal of the workshop was to merge the diversity of opinions and topics from the working groups and the participants at large to give a balanced representation of the overall findings. There was not time to do so.

A consolidated document was edited by John Rather with the assistance of the California Institution of Technology and the Jet Propulsion Laboratory. It was reviewed by members of the Steering Committee, the working group chairmen, and twenty other workshop participants who had specifically asked to review the document. A large number of detailed criticisms were received, carefully assessed, and incorporated, where possible. It was impossible to achieve agreement on all topics. These Proceedings contain only the papers and workshop summaries on which there was rough consensus. The final section discusses directions for future research that emerged from the workshop, reviews some of the reactions to it, and indicates unresolved issues that could be profitably addressed by subsequent workshops.

The Steering Committee

Executive Summary

Introduction and Systems Overview: In the last decade, there has been a major shift in the perception of potential hazards to human life from Earth-approaching cosmic objects. A vast increase in evidence linking large-scale extinctions of species to past impacts on the Earth has driven increased concern. Simultaneously, there has been a great increase in the rate of discovery of near-Earth objects (NEOs), including some which have passed near the Earth. In response, Congress directed NASA to study ways to increase the detection rate of Earth-approaching objects and ways to deflect or destroy objects that posed a danger to life on Earth, two Workshop studies have been conducted. Their final reports were submitted to Congress by NASA in March, 1992. The detailed report of the NEO Detection Workshop was published under separately.

The technical papers and technical findings from the NEO Interception Workshop are contained in the present volume, which is available from Los Alamos National Laboratory. Interception Workshop members argued that there now exist technically credible approaches to preventing many impact catastrophes, provided that the requisite technology capabilities could be developed in a timely fashion. Progress could result from sharing existing search, tracking, and homing technologies with the civilian and defense sectors and with friends and allies, and from implementing protocols to transfer data on NEO discoveries from defense and intelligence assets to appropriate centers for determining precise orbits. The following paragraphs summarize the opinions of each of the topical working groups.

Astrodynamics of Interception: Interception of Earth-approaching asteroids or comets cannot be decoupled from comprehensive observations. Early detection gives a longer reaction time, and interceptions far from Earth are much more desirable and easier than interceptions nearby Earth. For cases in which exact orbits can be predicted decades to centuries in advance, which is happily the most likely case, it should be possible to send precursor missions to the object to deflect it or prepare for its subsequent interception. In these cases, it is usually best to impart an impulse to the object at its perihelion position.

If the warning time is only a few years, the orbit will be less certain and an immediate effort will be needed to refine it. Precursor missions would be more difficult, and the required launch energy would be much higher than for the first class of objects. With less than a year's warning, e.g., a long-period comet on a collision course, a high-energy interceptor would have to be launched in short order. For the worst case, a large object discovered on a collision course with Earth in a matter of days, there is currently no response with a high probability of success. Thus, a program for their early detection is essential; improved interceptors can follow. With proper development and improved detection, this worst case need never arise.

Energy Delivery--Materials Interaction: The kinetic energy of a mountain-sized object traveling at 20-30 km/s is measured in thousands to millions of megatons. If detected at great range, or many orbits prior to impact, even quite large NEOs could be deflected with energies available from chemical rockets or explosives. For intercepts during final approach, kinetic energy from fast interceptors could be adequate for NEOs of up to 70-100 m diameter. Other options such as kinetic energy devices for deflection or pulverization, thrust from attached mass drivers, solar sails, crack outgassing, laser deflection, etc., are either less effective, require extensive research and engineering, or appear expensive. Nonnuclear kinetic energy payloads or other nonnuclear *in-situ* options currently appear useful only for small NEOs, interaction at perihelion, or for larger objects when many years are available to effect a change. Nuclear energy could be used to provide efficient propulsion for distant engagements.

Nuclear energy could also be used to provide explosive energy for deflection or destruction; it appears to be favored for NEOs over about 100 m diameter. For kilometer-sized objects, the energy of the largest nuclear explosives ever built is small by comparison, thus, it is likely that nuclear technologies could play an essential role in delivering enough energy to deflect a large NEO that would otherwise impact the Earth soon. Buried explosions maximize the efficiency of fracture or pulverization. Stand-off irradiation is robust, efficient, and insensitive to

uncertainties in NEO materials and geometry. Stand-off requires less knowledge of the NEO's geology and topography, carries less fracture probability, and requires less knowledge of the NEO's rotation state, center of gravity, and other mechanical properties. Surface-bursts could produce 10-100 times more deflection, but would do so at the risk of fracturing the NEO into multiple pieces, each of which is potentially hazardous. Any such use of nuclear devices will require appropriate international agreements and protocols.

Acquisition, Tracking, and Homing: The telescope system proposed by the Detection Workshop appears to be an efficient way to achieve a census of the large, threatening NEOs that could approach the Earth from distances of about 1 astronomical unit (AU \approx 150 million kilometers, the rough distance from the Earth to the sun) within a few years. With upgrades to accommodate existing and emerging technologies, sensors using visible-light cameras and microwave radars could provide adequate acquisition and track of large objects and timely search, detection, track, and assessment of the smaller ones of current concern within a few decades. Computers and advanced algorithms could support automated detection and tracking.

Radars can measure physical characteristics, composition, and shape of objects with 0.1 AU from Earth for objects 100 m or more in diameter. Homing has been less well studied, but ground-based optical and radar sensors could refine an NEO's trajectory and establish its orientation for precise delivery. The interceptor then could be guided to within range of the object and control transferred to on-board optical or radar sensors and computers. Impact prediction on comets would be more difficult because their comas obscure their nucleus, but that could be overcome with multiple probes and interceptors.

Vehicles and Payloads: Two types of missions have been studied: (1) precursor reconnaissance missions and (2) missions aimed at diverting or fragmenting an NEO of any size. The prime objective of precursor reconnaissance missions is to characterize the diversity of NEOs, because objects with different material composition will respond differently to perturbations. Relatively low-cost missions using small, lightweight spacecraft and launch vehicles could fly by, rendezvous with, or land on NEOs. The Department of Defense has developed a number of lightweight technologies which could be used for such missions in their present configuration or after some modifications. NASA probes could also be adapted. The preferred alternative would be for the two to be fully integrated. An active effort to divert or fragment an NEO would require a large launch vehicle to carry a payload capable of changing the orbit or pulverizing the NEO. Advanced upper stages and propulsion concepts offer significant potential increases in useful payload weight in the long term. It would be feasible to perform experimental missions to observe a representative sample of NEOs in the near term with small modifications of existing capabilities in order to improve the required knowledge base for deflection.

Assessment of Current and Future Technologies: Intercepts distant from Earth are less difficult than are close-in intercepts. Smaller deflections suffice, so less energy need be delivered. Travel time is less of an issue, so deficiencies in deep-space payload capability are less of a restriction. Opportunities exist to deflect, look, and deflect again; and distant intercepts offer a greater range of propulsion, deflection, and destruction options. Existing options for distant intercepts focus upon chemical rockets with chemical or nuclear payloads. Near-term innovative options-potentially available within two decades-include nuclear rockets for fast transport of heavy payloads, landing nuclear rockets on the NEO's surface to utilize *in-situ* water as a propellant; mass drivers on the NEO's surface, or, conceivable, laser transmitters on the Earth or the moon to perturb the NEO orbit by ablating material from the surface. All require development. Creative concepts potentially available many decades from now might include solar sails and the use of small asteroids to deflect larger ones. These options appear technically feasible, but affordability and risk vary greatly. Close-in intercepts, on the other hand, are very difficult: large deflections require substantial energy; travel time is very important; time will allow only one or two deflection attempts; and there are fewer technology options that appear feasible. Existing technologies for close-in intercepts include only chemical rockets with

explosive payloads. Near-term possibilities include nuclear rockets with nuclear explosives. Longer term concepts are speculative and involve greater degrees of risk.

Future Research Options Impacts on Earth from asteroids and comets occur infrequently, but have potentially very serious consequences that justify initiating efforts directed toward mitigation. It is essential to improve the detection capability to increase the warning time before investing heavily in specific mitigation systems. In order of increasing commitment of resources, several levels of programmatic efforts are (1) enhanced observational, laboratory, and theoretical studies and analysis of the NEOs, which have estimated costs of a few \$M/yr.; (2) construction of dedicated telescopes and other instruments and systems to dramatically increase the state of knowledge and detection rate of NEOs, together with augmented laboratory and theoretical studies for both detection and interception, which would cost about \$10M/yr.; (3) robotic spacecraft missions to sample and characterize representative NEOs, which might cost about \$100M/yr.; and (4) definition of appropriate interception system requirements. A later implementation program might cost substantially more, even if pursued as an evolutionary step. The nature of the hazard is global in scope, and planning should be shared among the world's nations, although the U.S. is perhaps now best-suited to a leadership role. Presently, there is no organized program to address the NEO hazard. The research discussed above could form a sound basis for formulating the appropriate national and international mechanisms.

Near-Earth-Object Interception Workshop

List of Participants

Chair: John Rather, NASA Office of Aeronautics and Space Technology
Co-Chair: Jurgen Rahe, NASA Office of Space Science and Applications

Steering Committee Members

John Rather (NASA Headquarters, Washington, DC), Chair
Johan Benson (Consultant, Washington, DC)
Gregory Canavan (Los Alamos National Laboratory, NM)
Harry S. (Terry) Dawson (Staff, U. S. House of Representatives, Washington, DC)
Thomas Morgan (University Space Research Association, Washington, DC)
Stuart Nozette (U. S. Department of Energy, Washington, DC)
James Powell (Brookhaven National Laboratory, NY)
Jurgen Rahe (NASA Headquarters, Washington, DC), Co-Chair
John Remo (Quantametrics, Inc., NY)
Lt. Col. Pete Rustan (Strategic Defense Initiative Organization, Washington, DC)
Eugene Shoemaker (U. S. Geological Survey, AZ)
Johndale Solem (Los Alamos National Laboratory, NM)
Edward Tagliaferri (SRA Corporation, CA)
C. Bruce Tarter (Lawrence Livermore National Laboratory, CA)
Col. Simon P. Worden (Strategic Defense Initiative Organization, Washington, DC)

Working Groups

Systems Analysis

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Lyle Jenkins (NASA/Johnson Space Center, TX)
David Morrison (NASA/Ames Research Center, CA)
John Remo (Quantametrics, Inc., NY)
Andrew Smith (Safety Engineering Research, NM)
Anthony Zuppero (Idaho National Engineering Laboratory, ID)

Astrodynamics of Interception

Claude Phipps (Los Alamos National Laboratory, NM), Chair
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SUMMARY OF THE FINDINGS OF THE NEAR-EARTH-OBJECT (NEO) INTERCEPTION WORKSHOP

Background

In the last decade, there has been a major shift in the perception of potential hazards to human life from Earth-approaching cosmic objects. A vast increase in evidence linking large-scale extinctions of species to past impacts on the Earth has driven this increased concern. Simultaneously, there has been a great increase in the rate of discovery of near-Earth objects (NEOs), including some which have made near passes by Earth.

In response to a Congressional direction for NASA to study ways to increase the detection rate of Earth-approaching objects and ways to alter the orbits of or destroy such objects if they should pose a danger to life on Earth, two workshop studies have been conducted. The NEO Detection Workshop held three formal meetings: 1) June 30-July 3, 1991, at the San Juan Capistrano Research Institute, 2) September 24-25, 1991, at NASA's Ames Research Center, and 3) November 5, 1991, in Palo Alto, California; all these meetings were held in conjunction with more general science meetings. Participants in the workshop came from the United States, Australia, Finland, France, India, and Russia. The detailed findings and the technical papers presented at this workshop will be available from NASA's Office of Space Science and Applications.

The NEO Interception Workshop was hosted by the Department of Energy's Los Alamos National Laboratory on January 14-16, 1992, and the detailed findings and the technical papers presented at that workshop will be available from the Los Alamos National Laboratory in Summer of 1992. A summary of the Interception Workshop follows.

Importance of Early Detection

The consensus of the Interception Workshop is that there now exist technically credible approaches to preventing an impact catastrophe provided that the requisite technology capabilities are developed. Important immediate progress can result from the utilization of existing defense technologies and from implementing protocols to transfer data on NEO discoveries from defense and intelligence assets to appropriate entities for determining precise orbits and other relevant data.

Interception of Earth-approaching asteroids or comets cannot be decoupled from comprehensive observations. Early detection obviously gives a longer reaction time, and interceptions far from Earth are much more desirable and easier to accomplish than interceptions near Earth. For cases in which a threat has been identified and the orbit can be predicted reliably decades or centuries in advance, it may be possible to send precursor missions to the object to prepare for a subsequent interception.

Interception Techniques

It would be most efficient to impart an impulse to the object at its perihelion position, defined as the point at which a body moving in an elliptical orbit is at its closest distance to the Sun. For the unlikely situation in which the threat is identified only a few years in advance, the orbit would be less certain, precursor missions would be very difficult, and the required launch energy would be much higher than in the first case. With less than a year warning that an object (probably a long-period comet) is on a collision course with Earth, an interception device must be launched in short order with a high launch energy--perhaps 100 times higher than that required in the first case. However, the likelihood of having less than decades of warning before a catastrophic collision is minimal.

The kinetic energy of a mountain-sized object traveling at 25 kilometers per second is enormous, dwarfing the energy of the largest nuclear weapons ever built. Powerful explosive devices would be needed to impart enough energy to a large NEO to perturb it from a trajectory that passes through Earth, or to destroy it. Such explosives could be used in either surface-burst modes or a stand-off mode: surface-burst modes would provide two orders of magnitude more deflection, but would risk fracturing the NEO into multiple potentially hazardous pieces. In comparison to other options, the stand-off approach requires less knowledge of the NEO's geology and topography, carries less fracture probability, and requires less knowledge of the NEO's rotation state and center of gravity.

Other options discussed--including explosives at the surface or interior; kinetic energy devices for deflection or pulverization; attached thrust by mass driver, solar sail, or crack outgassing; or laser deflection--either are ineffectual, less desirable, or require extensive research programs and the construction of major space assets.

Technological Requirements

With upgrades to accommodate existing technologies, sensors using visible-light cameras and microwave radar will be adequate for detecting, tracking, and assessing, within a few decades the most threatening objects during approaches to within 1 astronomical unit (AU: approximately 150 million kilometers). Computers and algorithms could support automated detection and tracking. Radars can measure sizes, shapes, spin vectors, and surface characteristics of most NEOs, often within months of discovery.

Homing has been less well studied, but ground-based optical and radar sensors could refine an object's trajectory and establish its orientation for precise delivery of an interceptor. An interceptor could be guided to within range of the object and control would then be transferred to on-board sensors (which could be optical or radar) and computers. Impact prediction for comets would be more difficult than for asteroids, because the comets atmosphere visually obscures the nucleus and because outgassing causes nongravitational acceleration.

Mission Types

Two types of missions could be studied: (1) precursor reconnaissance missions and (2) missions aimed at diverting or fragmenting a NEO of any size once a threat has been identified. The prime objective of precursor reconnaissance missions would be to characterize the diversity of NEOs because objects with different material composition will respond differently to perturbation effects. Such relatively low-cost missions using small lightweight spacecraft and launch vehicles could fly by, rendezvous, or land on NEOs. An active effort to divert or fragment a NEO would require a large launch vehicle to carry a payload capable of changing the orbit or fragmenting a NEO. Experimental missions to characterize representative NEOs as fully as possible in the near term would greatly improve the currently poor knowledge base for deflection.

Interception Distances

Intercepts distant from Earth are, paradoxically, much less difficult to achieve than are close-in intercepts: smaller deflections are required so less energy need be delivered; travel time is usually not an issue; opportunities exist to deflect, look, and deflect again; and there is a greater range of propulsion and deflection or destruction options. Existing options for distant intercepts focus exclusively upon chemical rockets with high-energy explosive payloads. Near-term options -- potentially available within two decades -- include nuclear rockets for fast transport of heavy payloads, landing nuclear rockets on the NEO's surface to utilize in-situ water as a propellant, and mass drivers on the NEO's surface. Options potentially available more than two decades from now might include solar sails. All of these options appear technically feasible, although relative affordability and risk factors need much further examination.

Close-in intercepts, on the other hand, are very difficult. Large deflections require substantial energy; travel time is short; a short warning time will allow only one or two deflections; and there are fewer technology options. Large high-energy explosives may shatter the object into more projectiles, while the technical feasibility and affordability of some of the other technologies are still under study.

Conclusions

Impacts on Earth from asteroids and comets occur rarely, but have potentially very serious consequences that justify initiating efforts directed toward detection and mitigation. In order of increasing commitment of resources, several levels of programmatic effort are: (1) Enhanced observational, laboratory, and theoretical studies and analysis of the NEOs; (2) Construction of dedicated telescopes and other instruments to dramatically increase the state of knowledge and detection rate of NEOs, together with augmented laboratory and theoretical studies; (3) Robotic spacecraft missions to characterize a sample of NEOs that is representative of their broad diversity; (4) Definition of appropriate mitigation system requirements and implementation options concerning launch infrastructure, an interceptor vehicle, a target acquisition capability, and explosive devices.

The nature of the hazard is global in scope, and planning should be shared among the world's nations. The United States is best-situated to take a leadership role. Presently, there is no organized program to address the NEO hazard. A decision to proceed should not be delayed in anticipation that new data will soon substantially modify our present understanding.

Fortunately, impacts of large near-Earth objects are extremely rare and in most cases, the objects can be readily detected with current ground-based technology. If one were on a collision course with Earth, it probably would be found decades in advance of any collision, after which an orderly scheme of characterization and mitigation could be implemented.

SUMMARY OF THE FINDINGS OF THE NEAR-EARTH OBJECT (NEO) DETECTION WORKSHOP

Background

Impacts by Earth-crossing asteroids and comets (collectively known as near-earth objects or NEOs) pose a significant hazard to life and property. Although the annual probability of the Earth being struck by a large asteroid or comet is extremely small, the consequences of such a collision are so catastrophic that it is prudent to assess the nature of the threat and to prepare to deal with it. The first step in any program for the prevention or mitigation of impact catastrophes must involve a comprehensive search for Earth-crossing asteroids and comets and a detailed analysis of their orbits.

In response to Congressional direction for NASA to study ways to increase the detection rate of Earth-approaching objects and ways to alter the orbits of or destroy such objects if they should pose a danger to life on Earth, two workshop studies have been conducted. The NEO Interception Workshop was hosted by the Department of Energy's Los Alamos National Laboratory on January 14-16, 1992, and the detailed findings and technical papers presented at that workshop will be available from the Los Alamos National Laboratory in Summer 1992.

The NEO Detection Workshop held three formal meetings: 1) June 30-July 3, 1991, at the San Juan Capistrano Research Institute, 2) September 24-25, 1991, at NASA's Ames Research Center, and 3) November 5, 1991, in Palo Alto, California; all these meetings were held in conjunction with more general science meetings. Participants in the workshop came from the United States, Australia, Finland, France, India, and Russia. The detailed findings and the technical papers presented at this workshop will be available from NASA's Office of Space Science and Applications. A summary of the Detection Workshop follows.

Impact Hazard

The greatest risk from cosmic impacts is associated with objects large enough to disturb the Earth's climate on a global scale by injecting large quantities of dust into the stratosphere. Such an event would depress temperatures around the globe, leading to massive loss of food crops and possible breakdown of society. Such global catastrophes are qualitatively different from other more common hazards that we face (excepting nuclear war), because of their potential effect on the entire planet and its population. The possibility of such a global catastrophe is beyond question, but determining the threshold impactor size to trigger such an event is more difficult. Various studies have suggested that the minimum mass impacting body to produce such global consequences is several tens of billions of tons, resulting in a groundburst explosion with energy approaching a million megatons of Tinitrotoluene (TNT). The corresponding threshold diameter for Earth-crossing asteroids or comets is between 1 and 2 kilometers. Smaller objects (down to tens of meters in diameter) can cause severe local damage but pose no global threat.

Search Strategy

Current technology permits us to discover and track nearly all asteroids or short-period comets larger than 1 kilometer in diameter that are potential Earth-impactors. These objects are readily detected with moderate-size ground-based telescopes. Most of what we now know about the population of Earth-crossing asteroids has been derived over the past two decades from studies carried out by a few dedicated observing teams using small ground-based telescopes. Currently, several new NEOs are discovered each month. At this rate, however, it will require several centuries to approach a complete survey, even for the larger objects. What is required to assess the population of NEOs and identify any large objects that could potentially impact the Earth is a systematic survey that effectively

monitors a large volume of space around our planet and detects these objects as their orbits repeatedly carry them through this volume of space. In addition, the survey should deal with the long-period comets, which are thought to constitute about 5 to 10 percent of potential Earth-impactors. Long-period comets do not regularly enter near-Earth space; however, most Earth-impacting long-period comets could be detected with advance warning several months before impact, using the same telescopes used for the NEO survey. Finally, it is desirable to discover as many of the smaller potential impactors as possible.

Lead Time

No object now known has an orbit that will lead to a collision with our planet during the next few centuries, and the vast majority of the newly discovered asteroids and comets will also be found to pose no near-term danger. Even if an NEO has an orbit that might lead to an impact, it will typically make hundreds of moderately near passes before there is any danger, providing ample time for response. However, the lead time will be much less for a comet approaching the Earth on a long-period orbit.

Spaceguard Survey Network

The survey outlined in this report involves a coordinated international network of specialized ground-based telescopes for discovery, confirmation, and follow-up observations. Observations are required from both the northern and southern hemispheres, monitoring about 6,000 square degrees of sky per month. In order to provide reliable detection of objects as small as 1 kilometer in diameter within a suitably large volume of space, the telescopes should reach astronomical magnitude 22. The telescopes that are suitable for this survey have apertures of 2 to 3 meters, moderately wide fields of view (2 to 3 degrees), focal-plane arrays of large-format charge-coupled device (CCD) detectors, and automated signal processing and detection systems that recognize the asteroids and comets from their motion against the background of stars. The technology for such automated survey telescopes has been developed and demonstrated by the 0.9-meter Spacewatch telescope of the University of Arizona. For purposes of this study, we focus on a Spaceguard Survey network of six 2.5-meter aperture, $f/2$ prime focus reflecting telescopes, each with four 2048 x 2048 pixel CCD chips in the focal plane.

Follow-up and Coordination

In addition to the discovery and verification of new Earth-approaching asteroids and comets, the Spaceguard Survey program will require follow-up observations to refine orbits, determine the sizes of newly discovered objects, and establish the physical properties of the asteroid and comet population. Observations with large planetary radars are an especially effective tool for the rapid determination of accurate orbits. Radar data will be required to ascertain whether potentially hazardous objects will miss the Earth or, if this is not the case, to determine the exact time and location of the impact. Desirable for this program would be increased access to currently operating planetary radars in California and Puerto Rico, and provision of a suitable southern-hemisphere radar in the future. Although one or more dedicated follow-up telescopes would greatly improve our ability to study faint and distant asteroids and comets, we anticipate that much of the optical follow-up work can be accomplished with the survey telescopes themselves if they are suitably instrumented. The survey program also requires rapid international electronic communications and a central organization for coordination of observing programs and maintenance of a database of discovered objects and their orbits.

Expected Survey Results

Numerical modeling of the operation of the Spaceguard Survey network indicates that about 500 NEOs will be discovered per month. Over a period of 25 years we will identify more than 90 percent of potentially threatening NEOs larger than 1 kilometer in diameter; a

dark-sky survey will detect most incoming comets several months before they approach the Earth. At the same time, tens of thousands of smaller asteroids (down to a few meters in diameter) will also be discovered, although the completeness of the survey declines markedly for objects smaller than about 500 meters. The advantage of this survey approach is that it achieves the greatest level of completeness for the largest and most dangerous objects; however, if continued for a long period of time, it will provide the foundation for assessing the risk posed by smaller impacts as well. Continued monitoring of the sky will also be needed to provide an alert for potentially hazardous long-period comets.

Implementation of the Spaceguard Survey

The survey can begin with current programs in the United States and other countries, which are providing an initial characterization of the ECA population and can serve as a testbed for the technologies proposed for the new and larger survey telescopes. A modest injection of new funds into current programs could also increase current discovery rates by a factor of two or more, as well as provide training for personnel that will be needed to operate the new survey network. For the new telescopes, we assume the use of modern technology that has, over the past decade, substantially reduced the construction costs of telescopes of this aperture. If construction were to begin in Fiscal Year 1993, the survey could be in operation by about 1997.

Conclusions

The international survey program described in this report can be thought of as a modest investment to provide insurance for our planet against the ultimate catastrophe. The probability of a major impact during the next century is very small, but the consequences of such an impact, especially if the object is larger than about 1 kilometer in diameter, are sufficiently terrible to warrant serious consideration. The Spaceguard Survey is an essential step toward a program of risk reduction that can reduce the risk of an unforeseen cosmic impact by more than 75 percent over the next 25 years.

1. BACKGROUND FOR THE WORKSHOP

NEAR-EARTH OBJECT INTERCEPTION WORKSHOP SUMMARY

by

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ABSTRACT

A workshop held at Los Alamos in January 1992 evaluated the issues involved in intercepting celestial objects approaching the Earth. It covered the technologies for acquiring, tracking, and homing on them, as well as those for the interceptors to inspect, rendezvous with, land on, irradiate, deflect, or destroy them. This report reviews the presentations, issues, and conclusions.

1. Introduction

At irregular intervals, the Earth is struck by objects from space. There is evidence that the age of dinosaurs was brought to an end by the impact of an asteroid 10 to 20 kilometers across.¹ Such large impacts apparently occur every few tens of millions of years. Smaller objects strike more frequently, but do correspondingly less damage. In 1908 a stony meteoroid about 50 meters across exploded in the air above the Tunguska river in Siberia, devastating the countryside over thousands of square kilometers.^{2,3} Impact craters on the surface of the Earth and moons suggest that such impacts occur every few hundred years and that objects of intermediate sizes impact at essentially all intermediate frequencies.⁴

Recognizing the potential seriousness of such impacts, in 1991 Congress mandated two workshops on the detection and interception of such near-Earth objects (NEOs). The first defined a plan for detecting—in the next few decades at distances of a few AU (1 Astronomical Unit is about 150 million kilometers, the distance from the Sun to the Earth)—NEOs a kilometer or larger in size that might impact the Earth.⁵ The first workshop on detection defined the expected threat and the means to refine it. The second workshop studied potential responses. It examined the issues

involved in deflecting or destroying NEOs on trajectories that would impact the Earth; the presentations, issues, and conclusions are summarized in this report. The usefulness of the two workshops was enhanced by considerable cross-fertilization and joint membership.

The remainder of this section introduces the various perspectives on the NEO threat and potential solutions that were provided at the Interception Workshop. The following sub-sections discuss the elements of these solutions, organized by working group subjects that were used to facilitate the Workshop: astrodynamics of interception; energy delivery and materials interaction; vehicles and payloads for intercepts; acquisition, tracking, and homing on NEOs; the assessment of future technologies; and future directions for research. The remaining sections expand on these discussions, their conclusions, and the reactions to them. Each subject starts with a summary assessment that was prepared by the working group members listed in the Executive Summary. They are followed by the texts of the principal papers presented in each area, which were the principal product of the Interception Workshop. The summary assessments were discussed at some length within each working group, but there was not time to reach a consensus within each working group, let alone on the overall conclusions and recommendations of the whole group. Thus, this paper does not attempt to formulate priorities, which are addressed in a separate report prepared for NASA by John Rather through the Jet Propulsion Laboratory of the California Institute of Technology (JPL of CIT).⁶ Remaining issues are addressed in the final sections.

"Background for the Workshop" gives the motivation; reviews the historical evidence for NEO impacts; gives the rough size, velocity, warning time parameters for threatening NEOs; and indicates the order of magnitude of their frequency and expected damage. It also reviews what is known about the composition and frequency of different types of stony and metallic NEOs. It concludes with summaries of representative exploratory and negation missions.

"The Impact Hazard" by David Morrison summarizes the results of the NASA NEO Detection Workshop, paying particular attention to the evaluation of the nature and magnitude of the impact hazard. It argues that "Earth-approaching asteroids and comets pose a significant hazard to life and property...[and that] the greatest risk is associated with objects large enough to disturb the Earth's climate on a global scale by injecting large quantities of dust into the stratosphere." Such impacts pose a threat much like that of nuclear winter, which was discussed in the scientific literature of nuclear exchanges in the depths of the cold war. The paper argues that the threshold for NEOs that could lead to global crop failures and widespread starvation is not well known, but is probably between 1 and 3 km in diameter, and that the first priority in dealing with the impact hazard is to identify potential impactors in this size range.

"The Impact Hazard" notes that smaller NEOs, down to 50-100 m in diameter, could cause severe local damage, but would not perturb the global climate. The individual risk from such impacts is orders of magnitude less than that of a globally catastrophic impact. The paper argues

that even their cumulative effect is substantially less than that posed by objects greater than 1 km in diameter. For stony asteroids a second threshold is passed at about 40 m diameters, below which most of their energy is dissipated high in the atmosphere, and little damage is produced on the surface. This second threshold is dependent on the composition of the impactor; iron objects down to a few meters in diameter are capable of penetrating the atmosphere. Morrison argues that there is little reason to be concerned with objects much smaller than 100 m in diameter—a result that was disputed by some attendees at the Workshop, who expressed concern over much smaller NEOs.

In summarizing the results of *The Spaceguard Survey Report*,⁷ Morrison notes that the NASA Detection Workshop group proposed the construction of a network of 6 ground-based telescopes to carry out an automated sky survey for the detection of objects down to astronomical magnitude 22, approximately to the brightness of a 1-km diameter dark asteroid at a distance of 1.5 AU. If pursued for two decades, such a survey could discover 90 percent of asteroids larger than 1 km in Earth-crossing orbits, while at the same time finding tens of thousands of additional smaller objects. The great majority of these objects will be discovered long before they pose a direct threat, thus providing decades of warning for any impact. This survey would also detect potentially dangerous incoming comets, but with much less warning—in some cases less than 12 months.

"The Spacewatch CCD [charge-coupled device] Search" by Tom Gehrels described the University of Arizona's 0.9-m Spacewatch Telescope on Kitt Peak. Federally funded since 1980 to search for NEOs, it is dedicated to the development of new techniques for their discovery. It presently scans the sky with a 2048² CCD detector array, computer processing the output in near-real time. Its discovery rate in 1991 was 15 NEOs/yr; with new CCDs of higher quantum efficiency, the discovery rate is now about 30 NEOs/yr. About an order-of-magnitude improvement in detection rate is anticipated with the 1.8-m Spacewatch Telescope now under construction. Gehrels's data resembles that summarized in Morrison's "Impact Hazard," but has higher impact frequencies for smaller NEOs. The impact of the differences between Gehrels's and Morrison's data, which represent the major uncertainty in the assessment of the NEO hazard, are discussed below at some length in the paper on "Value of Space Defenses."

"Some Perspectives on the Search for Near-Earth Objects" by Duncan I. Steel describes the search for new and smaller NEOs by combining current technology and previous observations. He describes the difficulties with new Aten objects (period < 1 yr, aphelion > 0.9833 AU), which are difficult to detect with conventional telescope searches because of their unfavorable geometry. Steel also discusses the challenges of searching for new classes of NEOs in highly inclined orbits, like Halley's comet. He summarizes experience with radars, which can categorize NEOs easily. He also discusses the traditional difficulties in predicting the history or trajectory of NEOs subject to

non-gravitational perturbations, which make distant impacts hard to predict. He ends with a useful summary of the current debate on coherent versus stochastic catastrophism, i.e., the possibility that much recent damage has been done by multiple intercepts by < 100 m fragments from large NEOs that have broken up in the past.

"To Hit or Not To Hit" by Brian Marsden also questions the value of secular perturbation calculations for objects that would not hit the Earth for 200 years or more. He provides a useful table of possible large NEOs that might become threats under such influences, but finds few threats in the next few decades. He discusses the uniquely stressing threats posed by long-period comets, which are numerically less likely, but more of a problem due to their short warning and very high kinetic energy. He notes that satellites deployed on the opposite side of the sun would be useful in detecting them early—if they were about 100 times more sensitive than the telescopes proposed by the detection workshop. The strong time-luminosity curves of such objects kept the IRAS satellite from detecting anything that could not be detected easily from ground-based telescopes. Their performance would improve if the telescopes were deployed very far from the Earth—possibly closer to the sun—and perhaps around Venus.

"Airblast Damage from Small Asteroids" by Jack G. Hills and M. Patrick Goda explores the difficult and controversial subject of the damage from small NEOs that break up in the atmosphere before they hit the ground. Using detailed models of the fragmentation of stony meteorites as they decelerate at a few scale heights in the atmosphere, they find that the energy deposition from NEOs of 50-250 m diameter can accidentally approach the "optimal height of burst" used for nuclear weapons, and hence produce the maximum ground damage possible for a given kinetic energy. They conclude that stony asteroids under 250 m and iron asteroids under 60 m diameter probably won't survive—tending to break up at a few scale heights. However, those with diameters down to about 40 to 4 m, respectively, could produce great damage by depositing their energy in the airblast and spreading their fragments over distances of kilometers. Their calculations interpret the Tunguska event as roughly an 80 m diameter stony meteorite with a kinetic energy of about 40 MT (megaton, the energy equivalent of 1,000,000 tons of high explosive, or about 4×10^{15} joules).

These results make it possible to refine the qualitative thresholds in phenomenology posed above by Morrison and make a more quantitative assessment of the damage from modest-sized NEOs, which has been one of the most divisive issues in the field of late. The physics of NEO breakup is far from certain; data are only starting to filter in.⁸ The breakup of meteoroids in the Earth's atmosphere has been thought to explain twin craters, but recent evidence indicates that of

the 30 largest craters, at least 6 occur in pairs in configurations that Jay Melosh of the University of Arizona asserts cannot be explained by the dispersion argument assumed in these calculations. Instead, attention is shifting to the notion that NEOs could circle in pairs or groups, in which case NEO intercepts would also have to be executed in pairs.

While the physics of small NEO damage is better understood through the work of Hills and Goda, the damage mechanisms for NEOs with intermediate diameters of 50—2,000 m are still uncertain. It would be useful to integrate the thoughtful scaling analyses of hypervelocity impacts that have been performed by Russian and other Former Soviet Union scientists over the last few decades, going back to the fundamental scaling work of Sedov and Zeldovich.⁹

2. Astrodynamics of Interception

Detection and interception are interrelated. In general, the farther away a threatening NEO is detected, the farther away it can be engaged, and the easier it is to deflect or destroy. The working group summary paper on "Astrodynamics of Interception" reviews likely intercepts, from the least to the most stressing, and attempts to assign the rough warning times, probabilities, interaction distances, and velocity increments for each. It also gives elementary discussions of the key issues associated with intercepts ranging from those many orbits prior to impact to those attempted during the final approach, which establishes the rough launch requirements for each type of intercept.

Table 2-1 illustrates these requirements. For a NEO whose exact orbit could be established decades ahead of its projected impact, interaction could take place at a distance of several AU and require only about 1 cm/s. Thus, it should be possible to send out a mission to rendezvous with it at perihelion and apply just enough impulse to shift its trajectory enough to miss the Earth. A NEO with a diameter of 2 kilometers and density $\mu \approx 3,000 \text{ kg/m}^3$ has a mass $m = 4\pi\mu(D/2)^3/3 \approx 1.2 \times 10^{13} \text{ kg}$. Changing its velocity by 1 cm/s at perihelion could be effected by ejecting about $1.2 \times 10^{13} \text{ kg} \times 1 \text{ cm/s} / 3 \text{ km/s} \approx 40$ tonnes of material at a typical rocket specific impulse of 300 seconds, i.e., an exhaust velocity of $c = 3 \text{ km/s}$. That is arguably feasible, although stressing, with nonnuclear means. For example, a single *Energia* booster could put about 100 tonnes in low Earth orbit and accelerate about 30 tonnes escape velocity. Higher specific impulse concepts could in time significantly lower these mass requirements.

For less certain orbits, which would only permit response times of about a year, the velocities required increase by one to two orders of magnitude, and the masses and energies required for deflection increase with them. For very short-warning objects such as smaller-diameter asteroids or long-period comets, which are more difficult to detect, the interceptor would have to deflect or destroy the NEO during its final approach. It is possible to illustrate the energies required. If an NEO 2 km in diameter could be split in half at a range $R \approx 1 \text{ AU}$, and each half

given just enough transverse velocity v_T to miss the Earth, that would require a divert velocity of $v_T \approx v(R_e/R) = 30 \text{ km/s} (6,400 \text{ km} / 1.5 \times 10^8 \text{ km}) \approx 1.3 \text{ m/s}$, where R_e is the Earth's radius. That would require a kinetic energy of $mv_T^2/2 = 1.2 \times 10^{13} \text{ kg} (1.3 \text{ m/s})^2/2 = 10^{13} \text{ joule} \approx 2.5 \text{ KT}$ (kiloton), neglecting the energy to split the NEO, which could be much larger.

In short-warning engagements, this whole detection range would not be available for deflection. A NEO approaching at a velocity $v = 30 \text{ km/s}$ that was detected at a range of $R = 1 \text{ AU}$ would permit a response time of at most $\approx R/v \approx 2 \text{ months}$. For an interceptor that flew out to it with a speed of $V = 3 \text{ km/s}$ that could be generated by chemical rockets, the intercept would take place at a time $T = R/(V + v) \approx R/v$ after detection at a range of about $R_i \approx VT \approx R V/(V + v) \approx R/11 \approx 0.1 \text{ AU}$. The transverse velocity required would then increase to about $v_T \approx 13 \text{ m/s}$ and the kinetic energy to about 250 KT. If the NEO was only detected at 0.1 AU and the intercept took place at about 0.01 AU, the interceptor would need an explosive energy of 25 MT. This progression illustrates the strong sensitivity to warning and interceptor performance in the terminal regime and demonstrates that for short-warning engagements during the final approach, the energies required are about at the limit of those that can now be generated by man.

"Deflection and Fragmentation of Near-Earth Asteroids" by Thomas J. Ahrens gives a good overall summary of the types of NEOs that pose likely threats. It bounds the requirements for deflection at distant rendezvous, estimating the requirements to be in the range of a few m/s to a few cm/s, depending on the warning and rendezvous time and the type of deflection attempted. It indicates why parallel perturbation at perihelion is most efficient, and gives useful approximations to the displacements generated as a function of the locus and magnitude of the velocity increments applied. It then relates these velocity requirements to the capabilities of the small nuclear explosives or mass drivers required for dispersal or fragmentation, which the paper suggests could be developed through affordable programs.

"Dynamics of NEO Interception" by Claude Phipps provides a basis for independent numerical estimates by those who are quantitatively inclined. It treats the whole intercept problem in an integrated graphical fashion. It reviews NEO detection range as function of scattered light, showing that for typical brightnesses, warning times could plausibly vary from years to days. It then estimates the velocity vector change and energy momentum coupling required. That provides a road map for interception, deflection, and fracture. These coupled estimates give an overall set of nomographs for general solutions, within which the point estimates of other papers fit in a reasonably consistent way.

3. Energy Delivery and Materials Interaction

If the NEO can be intercepted several orbital periods before collision, it can be adequately deflected with far less energy. Mass drivers, rockets, or possibly even Earth- or moon-based lasers might suffice, although they would represent formidable engineering chores. For larger NEOs, when the realities of energy delivery and coupling efficiency are taken into account, the energies required are even larger than those estimated above. The most effective method of deflection is to blow off part of the NEO's surface and obtain the transverse velocity needed by reaction. The smallest NEOs might be negated by nonnuclear interceptors, which could use just their kinetic energy to pulverize or deflect NEOs.

The "Workshop Summary" on energy delivery argues that for NEOs 100 meters or larger, nuclear explosives appear to be mandatory for intercepts at ranges under an AU. The most straightforward approach is to explode them at or near the NEO's surface, generating impulse as the reaction to the ejecta blown off from the resulting crater. Detonations at an optimum subsurface depth could be an order of magnitude more effective than surface detonations, but the apparatus needed for penetration could be so massive as to cancel this advantage. Furthermore, subsurface explosions have a higher probability of fracturing the NEO into a few lethal chunks on nearly the original trajectory, which could produce an even less manageable threat. The probability of fracture is minimized by an enhanced radiation explosion at a distance of about half a radius above the surface of the NEO. Energy deposition by neutrons would heat and blow off a thin layer, whose recoil would deflect the NEO. While minimizing stresses and the need for knowledge about the NEO's interior, this approach would require about a factor of 100 more energy than a surface explosion.

"Nuclear Explosive Propelled Interceptor for Deflecting Comets and Asteroids on a Potentially Catastrophic Collision Course with Earth" by Johndale C. Solem is motivated by the observation that the effectiveness of kinetic-energy deflection increases rapidly with the specific impulse of the interceptor rocket, because not only does the higher velocity interceptor create more transverse momentum by producing a larger crater and higher specific energy blow-off, but also it gets to the NEO faster, so a smaller imparted momentum can produce a given miss distance.

An interceptor using chemical propulsion might only be able to intercept an NEO at about 10% of its detection range, which makes deflection difficult. With much higher specific impulse and thrust, the interceptor could be accelerated to a much higher velocity, which would increase the intercept distance and reduce the needed deflection. If the interceptor accelerated all the way up to the NEO's speed, it would impact at about 1/3 of the detection distance, which would reduce the transverse velocity required by a factor of 3 and the kinetic energy by a factor of 10. Its specific energy release would be increased by a factor of $[(30+30 \text{ km/s})/(30+3 \text{ km/s})]^2 = 3.3$, which would make it possible to reduce the interceptor mass by a like amount.

A spacecraft uniquely combining high specific impulse and high thrust is one propelled by nuclear explosives. An unmanned vehicle can be very efficient, because it can be designed without a massive shock mitigation apparatus. The paper provides a set of analytical expressions for evaluating the performance of a nuclear explosive propelled interceptor and compares it to a chemically propelled rocket for the deflection of a 200-m asteroid detected at 1/10 AU. The nuclear interceptor weighs only 2 tons rather than the 5,000 tons of a chemical rocket, has a much smaller probability of fracturing the asteroid, and offers the option for multiple shots. The interceptor would require about 100 explosives of about 2 KT each. If the nuclear propulsion was used only in space, it should present no radiation hazard to the Earth

"Interception of Comets and Asteroids on Collision Course with Earth," also by John Dale C. Solem, discusses optimal strategies for diversion or disruption of NEOs whose collision is imminent. Such scenarios would apply for launches when the object is less than one AU from the Earth, which is a reasonable assumption for asteroids less than one km in diameter due to the difficulty of detecting them. The paper treats the diversion of the objects by blowing mass off their surface, whose recoil imparts transverse velocity to the NEO. Four mechanisms for imparting energy are considered: (1) kinetic energy of impact; (2) surface-burst nuclear explosives; (3) penetrating nuclear explosives that detonate at the optimal depth; and (4) stand-off nuclear explosives, which heat and blow material off the surface with neutrons and x-rays.

"Interception" shows that kinetic-energy deflection is effective only for quite small bodies intercepted at a substantial fraction of an AU from the Earth. Because most of the objects in this range would produce little or no damage, kinetic-energy deflection seems to be of minimal use. Nuclear explosive deflection is needed for larger objects. Nuclear surface bursts offer a 3-to-4 order of magnitude mass reduction over kinetic-energy devices, although their advantage decreases slightly with specific impulse and dramatically with NEO relative velocity. Fragmentation is a problem for intercepts closer than 1/30 AU. Because of the weight penalty associated with the penetration vehicle, nuclear penetrators offer no significant advantage over surface bursts for deflection, but are better for pulverization. Stand-off deflection greatly reduces fragmentation problems, but requires a 10 to 100-fold increase in interceptor mass.

"Cosmic Bombardment III: Ways- and Means of Effectively Intercepting the Bomblets" is the third in a series of unpublished reports by Roderick Hyde, Nicholas Colella, Muriel Ishikawa, Arno Ledebuhr, Yu-Li Pan, Lyn Pleasance, and Lowell Wood of Lawrence Livermore National Laboratory that explore various ways of countering NEOs. Only the charts are available, which is unfortunate, given the significant popular comment the presentation generated, but even the charts are stimulating. They argue that NEOs of all diameters greater than 100 m are worth intercepting, and provide economic calculations that argue that even smaller NEOs are worth addressing. Such NEOs could be addressed by current technology. The paper argues that for humanitarian as well as

economic reasons, we should address all the NEOs we can. That leads to an awkward point, because the main challenge in intercepting small NEOs is in detecting them. Given that, the rest of the technology seems to be in hand. Some advanced telescope concepts for detecting small, nearby NEOs were presented, but not in enough detail to permit their evaluation in the context of the sensors proposed by the Detection Workshop.

"Cosmic Bombardment III" argues that given our limited knowledge, big, fast NEOs on their first pass appear to present the gravest danger. It advocates a defense with several layers: flyby inspections, distant intercepts and deflections, and terminal defenses with successively larger explosives. It recognizes the need to shove, not shatter, NEO, and that precise emplacement or cratering looks hard. Thus, it also advocates standoff neutronic coupling. But it recognizes that for very big NEOs, the inefficiency of standoff coupling could impose unacceptable penalties. For them, it advocates detonation of explosives deep within the NEO—using a chain of explosions to emplace the final explosive at the optimal depth. Deflection could take hundreds or thousands of MT of explosives, although the amounts could drop to hundreds of MT if the NEO was only fractured and dispersed. It does not give quantitative estimates for the delivery systems required, but overall estimates appear to be consistent with those given by Solem.

"Cosmic Bombardment" starts with the smallest and most frequent threats and stresses the need to begin testing our ability to intercept them—an argument that was not generally accepted. Their logic is that the "next one is due anytime—[there is] no known 'leading indicator'...The empirical expectation is about "once per human lifetime of 10-100 MT events." While there are controversies over the details of these estimates—particularly over the damage due to very small NEOs—it argues that "terrestrial life just now has a representative capable of actively defending itself from the bombardment, after 4.0 eons of simply enduring it."

"Asteroid/Meteorite Analogs and Material Properties" by John L. Remo presents analogs between meteorites and asteroids that permit a classification scheme for NEOs in terms of their mechanical strength and thermal properties, which could reduce the uncertainties strategies for their interception. It presents and discusses an abridged data base to flesh out that classification, including a useful appendix on NEO materials properties, and discusses the material science work needed to support intercept experiments.

"Some Notes on Terrestrial Blasting Design and NEO Interception" by Richard Gertsch gives a helpful review of experience with terrestrial blasting. The discussion is qualitative, like blasting practice itself. It discusses the scaling of the "powder factor," which is the amount of energy and mass required to fragment a unit of rock, and of the "geometry," that determines how energy is delivered in space and time, which has a profound influence on powder factor. While not discussed explicitly, these concepts have direct analogs in the nuclear yield and placement arguments in the papers above.

The report illustrates the key problem with conventional explosives: standard high explosive (HE) powder factors are 0.05-0.5 kg HE per ton of rock, so a 1 million ton asteroid would need 50-500 tons of HE, which appear prohibitive. The preferred free-face geometry is similar to the standoff preferred for nuclear explosives. So are the optimal energy placement in space and time, the use of shaped charges and arrays, and the practical problems of material rotation, gravel pits, overkill, and fratricide. Gertsch concludes that a large single point explosion is generally less efficient than an array of smaller explosions, whose device size, number, and energy depend on geometry. It concurs with the papers discussed above in concluding that uncontrolled fragmentation is the least desirable result and that the best defense is reasonably designed overkill. Overall, most lessons from conventional explosive mining appear to carry over almost directly to kinetic energy and nuclear explosive defenses against NEOs.

"Penetrator Device Applications and NEO Materials Properties" by John L. Remo shows that penetrator devices can optimally place explosives within NEOs to optimize energy and momentum transfer and pulverization, in accord with the discussions above. But it goes further to show that penetrators have disadvantages in mass, particularly for conventional uranium alloy penetrator cores. It discusses the metallurgical properties of penetrators optimized for NEOs.

"NEO Interaction with X-Ray and Neutron Radiation" by Peter Hammerling and John L. Remo is a broad technical analysis that is intended to be accessible to a wide audience. It treats repetitive and combined x-ray and neutron interactions, seeking synergistic interactions that could reduce energy requirements. It provides analytic treatments of optimal deposition and impulse, paying particular attention to an example of x-ray coupling from an explosion of about 1 MT above the surface of the NEO. Its treatment of neutron coupling appears consistent with that of Solem. It uses the earlier Snowmass Report to estimate the total impulses needed, concluding that both x-rays and neutrons should be used to reduce the total energies required for NEOs of moderate sizes.

"Near-Earth Object Orbit Management by Explosive Impulse Thrusters" by John L. Remo and P. M. Sforza discusses penetrators with high explosive or nuclear impulse generators for orbital adjustment, surveying energy requirements for a wide parameter space. Where comparisons are possible, its results correspond to Solem and others' point calculations.

4. Vehicles and Payloads

Interception involves two types of missions: precursors to measure NEO dimensions and composition, and intercepts to divert or destroy them. The former could involve relatively low-cost interceptors derived from current defensive technologies. For useful ranges, the latter would require much larger payload masses and higher velocities than those currently available. They could benefit from research on advanced upper stages, electric, and nuclear propulsion. The nuclear rocket discussed in the first of the two papers by Solem illustrates their advantages.

The "Workshop Summary" describes typical missions: precursors to examine NEOs, intercepts to divert or fragment them, and collisions to destroy large NEOs on short notice. The report summarizes the payload mass required for each, which increase rapidly with size. It also summarizes current capabilities for delivering such masses and energies to escape velocities. The discussion of DoD capabilities is stronger than that of NASA's capabilities simply due to the interests of the attendees at the Workshop. There would appear to be an adequate set of vehicles for flyby and rendezvous missions. There is also an adequate set of small payloads with relevant passive and active visible and infrared sensors for information gathering missions from U.S. strategic defense developmental programs, which are to be tested in the next 1-2 years.

"The Strategic Defense Initiative Organization Clementine Mission" by Col. Simon P. Worden, Deputy Director for Technology of the Strategic Defense Initiative Organization (SDIO), describes a small satellite whose main mission is to test the survivability and effectiveness of an applicable set of advanced SDIO vehicles and sensors in realistic operating space conditions. Clementine will test passive and active sensors that could be useful in characterizing NEO composition and configuration through a flyby of Geographos, one of the better-known Earth-crossing asteroids. Clementine is to approach within a few kilometers, from where its lidar could map Geographos's surface with resolutions of centimeters to meters. Its detailed spectral information should also support useful resource maps and materials measurements.

The options for diverting NEOs at long range appear feasible, but are marginal and undeveloped. There does not appear to be adequate payload for divert missions at closer range, other than nuclear diversion of small NEOs. The larger launchers of the former Soviet Union could improve the capability for longer range, higher-payoff divert and destroy missions, if they could be harnessed to international needs, as suggested by current trends. The launch vehicles and payloads needed for large NEOs that approach out of the sun with little warning, as could be the case for long-period comets, appear well beyond current or planned capacity. Earlier warning with non-terrestrial sensors could reduce the intercept requirements to feasible levels.

5. Acquisition, Tracking, and Homing

NEOs must be deflected very precisely; thus, their initial trajectories and composition must be known precisely. NEOs discovered by visible sensors at ranges out to a few AU can be put into secure orbits by tracking observations with existing radars when they approach within about 0.1 AU of the Earth, as demonstrated by Workshop member Steven Ostro of JPL. Donald Yeomans, also of JPL, demonstrated that these orbits could then be extrapolated decades into the future with sufficient accuracy to assess hazards. Daniel Prono of Livermore discussed advanced technologies derived from DoD-SDIO work on free-electron lasers that could extend those ranges to ~ 1 AU.

The "Workshop Summary" describes the status of visible sensors, radars, and homing sensors. Visible cameras are quite adequate to reacquire tracks established by the telescope survey system proposed by the Detection Workshop. Radars are a proven and valuable sensor for converting rough tracks into secure orbits that can be predicted forward with confidence. They can also measure key surface and geometric properties of NEOs. While the current radar network is adequate for current discovery rates, it would be swamped by the proposed telescope array. Radars in the Southern Hemisphere would be useful in speeding up search and orbit securing. So would brighter versions that could secure the orbits of NEOs detected visibly at longer ranges than the 0.1 AU of current radars. Homing sensors for interceptors are demanding but straightforward derivatives of current defensive technologies. For a comet, however, obscuration of its nucleus by its coma may make detecting the appropriate target and precision impact more difficult.

"Acquisition and Track of Near-Earth Objects" by Gregory H. Canavan uses simple scaling arguments to compare optical and radar search and track for NEO reacquisition. Passive optical search is superficially different than radar search, but is shown to scale similarly. Optical sensors are good for long-range search; modest telescopes of a few meter diameter appear suitable for reacquisition out to about 1 AU. Efficient visible detector arrays appear feasible and attractive; recent advantages in processing could reduce false-track problems, increase speed, and automate search. Radars are useful for track and characterization, although they have shorter ranges, because they are active, and hence have better metrics, which are needed for the precise trajectory information needed to secure the orbits of newly discovered objects. Existing defense radars could have some useful capabilities for near-Earth search and track. Bistatic geometries do not appear to offer advantages. Radar and optical sensors are largely complementary. Optical sensors are best for search at long range; radars are better for track and NEO characterization at shorter ranges.

"Fireball Observation Via Satellite" by D. A. Reynolds shows that existing defense visible and infrared warning satellites could have considerable value in augmenting searches for NEOs of relevant magnitudes. It reports the detection by satellite optical sensors of an intense flash of light over the Western Pacific Ocean on 1 October 1990. The sensors, though optimized for nuclear bursts, gave high-quality intensity-time data on a fireball of visual magnitude -23. Even better performance could be expected with more modern sensors and processing. It would be desirable to fuse defense data with civil NEO searches. Had this event been recorded a year later over the Mideast, it could have been misinterpreted as the use of a nuclear weapon in the Gulf War.

6. Assessment of Future Technologies

The "Workshop Summary" gives a wide-reaching, if somewhat controversial view of the technologies that might be available for NEO interception at various future time periods. The array of technologies surveyed is encyclopedic, ranging from lasers to "brilliant mountains." The

assessments of the risks associated with the different approaches were not without controversy. Many reviewers found the survey too speculative, but the authors suspect that if anything, it is probably too conservative for the 50-100 year time frame in which stressing threats are likely to develop. Scientists are generally too optimistic about what can be done in the next few years and too pessimistic about what can be done in the next few decades. Those who try to predict even to the end of the century are looked at askance by their peers. Anyone who speculates decades to centuries ahead tends to be dismissed as irresponsible. Recognizing that, we have chosen to suspend judgment on the "Workshop Assessment of Future Technologies" and present it as written—not as a considered assessment, but as a collection of quantitative treatments of current concepts—in the hope that it will stimulate a fuller discussion in the next Workshop.

Distant intercepts provide options for advanced propulsion and deflection. Nuclear rockets could accelerate larger payloads to much higher velocities than current chemical rockets; materials mined in space could be used as expellants for rockets or mass drivers on the NEO's surface. Short-warning, close-in intercepts offer more of a challenge and fewer options. Flyout velocities needed are very high and the energies required are immense. The greatest leverage would appear to be in improving detection so that most engagements could occur at long ranges, which argues for the placement of sensors in space.

"Space Optical and Low-Frequency Radio Searches for Earth-Crossing Asteroids and Comets" by Jack G. Hills argues that spacecraft closer to the Sun would reduce biases in searching for Earth crossing asteroids. Lagrange points or orbits around Venus would not miss any NEOs approaching the Earth, even from the Sun-ward direction. Comet outgassing generates low-frequency radio emission by wiggling the magnetic field in the solar wind; thus, radio emission from NEOs is expected, and could be observable from radio arrays in space or on the moon. While there are various options for basing, the main point is that the most stressing threats appear to be long-period comets on their first approach, which tend to come out of the sun. Sensors in orbits that could view these portions of space could increase warning from months to years, which would reduce intercept requirements by orders of magnitude.

"Capturing Asteroids Into Bound Orbits Around the Earth: Massive Early Return on an Asteroid Terminal Defense System" by Jack G. Hills advocates the capture of 20-50 m asteroids into bound orbits about Earth as a way of making NEO defense pay for itself from the outset. Captured asteroids would be valuable both for material and for manned activity. Close, slow asteroids could be captured with modified ICBMs. About 5% of them are nickel-iron, and a 30 m nickel meteoroid comes within 10 Earth radii every year. Such a platform could be a major asset for future manned space programs. It could be captured for a deflection of about 1.5 km/s, which

is within reach of about 150 KT of nuclear explosives. It should be possible to practice capture beyond the moon. Doing so might take \$1-10M/ton per capture with surplus ICBMs, which could give a cost effectiveness ratio of about 10,000:1. Captured asteroids could be hollowed out for a space station or used as platforms for railguns, solar furnaces, etc.

"Discovery in Near-Earth Space" by Anthony Zuppero notes that there are many kilometer-sized objects in space with much water—some so much that asymmetric evaporation continually changes their orbits. Comet cores could be useful. They are massive and accessible sources of mass. They could give simple fuels, which could provide big, early paybacks. The paper gives a list of likely comet and NEO candidates that are close enough to be interesting to fuel a tanker to gather water for 10,000 ton payloads, which could push killer comets out of Earth-collision orbits.

"Laser Deflection of NEOs" by Claude Phipps explores the option of using ground-based lasers with mirrors in space to irradiate NEOs, generate ablation, and use the reaction to deflect them. Thrust rates are low if warning times are long, so the concept does not look impractical. The paper proposes innovative designs for space mirrors 10 to 1,000 m in diameter and lasers with pulse energies of tens of thousands of megajoules, which might be built and operated for a few billion dollars. Such lasers could also be used for metrics or as searchlights for restricted areas.

7. Future Directions for Research

NEO impacts are infrequent, but potentially serious. Impacts by very large NEOs are potentially catastrophic, but it is unlikely that there are any in orbits that will intersect the Earth in the next few centuries. This interval could give time for the development of more advanced detection and intercept technologies. Smaller NEOs impact more frequently, but their losses are bounded. Current data seem to imply that their impact frequency varies inversely with their energy, i.e., inversely with the cube of their diameter, out to diameters of a few tens of meters. It then falls roughly inversely with the square of diameters out to NEOs a few kilometers across, and a bit more slowly for very large NEOs.¹⁰ The NEOs' damage mechanisms are varied and uncertain, but the total area rendered unproductive by a NEO is generally thought to vary roughly as the square of its diameter. Convolving this impact frequency and damage area produces the total expected damage in the absence of defenses.

"Value of Space Defenses" by Gregory H. Canavan uses the empirical data in the papers discussed above to provide simple estimates of the expected losses from various classes of NEOs. For nominal parameters, the smallest NEOs, i.e., those with diameters of about 50 m or less, produce localized damage. The predicted value of the loss depends on the diameter of the smallest NEOs that can penetrate down into the atmosphere far enough to cause damage on the surface. Small stony NEOs cause little damage; the expected losses from metallic NEOs appear to be on the order of a \$M/yr.

Intermediate NEOs, with diameters from 50 to about 2,000 m, contribute more. Each octave in diameter contributes about equally to the damage, so the total damage from intermediate sized NEOs depends logarithmically on the ratio of the largest to the smallest NEOs that can cause massive but not catastrophic damage. The total loss is sensitive to uncertainties in overall collision frequencies; current data indicate expected losses on the order of \$10M/yr, which is perhaps worth insuring against.

The largest NEOs, with diameters over about 2 km, appear to hit every few million years. They have the potential to interrupt production of food and other necessities over much of the surface of the Earth for decades. With warning and preparation, damage might be kept to the world gross product for a few decades. In that case, the losses would amount to a few \$100M/yr. A by-product of this evaluation is the demonstration that detection alone would have great value in providing warning, determining the supplies needed, and identifying the areas to be evacuated.

Expected losses are sensitive to the variation of impact rates with NEO size, which is not known precisely; the area devastated by an NEO of a given size and energy; and the Earth's recovery rates. If impacted areas are only uninhabitable for a few tens of years, NEO defenses are estimated to be worth on the order of a few tens to hundreds of millions of dollars per year. If the devastated areas remained uninhabitable for much longer times, the value of defenses could increase by roughly an order of magnitude.

Thus, for nominal parameters the average loss rate has a bounded contribution from the small and intermediate NEOs that regularly damage the Earth's surface and a potentially much larger contribution from large NEOs, if any. Logically, we should properly insure against both, but their premiums and programs vary widely. A few million dollars per year could support observations with existing international Spacewatch facilities as well as theoretical and laboratory work on advanced detection and interception concepts. A few tens of millions of dollars could provide the Spaceguard telescopes proposed for the detection of large Earth-threatening NEOs. A few tens of millions per year could provide research on improved sensors for the prompt detection of smaller asteroids and long-period comets and test the robotic spacecraft missions needed to characterize NEOs of all sizes. Actual defenses against intermediate and large NEOs could ultimately cost hundreds of millions to develop and billions to deploy—but over times of decades. Unfortunately, confusion over the relative priorities of detection and interception has thus far tended to delay action on either,¹¹ even though preliminary economic estimates above indicate that the return for either would justify the research for both.¹² The hazards are global; the responses should be, too. The required actions are amenable to international execution, but the most pressing actions could be started even without international organization.

"Why Now?" Edward Teller's after-dinner speech for the Workshop, gives a tentative place to start. Observing that we weren't even able to foresee the major events of the last few years, let alone predict the rapid march in enabling technologies such as lasers, lidars, and radars, he argues that we should proceed in stages. First, we should simply accumulate knowledge, finding out all we can about meteorites from the Earth or space—and in the process, gaining useful information on backgrounds and variable stars. Second, we should experiment, trying to rendezvous with targets of opportunity, in order to see what we could do in practice. Third, we should try to intercept an NEO that wouldn't hit the Earth. Fourth and finally, we should attempt to destroy or deflect one that would.

Teller noted that the Baruch plan proposed after WWII for the international control of nuclear technology offers some guidance for the international control of the large nuclear energies and delivery means required. He ended with a challenge: "We can solve the problems both of war and meteorites. But we shall not lack problems. Man has been called a problem-solving animal. Man and woman should be called problem-creating animals. We will have *new* problems to solve."

8. Popular Reaction

NEO interception in general and the Workshop in specific received a reasonable amount of coverage in the media over the last year. This section gives a brief review of the main responses, and relates them to the Workshop's main thrusts, issues, and conclusions.

The earliest and most accessible of the popular articles was "When Worlds Collide: the Beginnings and Ends of Worlds" by Carl Sagan, which stimulated much of the early interest in the subject.¹³ Sagan argues that close encounters between heavenly bodies tend to tear them to pieces, which tends to leave our solar system a rather littered and somewhat dangerous shooting gallery. Asteroids accumulate; they wander around; they hit things. The evidence is obvious on all the moons and planets. Even the Earth shows damage, although it is protected by a thick atmosphere and consoled by an environment that quickly smoothes damage to its surface.

"When Worlds Collide" focuses attention on about 150 Earth-crossing asteroids, many of which make near misses—or "near hits," in Sagan's terminology—on geologic time scales. It observes that "it may not be beyond our ability to bring a large rocket motor to the surface of an errant asteroid and alter its trajectory just enough so it misses the Earth." It goes on to point out that "this is a much better idea than the alternative--blowing an asteroid to smithereens with a 20-megaton nuclear weapon and hoping that each smithereens burns up while entering the Earth's atmosphere." In private correspondence, Sagan acknowledges that for the biggest and fastest NEOs with the least warning time, nuclear thrust or explosives have an advantage due to their million-fold higher energy per unit mass, but he also expresses concern over the relative hazard of the NEOs and the control of the armadas needed to negate them.¹⁴

Sagan argues that "we must first know where the asteroid is and where it's headed...we're not doing a very good job in looking for them." He cites the efforts of two of the Workshop participants, Eleanor Helin and Eugene Shoemaker, who were funded in part by Sagan's Planetary Society, and calls for "a much more comprehensive search...building on the work of these pioneers." He concludes by arguing that it might be time for a "round-trip to Asteroid 4660. The rocket technology to get there already exists. It's real exploration of a truly new world, rather than the monotonous orbiting of the Earth at low altitude that is sometimes passed off as space 'exploration.' *And it might not be too soon to start practicing getting to these worldlets and diverting their orbits, should the hour of need ever arrive.*" (emphasis added).

A set of articles by Fran Smith, of the *San Jose Mercury News*¹⁵ reviews the main issues and controversies in the Workshop. A lively and accessible article in *Mercury, the Journal of the Astronomical Society of the Pacific*, presents many of the issues in the words of the participants.¹⁶ It notes that a number of novices to NASA's rendezvous programs, ourselves included, tended to dominate the meeting. It properly and correctly addresses the key issue: "What size of rock is the biggest danger?" properly assesses the "micro-asteroid threat," and notes the contradictions in the assertions by some that the Earth's atmosphere provides adequate protection against all NEOs. The articles properly capture the tension some scientists felt when they had to come to grips with the fact that the only energy sources that could keep us from sharing the fate of the dinosaurs might be the ones that brought us to the brink of extinction in the cold war. That issue of *Mercury* also contains accessible summaries of the Detection¹⁷ and Interception¹⁸ Workshops.

Perhaps the greatest publicity was generated by the editorial "Star Warriors on Sky Patrol" by Robert L. Park of the American Institute of Physics.¹⁹ It covered most of the controversies raised in the Workshop, including Dr. Edward Teller's response that it should be possible to build the nuclear explosives needed for intercept during final approach, although it would require "the development of a new super bomb—ten thousand times more powerful than any bomb ever built, a bomb so powerful it could never be detonated on Earth." The editorial also recorded one participant's reaction—"nukes forever"—although the author, who was not there, did not note that this comment simply reflected a general recognition of the enormity of the energies required for negation on final approach, not enthusiasm for nuclear weapons design. The construction of such immense explosives would involve only fairly pedestrian engineering details.

The rest of the article is a thoughtful review of the evidence for the role of NEOs in dinosaur extinction, which it credits for permitting the rise of man; the frequency of impact of NEOs of various sizes; qualitative comments on the damage they could produce; and the essentials of the proposed of detection program for very large NEOs. It concludes that very large Earth-

threatening NEOs are a "menace that, if it exists at all, might not threaten Earth for millenniums--or thousands of millenniums" by which time civilization will presumably be better equipped to deal with the problem. It ignores the question of what to do if one is detected tomorrow, which is just as likely as any given future date, as Swift-Tuttle demonstrated soon thereafter.

The editorial states that "asteroids larger than a few hundred feet in diameter can be detected and tracked with relatively modest telescopes; once located, their orbits can be refined using large planetary radars." Were that statement accepted, there would have been little controversy to report. Unfortunately, the telescopes proposed for looking for NEOs larger than a kilometer in diameter are not appropriate for detecting ones "a few hundred feet [= 100 meters] in diameter" in a timely fashion, which was an issue that divided Intercept Workshop participants. Spaceguard telescopes would detect smaller NEOs too close for action and too briefly for cataloging. There was also disagreement among the optical community over the role of more and improved radars.

In describing the Workshop as a "revival meeting for SDI true believers [who] proposed to defend Earth at stupendous cost against an imagined menace..." the editorial returned to the serious issue raised earlier by Sagan. The technologies and energies required for detection and defense against NEOs are at the limit of those possessed by man. Deciding how they should be controlled could be as difficult as developing them. It may be time to begin thinking about those issues.

Roger Lewin's "How to Destroy the Doomsday Asteroid"²⁰ covers many of the same issues as Dr. Park's editorial, but characterizes the Interception Workshop's approaches as "credible." It cites additional evidence from noted paleobiologists on extinctions, gives more data about recent misses, and raises the connection with nuclear winter. It is less concerned with the waste of resources than it is with the apparent enthusiasm some showed for finding something else to do with our nuclear arsenals.

Robert Matthews' "A Rocky Watch for Earthbound Asteroids"²¹ gives more information on the split within NASA and Dr. John Rether's role in directing attention to NEOs of diameters down to 50 m or so. It gives a stimulating discussion of the Earth's near-impact in January of 1991 with a 10 m NEO that came within 170,000 km of the Earth only 12 hours after it was discovered by University of Arizona astronomers with the 36-inch Spacewatch Telescope at Kitt Peak. It underlines the key economic issue noted above by reporting the estimate by Richard Binzel of MIT that searching for smaller, more frequent objects could be an order of magnitude more expensive than the telescopes optimized for very large NEOs only. The version of Matthews' story reported abroad, "Missiles to zap meteor menace," stressed the secrecy of the meeting at Los Alamos,²² although the Workshop was, in fact, unclassified. The press was not invited in an attempt to prevent sensationalization of the subject. So much for good intentions.

Bob Davis's "Never Mind the Peace Dividend, the Killer Asteroids are Coming" in part just reflects the *Wall Street Journal*'s wry humor, but it captures the essence of Solem's approach to giving large NEOs a "gentle push."²³ Kathy Sawyer's *Shooting Back at Space Rocks?*²⁴ gives more data on the Yucatan and Tunguska impacts. It also elicits a concrete answer from Dr. Morrison on what he would do about the "undetected 10% of NEOs:" "My approach is risk reduction, he said, not risk elimination." *Time*'s "Talk About Star Wars" notes that atomic-weapons designers [including its former man of the year] "appear to have been casting around for a mission" but concludes that "keeping an eye on runaway asteroids makes sense."²⁵

9. Critical Reaction

In addition to the popular comment discussed in the previous section, there was a considerable amount of technical correspondence between the authors, which materially improved the balance of the Proceedings, although it was ultimately unable to produce a consensus document. This section discusses the main issues raised, indicates which ones were solved, and reviews the state of play on those which are still open. The principal inputs from David Morrison, the Chairman of the Detection Workshop, and Clark R. Chapman of the Planetary Science Institute in Tucson, Arizona are discussed in order below.

Many objections had to do with the "Executive Summary and Program--Policy Options" section of the draft *Summary Report* prepared by JPL for NASA from the working group summaries from the Interception Workshop.²⁶ This *Proceedings* differs in essential ways from NASA's *Summary Report*. The *Executive Summary* of the *Proceedings* differs from that of the *Summary Report* by removing the statements on which there was no consensus, and the *Summary Report*'s "Program--Policy Options" was dropped and replaced by sections on "Future Directions for Research and Popular Reactions." The "Program--Policy Options" section of NASA's *Summary Report* is reproduced here as Appendix A--not by way of recommendations for this report, but as background for interpreting Morrison and Chapman's correspondence.

Much of the disagreement centered on the need for early deflection experiments, which could divert funds needed for the timely upgrading of existing and implementation of new detection capabilities. A second point of contention had to do with the desirability of early experiments on NEO deflection, which could lead to a preliminary capability for the interception of small NEOs. A third point had to do with the *ad hoc* suggestion that existing nuclear arsenals could be mobilized for protection against larger NEOs, which most found to be premature and undeveloped.

David Morrison summarized many of the criticisms of the draft *Summary Report* in a letter that was circulated to many of the workshop participants.²⁷ It stressed "a general failure to distinguish the greater hazard associated with 'large' impactors (greater than about a million megatons) from the smaller hazard posed by smaller bodies...[which] leads to an equally large

failure to apply any measures of cost-effectiveness to the various schemes proposed to deal with the impact threat. *Note that I am not objecting to the discussions of interception and deflection of objects in the 100 m to 1 km size range, but only to the lack of context in which some of the discussions are presented.*" (emphasis added). The calculations by Hills and Goda, which were the only quantitative estimates of damage presented, provide additional information on the damage from small and intermediate NEOs. They were used to estimate expected losses in the "Value of Space Defenses." Although there are significant uncertainties in the data, it appears that detecting and deflecting NEOs of both intermediate and large sizes is economically justified and that a responsible program would do both in an integrated fashion. Smaller NEOs appear to be of lesser concern for nominal collision rates; although, small metallic NEOs appear to be significant if more recent data is used in the evaluations.

The calculations in "Value of Space Defenses" form a rudimentary version of the cost-effectiveness analysis requested. They give expected losses that can be used to measure the effectiveness of proposed intercept schemes. They also give an expected value of detection alone, because they give an estimate of the expected frequency and extent of damage, which can be used to bound the effectiveness of evacuation and preparation. The calculations also attempt to bound the losses from very large NEOs, given warning and preparation. These estimates involve additional uncertainties due to current technical controversies over the extent and duration of global damage, which are discussed further below.

Morrison commented on the iterated draft of NASA's *Summary Report* in a 10 June letter, which was also circulated to participants.²⁸ The positive part was its statement that "as a member of the Program/Policy Options group, I can say that our chapter [of the *Summary Report*] seems to fairly represent the consensus conclusions of this group." The negative part was its assessment that "the [*Summary*] *Report* as a whole...remains unsatisfactory." The letter cited two major problems: "First, it is consistently and pervasively biased toward discussions aimed (!) at the smaller and less threatening objects...Second, Chapter 6 is simply dumb, irresponsibly so, and seriously undermines the credibility of the entire *Report*." It concludes that "I do not want to be associated with the [*Summary*] *Report* in its present form." It suggests that it would be better to "refer to the Morrison Report, summarize its conclusions, and note that the [*Summary*] *Report* differs in its interpretation and conclusions. You might even consider explaining why you differ..."

This *Proceedings* incorporates Morrison's suggestions to the maximum extent possible. "Future Directions for Research" follows the research recommendations of the Program/Policy Options group and presents a balanced view of large and small threatening NEOs. However, Chapter 6 is retained, albeit in modified form, for the reasons given above. In the long term we will need to address large, fast objects that approach with little warning. Current technology would

not be effective against such threats, and even those on the horizon appear marginal. Different and more powerful techniques are needed. There is apparently time to develop them, but no time to lose, so some stimulating discussion is essential. Having reviewed these changes, Morrison indicated his desire to be associated with the *Proceedings*.

Clark Chapman's initial criticisms of the *Summary Report* were transmitted in a letter of 8 April 1992 "In the hopes that the report will be modified so as to be improved and acceptable...the draft report demonstrates a lot of conscientious effort and it represents a nucleus of material that could be converted, in short order, into a good and acceptable report. I applaud everyone concerned for bringing the report to this state of readiness in only two months. Appropriate modifications could be made within a matter of weeks."²⁹ However, a second letter of 8 June 1992, which was also circulated and is reproduced as Appendix B, criticized the revision of the *Summary Report*, stating it is "biased and technically flawed...I do not wish my name associated with it...[and I] ask that my name be removed from the report.." It objects to technical material in the working group summaries in the *Summary Report* and to the implication that the working group members are responsible for materials on which no consensus was produced and which were rewritten by NASA and JPL. The *Proceedings* defines their responsibilities explicitly. Chapman also objects that the "Executive Summary" contains a recommendation for an experimental program that was not present in the summary NASA prepared for Congress. The *Proceedings* deletes that recommendation, which was not a consensus position of the workshop.

Chapman also objects to the "improper treatment" of the "relative importance of the Tunguska-class' impacts versus larger ones..." The estimates in the "Value of Space Defenses" attempt to remove this bias; its results support Chapman and Morrison's estimates that for nominal parameters the largest NEOs make the largest contributions to expected losses. Chapman objects to dismissing search as "futile." "Value" shows that search and warning have considerable value in preparing for impact, even in the absence of defenses. Chapman also objects to what appears to be a premature push for potentially expensive space experiments, which were not endorsed by all workshop participants. The *Proceeding* just notes that they will be appropriate at some time, but that a number of issues must be resolved before one can design a credible experiment. Chapman objects to "a bias toward SDIO spacecraft [that] ignores all NASA studies of NEO missions." Experiments should clearly involve the best of both NASA and DoD-SDIO technology. SDIO does have a requirement and program to develop relevant sensors and launchers. It would be shortsighted to neglect capabilities that could be applied with little cost to a pressing national program for purely jurisdictional reasons.

Chapman also criticizes the "crazy and dangerous option of outfitting the world's arsenal of rockets with the world's arsenal of nuclear weapons in order to address an aspect of the NEO hazard," which is a colorful restatement of the concern raised earlier by Sagan. Many participants felt that it was premature to consider nuclear tests in space, let alone outfit a nuclear armada. It is not even clear that the interceptors should be deployed in space. It is clear that discussions of deployments of nuclear weapons in space are premature. Most participants would apparently be critical of even nonnuclear deflection tests that preceded a demonstrated ability to measure trajectories and perturbations well enough to assure that the deflection would do more good than harm. Chapman is equally colorful in his assessment of the section on new technologies. The rest of his letter offers positive suggestions for improved wording.

Having reviewed the draft of the *Proceedings*, Chapman accepted our offer to publish his letter of 8 June,³⁰ and provided additional comments, which are included as Appendix B. He stated that he wished to do so because time prevented our iterating to convergence, not all of his points were addressed in the draft *Proceedings*, and his earlier comments are still relevant to the *Summary Report*, which may be published separately by NASA. Most of his points serve to clarify the impact of "Tunguska-class" NEOs. He argues that they are not worth insuring against, which agrees with the evaluation of "Value of Space Defenses," which lumps "Tunguska-class" impactors into the small NEOs that only appear to justify a few \$M/yr premium. Chapman also rightly notes that these small NEOs are difficult to detect, so it is unlikely that effective protection could be provided for so small a sum, which is also the conclusion of "Value of Space Defenses."

Chapman states the *caveat* that "if the preliminary results of the Spacewatch Program are correct about an enhanced number of 50-100 m objects, and if the threshold for global catastrophe is near the upper end of the range of uncertainties, then the annualized risk of fatalities might actually be dominated by Tunguska-class impactors...[but he] would still argue, however, that the globally catastrophic impactors deserve our attention far beyond their strictly numerical hazard. That is for the simple reason that if civilization is threatened, then all of history and everything that is important to us is at risk." This statement disagrees with "Value of Space Defenses" and raises a fundamental point.

Chapman and Morrison effectively argue that any NEO over a few kilometers in diameter could end civilization if not all life on Earth; hence, their potential loss is unbounded. "Value" assumes that with warning, evacuation, and preparation, civilization could bound its losses from most NEOs to the economic value of the structures destroyed, the production lost, and the cost of the foodstuffs and supplies that would have to be stored ahead of time for survival. This argument breaks down for NEOs of sizes that could literally fracture the Earth and dissipate its atmosphere, but that only for NEOs whose diameters were orders of magnitudes larger than the few kilometers Chapman and Morrison associate with global catastrophe—by which they actually just mean global

climate impact. The NEO community will probably have to repeat the learning process the "nuclear winter" community went through before it can estimate with confidence what it takes for catastrophic damage to society. Experience suggests that it will probably be easier to import those arguments than to solve them. Thus, the debates over expected losses from very large NEOs are likely to broaden and deepen rather than simplify over the next few years.

Similar civil defense efforts could offset the global impacts of either nuclear war or the impact of large NEOs. There is a difference. Civil defense as a response to nuclear war is opposed because its implementation might make war more thinkable and hence undercut its deterrence. NEOs cannot be deterred, so there should be no such popular impediments to the implementation of civil defense measures and evacuation, given adequate warning. For the same reason, there should be no popular impediments to the development of active defenses against NEO impacts.

10. Summary and Conclusions

Congress mandated two workshops to improve the means to detect and negate NEOs; this report reviews the results of the latter. It summarizes the Interception Workshop held at Los Alamos in January 1992, which evaluated the technical issues involved in intercepting approaching NEOs. The Workshop covered the technologies for re-acquiring, tracking, and homing on NEOs as well as the technologies for inspecting, rendezvousing with, landing on, irradiating, deflecting, or destroying them. It records the presentations and technical options reviewed, outlines the main points of agreement and disagreement, summarizes the status of the main remaining arguments, and outlines apparently fruitful areas for further research.

A background paper reviews the rough size, composition, velocity, and warning time for threatening NEOs, indicating the order of magnitude of their impact frequency and expected damage. It also summarizes representative intercept missions. An invited paper by David Morrison, who chaired the Detection Workshop, argues that NEOs pose a significant hazard to life and property and that they could disturb the Earth's climate on a global scale by injecting large quantities of dust into the stratosphere. He introduced the discussion of the relative importance of small and very large NEOs, which dominated the meeting, arguing for a long-term telescopic search that would first concentrate on identifying large NEOs.

Prominent astronomers discussed details, results, and prospects for NEO searches. Some were somewhat less sanguine than Dr. Morrison about predicting the history or trajectories of NEOs, once discovered, due to perturbations, which eventually randomize their orbits. They stressed threats posed by long-period comets, which are numerically less likely, but give less

warning, and have very high kinetic energies. Hills and Goda introduced the difficult and controversial subject of the damage from NEOs that break up in the atmosphere before hitting the ground, which made it possible to quantify the impact of smaller NEOs, and ultimately to reduce much of the confusion over the relative importance of very small and large NEOs.

It became clear during the workshop that detection and interception are interrelated, because the farther away a threatening NEO is detected, the farther away it can be engaged, and the easier it is to deflect or destroy. NEOs whose exact orbits could be established decades or centuries ahead of impact could be addressed by rendezvous missions that could apply impulses of centimeters to meters per second at perihelion to shift the NEOs' trajectory just enough to miss the Earth. For less warning, more deflection would be required, ultimately requiring nuclear propulsion or explosion. For short-warning NEOs on collision courses, the interceptor would have to deflect or destroy the NEO on its final approach. The energies required are at the limit of those that can now be generated by man.

The most effective method of deflection is to blow off part of the NEO's surface and use its reaction to obtain the transverse deflection of the NEO needed. A number of scientists discussed the advantages of emplaced, surface, and standoff explosions in a thorough and consistent manner. They argued that for intercepts on final approach, NEOs 100 meters or smaller could be addressed by nuclear rockets and kinetic energy kill, but that for larger NEOs, nuclear explosives appear to be essential. There appears to be a set of technologies that could provide some intercept capability against the smallest, most frequent impactors, although their detection would be difficult. The largest, fastest NEOs are the easiest to detect, but their intercept looks formidable. Enough is understood about NEO materials and geometries to reduce uncertainties in interception to levels that could make tests profitable and safe.

There are two types of precursor missions: those which seek to measure the properties of NEOs and those that seek to divert or destroy them. The former could involve interceptors derived from current defensive and civil technologies. There is an adequate set of lightweight passive and active sensors available from defense development programs. Inspection and intercept missions could both require larger payload masses and higher velocities than those currently available. If available, the large launch capacities of the Former Soviet Union could greatly improve the capability for longer range, larger payoff divert and destroy missions.

NEOs must be deflected very precisely, which means that their initial trajectories and composition must be known precisely. NEOs discovered by visible sensors at ranges out to a few AU can be put into secure orbits by tracking observations with existing radars when they approach within about 0.1 AU of the Earth. Their orbits could then be extrapolated decades into the future with sufficient accuracy to assess hazards. Homing sensors for the interceptors could be derived from current defensive technologies. While the current radar network is adequate for current

discovery rates, it could be swamped by the discovery rates from the proposed telescope array. Existing defense radars and optical and infrared sensors could have some useful capabilities for near-Earth search and track. Radars and optical sensors are largely complementary. Optical sensors are best for search at long range; radars are best for track and characterization at short ranges.

The report contains a section that gives a wide-reaching, if somewhat controversial, view of the technologies that might be available for NEO interception at various future time periods. The array of technologies surveyed is encyclopedic. Many found the survey too speculative, but the authors suspect that, if anything, it is probably too conservative for the 50-100 year time frames on which the most stressing threats are likely to develop. The assessments are presented, without endorsement, to encourage further discussion. One of the most intriguing concepts was capturing NEOs into bound orbits as a way of making NEO defense pay for itself from the outset.

NEO impacts are infrequent, but potentially serious. The average loss rate has contributions from NEOs of all sizes. Their contributions can be lumped into three rough categories, which are determined by the empirical variation of impact frequency with NEO diameter. Stony NEOs down to about 40 m in diameter can produce damage on the Earth's surface, but the damage is local and modest; hence, their contribution to the total loss only amounts to a few \$M/yr for nominal parameters. Intermediate size NEOs with diameters from 50 m to about 2 km contribute about equally to expected damage, giving a value of warning or defense of \$10—100M/yr, depending on uncertainties in impact frequencies. NEOs with larger diameters can produce global effects. There is some controversy over how to estimate their impact, but it appears that their contribution is one to two orders of magnitude greater than that from intermediate size NEOs.

Logically, both intermediate and large NEOs should be insured against, but their premiums vary greatly. A few \$M/yr could support observations and theory on detection and interception. A few \$10M could provide the Spaceguard telescopes proposed to search for large Earth-threatening NEOs. A few \$10M/yr could provide research on improved sensors for the prompt detection of smaller asteroids and test spacecraft missions to characterize NEOs of all sizes. Actual defenses would ultimately cost a few \$100M to develop and a few \$B to deploy over a few decades. Unfortunately, confusion over the relative priorities of detection and interception has delayed action on either. In his concluding talk, Edward Teller proposed a knowledge-driven, multi-stage program as a way to break this logjam.

The Workshop received a reasonable amount of coverage in the media. The report gives a brief review of the main responses, and relates their main thrusts with the Workshop issues discussed above. The most publicity was generated by an editorial that reported most of the controversies raised in the Workshop, including "the development of a new super bomb," which,

as indicated above, just reflected a recognition of the enormous energies required for intercepts in the final phase. The rest of that article, and most of the other popular coverage, gave thoughtful reviews of the role of NEOs in dinosaur extinction, frequency of impact, the damage they could produce, and the essentials of the proposed detection program.

There was significant, constructive critical reaction, which is also summarized. The comments by Morrison and Chapman were particularly helpful. They clarified the extent of agreement over the preferred emphasis on large versus small NEOs, readiness for test, the role of conventional and nuclear technologies, and the relative priorities of detection and deflection and of early and late intercept. This clarification could pave the way for a very productive follow-up meeting on NEO Interception. In preparation for such a meeting, it would be useful to peer review the detailed estimates of damage from small NEOs presented here, obtain quantitative estimates of global effects, and complete the bounding calculations of economic loss. It would also be useful to continue the exchange of information on NASA, DoD, and Russian launchers, payloads, and sensors, and solicit and integrate sensor inputs from multiple and national sources. It would also be appropriate to establish international cooperation on analysis, for which this volume provides some of the data needed, and to begin discussions on means for implementing and controlling the defensive concepts for NEO impacts, which now appear feasible.

13. Epilogue

It has been almost a year since the Interception Workshop was held. Much has happened in that time. Many of the subsequent technical exchanges, which led to much more of a consensus on the relative importance of NEOs of different sizes and other technical issues, are discussed above. A singular stimulating event was the reappearance of the comet Swift-Tuttle, which seemed to present just the stressing threat identified by the Workshop. Its orbit had enough uncertainty to cause Brian Marsden, a Workshop participant who runs the Smithsonian's NEO watch, to issue its first NEO impact warning,³¹ giving a probability of about 1 in 10,000 of an impact on Swift-Tuttle's return in 2126. That set off a vigorous round of interaction³² and rechecking, prominently involving many of the Workshop participants,³³ which is reviewed in the timely and accurate *Newsweek* report by Sharon Begley which is reprinted as Appendix D.³⁴

This interaction and rechecking has led to a lowering of the probability of impact, so the threat has receded. But the process gave a check on the relevance of the topics covered in the Workshop that is worth reviewing. As noted, the reappearance was noted and interpreted by the existing observational network, which attests to both its capability and the relevance of the improved Spaceguard network proposed by the Detection Workshop. Moreover, the main issues involved in the assessment of risk from Swift-Tuttle—uncertain observations, imprecise predictions, and non-gravitational effects—were precisely those debated by Brian Marsden, Don

Yeomans, Duncan Steel, and others at the Interaction Workshop. Even though Swift-Tuttle is enormous—about 10 km across—the participants were all comfortable with our ability to deflect or destroy it, given a century of warning, on the basis of the astrodynamical and energy delivery estimates presented at the Interception Workshop—even though it would in all probability involve a rather large nuclear weapon. The workshop also defined the materials information that would need to be measured by rendezvous missions prior to intercept in order to assure that the NEO could be pushed aside, rather than just fragmented. It even appeared that there might be relevant sensors and adequate lift capacity for the intercept.

If there was one area in which there were deficiencies, it was in the area of the sensors and boosters needed for rendezvous missions. Had we needed to inspect the materials, geometry, and integrity of Swift-Tuttle, the options for sensors and launchers were quite limited. At present only the visible and infrared active and passive sensors of the SDIO's Clementine mission have been lightweighted to the extent needed for the chase. Swift-Tuttle is out of the plane of the ecliptic and moving fast, so velocity increments of up to 30-40 km/s would be required for direct rendezvous. Even with a 3-10 kg instrument package and a specific impulse of 300 seconds, a chemical rocket would need to put about 3-10 kg $e^{(30 \text{ km/s} / 3 \text{ km/s})} \approx 70\text{-}200$ tonnes into escape velocity, as opposed to the few tens of tons now available from even a full international collaboration. Thus, work on more appropriate lightweight sensors, higher specific impulse and thrust rockets, and larger and more flexible payloads would be appropriate in preparation for another such alert. Still, it would appear that the deliberations of the Workshop carried over rather directly into the evaluation of Swift-Tuttle. The organizers might even persuade themselves that some of the relationships established at the Workshop were of value in the process. If so, the melding of the two communities should be of value in future alerts as well.

13. Acknowledgments

The authors, who are familiar with defensive technologies but relatively new to NEO detection and interception, would like to acknowledge many helpful and friendly conversations with the many participants from both communities who came together for the first time at this Workshop. They would particularly like to acknowledge the numerous and thoughtful communications with David Morrison and Clark Chapman, which greatly refined and ultimately reduced the confusion and disagreement over the relative importance of NEOs of different sizes.

They would also like to thank those authors who provided many corrections and positive suggestions for improving the clarity and technical content of the text. Brian Marsden, Tom Gehrels, and John Remo were particularly conscientious in that regard, as well as generous in sharing their more recent data. The authors would like to apologize for the delay in publishing the *Proceedings*, which was due in large measure to their diversion into formulating cooperative

scientific projects with the Former Soviet Union after the Washington Summit. That did, however, provide time for the further exchanges discussed, which greatly advanced our understanding of the contributions from NEOs of different sizes, leading to a final product that reflects much more consensus than was evident at the Workshop and in the immediate reporting thereafter.

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THE IMPACT HAZARD

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***Chair, NASA International Near-Earth-Object Detection Workshop**

ABSTRACT

Impacts by Earth-approaching asteroids and comets pose a significant hazard to life and property. The greatest risk is associated with objects large enough to disturb the Earth's climate on a global scale by injecting large quantities of dust into the stratosphere. Such an event would depress temperatures around the globe, leading to massive loss of food crops and possible breakdown of society. The possibility of such a global catastrophe is beyond question, but determining the threshold impactor size to trigger such an event is more difficult. Various studies have suggested that the minimum mass impacting body to produce such global consequences is tens of billions of tons, resulting in an explosion with energy approaching a million megatons of TNT. The corresponding threshold diameter for Earth-crossing asteroids or comets is between 1 and 2 km. Smaller objects (down to 100 m) can cause severe local damage but pose no global threat; the risk of such explosions is small compared to other common natural hazards such as earthquakes and severe storms. For sizes below 100 m, most projectiles disintegrate high in the atmosphere and pose no significant threat. Current technology permits us to discover and track nearly all Earth-crossing asteroids or short-period comets large enough to threaten global catastrophe. We require a long-term telescopic search that reaches stellar magnitude 22 in order to achieve a nearly complete census of objects 1 km or larger. If any object threatens impact with the Earth during the next century or so, we can expect it to be identified with a lead time of at least several decades, sufficient to plan an international campaign to deflect or destroy it.

THE IMPACT HAZARD

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BACKGROUND

The Earth resides in a swarm of cosmic debris that can, and do, impact its surface. The solar system contains a long-lived population of asteroids and comets, some fraction of which are perturbed into orbits that cross the orbits of the Earth and other planets. Spacecraft exploration of the terrestrial planets and the satellites of the outer planets has revealed crater-scarred surfaces that testify to a continuing rain of impacting projectiles. Additional evidence concerning cosmic projectiles in near-Earth space has accumulated since the discovery of the first Earth-crossing asteroid nearly sixty years ago, and improvements in telescopic search techniques have resulted in the discovery of dozens of near-Earth asteroids and short period comets each year. The role of impacts in affecting the Earth's geological history, its ecosphere, and the evolution of life itself has become a major topic of current interdisciplinary interest.

In the following discussion, we examine the risks posed by impacting objects of various sizes. These projectiles could be either cometary or asteroidal. In terms of the damage they do, it matters little whether they would be called comets or asteroids by astronomical observers. We term these objects collectively NEOs (Near Earth Objects). This analysis is derived from the NASA document *The Spaceguard Survey*, dated January 25, 1992, which is the report of the NASA International Near-Earth-Object Detection Workshop.

Estimates of the population of NEOs large enough to pose a global hazard are reliable to within a factor of two, although estimates of the numbers of smaller objects are more uncertain. Particularly uncertain is the significance of hard-to-detect long-period or new comets, which would generally strike at higher velocities than other NEO's, although asteroids (including dead comets) are believed to dominate the flux. However, the resulting environmental consequences of the impacts of these objects are much less well understood. The greatest uncertainty in comparing the impact hazard with other natural hazards relates to the economic and social consequences of impacts.

THE RELATIONSHIP OF RISK TO SIZE OF IMPACTOR

Small impacting objects -- the meteors or fireballs -- dissipate their energy in the upper atmosphere and have no direct effect on the ground below. Except for the rare iron objects, it is only when the incoming projectile is larger than about 100 m diameter that it begins to pose significant hazard to humans. The hazard can be conveniently divided into three broad categories that depend on the size or kinetic energy of the impactor:

- (1) Impacting body generally is disrupted at high altitudes, with its kinetic energy dissipated in the atmosphere.
- (2) Impacting body reaches the lower atmosphere (within 2 scale heights of the surface) or the ground sufficiently intact to inflict widespread local damage .
- (3) Large crater-forming impact generates globally dispersed dust to produce a significant, short-term change in climate, in addition to devastating blast effects in the region of impact.

The threshold size of an impacting body for each category depends on its density, strength, and velocity as well as on the nature of the target. The threshold for global effects, in particular, is not well determined.

Category 1: 10-m to 100-m diameter impactors

Bodies near the small end of this size range intercept Earth every decade. Bodies about 100 m diameter and larger strike, on average, several times per millennium. The kinetic energy of a 10-m projectile traveling at a typical atmospheric entry velocity of 20 km/s is about 100 kilotons TNT equivalent, equal to several Hiroshima-size bombs. The kinetic energy of a 100-m diameter body is equivalent to the explosive energy of about 100 megatons, comparable to the yield of the very largest thermonuclear devices.

For these projectiles, only rare iron or stony-iron projectiles reach the ground with a sufficient fraction of their entry velocity to produce craters, as happened at Meteor Crater (Arizona) 50,000 years ago or in the Sikhote-Alin region of Siberia in 1947. Stony bodies are crushed and fragmented in the upper atmosphere, and the resulting fragments are quickly slowed to free-fall

velocity, while the kinetic energy is transferred to an atmospheric shock wave. Part of the shock wave energy is released in a burst of light and heat (called a meteoritic fireball or bolide) and part is transported in a mechanical wave. Generally, these disruptions occur so high in the atmosphere that no damage occurs on the ground, although the fireball can attract attention from distances of 600 km or more and the shock wave can be heard and even felt on the ground.

With increasing size, asteroidal projectiles reach progressively lower levels in the atmosphere before disruption, and the energy transferred to the shock wave is correspondingly greater. There is a threshold where both the radiated energy from the shock and the pressure in the shock wave can produce damage. A historical example is the Tunguska event of 1908, when a probably stony body 50-100 m in diameter was disrupted in the atmosphere at an altitude of about 8 km. The energy released was about 12 megatons, as estimated from airwaves recorded on meteorological barographs in England, or perhaps 20 megatons as estimated from the radius of destruction. Siberian forest trees were mostly knocked to the ground out to distances of about 20 km from the end point of the fireball trajectory, and some were snapped off or knocked over at distances as great as 40 km. Circumstantial evidence suggests that fires were ignited up to 15 km from the endpoint by the intense burst of radiant energy. The combined effects were similar to those expected from a nuclear detonation at a similar altitude, except, of course, that there were no accompanying bursts of neutrons or gamma rays nor any lingering radioactivity.

Category 2: 100-m to 1-km diameter impactors

Incoming asteroids of stony or metallic composition that are larger than 100 m in diameter may reach the ground intact and produce a crater. The threshold size depends on the density of the impactor and its speed and angle of entry into the atmosphere. Evidence from the geologic record of impact craters as well as theory suggests that, in the average case, stony objects greater than 150 m in diameter form craters. They strike the Earth about once per 5000 years and -- if impacting on land -- produce craters about 3 km in diameter. A continuous blanket of material ejected from such craters covers an area about 10 km in diameter. The zone of destruction extends well beyond this area, where buildings would be damaged or flattened by the atmospheric shock, and along particular directions (rays) by flying debris. The total area of destruction is not, however, necessarily greater than in the case of atmospheric disruption of somewhat smaller objects, because much of the energy of the impactor is absorbed by the ground during crater formation.

Comets are composed in large part of water ice and other volatiles and therefore are more easily

fragmented than rocky or metallic asteroids. In the size range from 100 m to 1 km, a comet probably cannot survive passage through the atmosphere. This is a subject that needs additional study, requiring a better knowledge of the physical nature of comets.

Category 3: 1 km to 5 km diameter impactors

At these larger sizes, a threshold is finally reached at which the impact has serious global consequences, although much work remains to be done to fully understand the physical and chemical effects of material injected into the atmosphere. In general, the crater produced by these impacts has 10 to 15 times the diameter of the projectile; i.e., 10-15 km diameter for a 1-km asteroid. Such craters are formed on the continents about once per 300,000 years. At impactor sizes greater than 1 km, the primary hazard derives from the global veil of dust injected into the stratosphere. The severity of the global effects of large impacts increases with the size of the impactor and the resulting quantity of injected dust. At some size, an impact would lead to massive world-wide crop failures and might threaten the survival of civilization.

What happens when an object several kilometers in diameter strikes the Earth at a speed of tens of kilometers per second? Primarily there is a massive explosion, sufficient to fragment and partially vaporize both the projectile and the target area. Meteoric phenomena associated with high speed ejecta could subject plants and animals to scorching heat for about half an hour, and a global firestorm might then ensue. Dust thrown up from a very large crater would lead to total darkness over the whole Earth, which might persist for several months. Temperatures could drop as much as tens of degrees C. Nitric acid, produced from the burning of atmospheric nitrogen in the impact fireball, would acidify lakes, soils, streams, and perhaps the surface layer of the oceans. Months later, after the atmosphere had cleared, water vapor and carbon dioxide released to the stratosphere would produce an enhanced greenhouse effect, possibly raising global temperatures by as much as ten degrees C above the pre-existing ambient temperatures. Both the initial months of darkness and cold, and then the following years of enhanced temperatures, would severely stress the environment and would lead to drastic population reductions of both terrestrial and marine life.

THRESHOLD SIZE FOR GLOBAL CATASTROPHE

The threshold size of impactor that would produce one or all of the effects discussed above is not accurately known. The geochemical and paleontological record has demonstrated that one impact (or perhaps several closely spaced impacts) 65 million years ago of a 10- to 15-km NEO

resulted in total extinction of about half the living species of animals and plants. Such mass extinctions of species have recurred several times in the past few hundred million years; it has been suggested, although not yet proven, that impacts are responsible for most such extinction events. We know from astronomical and geological evidence that impacts of objects with diameters of 5 km or greater occur about once every 10 to 30 million years.

Death by starvation of much of the world's population could result from a global catastrophe far less horrendous than those cataclysmic impacts that would suddenly render a significant fraction of species actually extinct. The threshold almost certainly lies between about 0.5 km and 5 km diameter, and it probably lies near 2 km. In addition to all of the known variables (site of impact, time of year) and the uncertainties in physical and ecological consequences, there is the question of how resilient our agriculture, commerce, economy, and societal organization might prove to be in the face of such an unprecedented catastrophe.

An estimate of the threshold size was derived by Brian Toon, of NASA Ames Research Center. Of the various environmental effects of a large impact, Toon believes that the greatest harm would be done by the sub-micrometer dust launched into the stratosphere. The quantity of submicrometer dust required for these effects is estimated at about 10,000 Tg. ($1 \text{ Tg} = 10^{12} \text{ g}$) For a 30 km/s impact, this translates to a threshold impacting body diameter of between 1 and 1.5 km diameter. At the 1991 Near Earth Asteroid Conference in San Juan Capistrano, California, the most frequently discussed estimate of the threshold impactor diameter for globally catastrophic effects was about 2 km, which is generally consistent with Toon's estimate. Impacts of objects this large occur from one to several times per million years.

RISK ANALYSIS

If this estimate is correct, then the chances of an asteroid catastrophe happening in the near future -- while very low -- is greater than many other threats to life that our society takes very seriously. For purposes of discussion, we adopt the once-in-500,000 year estimate for the globally catastrophic impact. It is important to keep in mind that the frequency could be greater than this, although probably not by more than a factor of two. The frequency could equally well be a factor of two smaller.

Because the risk is very low of such an impact happening in the near future, the nature of the impact hazard is unique in our experience. Nearly all hazards we face in life actually happen to someone we know, or we read about them happening in the newspapers, whereas no large

impact has taken place within the total span of human history. (If such an event took place before the dawn of history roughly 10,000 years ago there would be no record of the event, since we are not postulating an impact large enough to produce a mass extinction that would be readily visible in the fossil record). But also in contrast to more familiar disasters, the postulated impact would produce devastation on a global scale. Natural disasters, including tornadoes and cyclones, earthquakes, tsunamis, volcanic eruptions, firestorms, and floods often kill thousands of people, and occasionally several million. But the civilization-destroying impact exceeds all of these other disasters in that it could kill a billion or more people, leading to as large a percentage loss of life worldwide as that experienced by Europe from the Black Death in the 14th century. It is this juxtaposition of the small probability of occurrence balanced against the enormous consequences if it does happen that makes the impact hazard such a difficult and controversial topic.

We begin to address the risk of cosmic impacts by looking at the frequency of events of different magnitudes. Small impacts are much more frequent than large ones, as is shown in Figure 1, which illustrates the average interval between impacts as a function of energy, as derived from the lunar cratering record and other astronomical evidence. For purposes of discussion, we consider two cases: The threshold globally catastrophic impact discussed above, and for comparison, a Tunguska-class impact from a smaller object perhaps 100 m in diameter. In all of the calculations given below, the numbers are approximate and are used only to illustrate the general magnitudes involved.

For the globally catastrophic impact (assumed 2 km threshold)

Average interval between impacts	500,000 years
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For the Tunguska-class impacts:

Average interval between impacts for total Earth:	300 years
Average interval between impacts for populated area of Earth	3,000 years
Average interval between impacts for world urban areas:	100,000 years
Average interval between impacts for U.S. urban areas only:	1,000,000 years

We see from this simple calculation that even for a large country such as the U.S., the Tunguska-class impacts on urban areas occur less often than the globally catastrophic impact, emphasizing the fact that the large impacts dominate the risk. This point is also made in Figure 2, which plots the expected fatalities per event as a function of diameter (and energy) of the impacting object. The figure shows schematically the transition in expected fatalities per impact event that takes

place as the global threshold is reached for objects between 0.5 and 5 km in diameter.

One way to express the risks is in terms of average annual fatalities. While such an index is convenient for comparison with other risks, we also stress the artificiality of applying this approach to the very rare impact catastrophes. The concept of equivalent annual deaths strictly applies only in a static world in which the population and the mortality rate from other causes do not vary with time. This figure is obtained by multiplying the population of the Earth by the total annual probability of death. In the case of the U.S. equivalent deaths, we allow for the higher than average population density in the U.S.

For the globally catastrophic impact: (assumed 2 km threshold)

Total annual probability of death:	1/2,000,000
Equivalent annual deaths for U.S. population only:	125
Equivalent annual deaths (worldwide population):	2,500

For the Tunguska-class impact:

Total annual probability of death:	1/30,000,000
Equivalent annual deaths for U.S. population only:	15
Equivalent annual deaths (worldwide population):	150

These figures can be compared with the mortality rates from other natural and man-made causes to obtain a very rough index of the magnitude of the impact-catastrophe hazard.

The above analysis is presented to facilitate comparison of impact hazards with others with which we may be more familiar. However, there is a major qualitative difference between impact catastrophes and other more common natural disasters. A global impact catastrophe could lead to a billion or more fatalities and an end to the world as we know it. No other natural disasters, including the Tunguska-class impacts, have this nature. They represent just one among many causes of human death. In contrast, the potential consequences of a large impact set it apart from any other phenomenon with the exception of full-scale nuclear war.

STRATEGY FOR DEALING WITH THE HAZARD

The greatest risk is from the impact of the largest objects – those with diameters greater than the global threshold, probably near 2 km. Such impacts, which occur on average from once to several times per million years, are qualitatively as well as quantitatively different from any other natural

disasters in that their consequences are global, affecting the entire planet. About 90 percent of the potential Earth-impacting projectiles are near-Earth asteroids or short-period comets, called collectively ECAs (Earth-crossing asteroids). The other 10 percent are intermediate or long-period comets (those with periods longer than 20 years).

The first step in dealing with the cosmic impact hazard is to identify potential impactors, with emphasis on the objects that pose the greatest risk: the ECAs. The ECAs have orbits that closely approach or intersect that of the Earth. Their normal orbital motion typically brings them relatively near the Earth at intervals of a few years, permitting their discovery. The objective of an ECA survey is to find these objects during their periodic approaches to the Earth, to calculate their long-term orbital trajectories, and to identify any that may impact the Earth over the next several centuries. If any appear to be on Earth-impact trajectories, there will generally be a period of at least several decades during which to take corrective action.

It should be emphasized that the ECAs are readily detectable in reflected sunlight and distinguishable from the stellar background by their motion. To deal with the threat posed by these objects, there is no requirement for either a short-range search or a quick-response defense system. The chance that an ECA will be discovered less than a few years before impact is vanishingly small. The nature of the ECA orbits allows us to carry out a deliberate, comprehensive survey with ample time to react if any threatening ECA is found. In contrast, the warning time for impact from a long-period comet might be as short as a few months, requiring a different class of response.

In order to carry out a deliberate and comprehensive search, we must detect, over a period of a decade or more, the ECAs larger than our size threshold (nominally 1 km diameter) that pass near the Earth. This requires that we monitor a region of space extending outward from the orbit of the Earth approximately as far as the inner edge of the main asteroid belt, at a distance of 200 million kilometers. The easiest way to detect these ECAs is by observing their reflected sunlight, although they can also be seen in the infrared using their emitted thermal radiation. More exotic technologies are not appropriate; search radar, in particular, is limited to targets close to the Earth, and so is unsuitable to a survey extending 200 million kilometers into space. In principle, the survey could be carried out either from the ground or from orbit. The brightness of a 1-km object at 200 million kilometers, assuming a reflectivity of 3 percent or more, corresponds to stellar magnitude 22. Although they are quite faint, such objects are readily detectable with conventional ground-based telescopes; thus there is no requirement for a more expensive space-based system. This brightness limit also determines the minimum telescope aperture of about 2 m that is required for a complete survey.

We have it within our current capability to construct a network of survey telescopes at relatively modest cost that can discover and track essentially all of the ECAs greater than 1 km in diameter. If the program is continued for several decades, it will eventually yield most of the smaller ECAs (from 100 m to 1 km diameter) as well. In addition, this same network of optical survey telescopes will be capable of detecting most incoming intermediate- or long-period comets and determining if any of them has the potential to strike the Earth. However, the time between detection and possible impact will be much shorter for the long-period comets.

The Spaceguard Survey described by the NASA International Near-Earth-Object Detection Workshop has the potential to alter fundamentally the way we view the threat of cosmic impacts. To date we have talked about a relatively undefined threat, to be discussed in terms of probabilities or statistical risks. While we know that such impacts must take place from time to time, we do not know if there are any specific bodies in space that might impact the Earth over the next few centuries. If this search program is carried out, however, we can answer this question for the ECAs, thus dealing with at least the 75 percent of the potential hazard. If such an object is found, then we can turn our attention to addressing the threat it poses. In other words, we have the capability to achieve at quite modest cost at least a 75 percent reduction in the hazard posed by cosmic impacts.

FIGURE CAPTIONS

Figure 1. Estimated frequency of impacts on the Earth derived from the present population of comets and asteroids and from the lunar crater record.

Figure 2. Schematic indication of the risk of impacts measured by the expected average fatalities per event. Large impacts dominate the risk, but there is considerable uncertainty in the threshold for global catastrophe, as indicated by the hatched region in the figure.

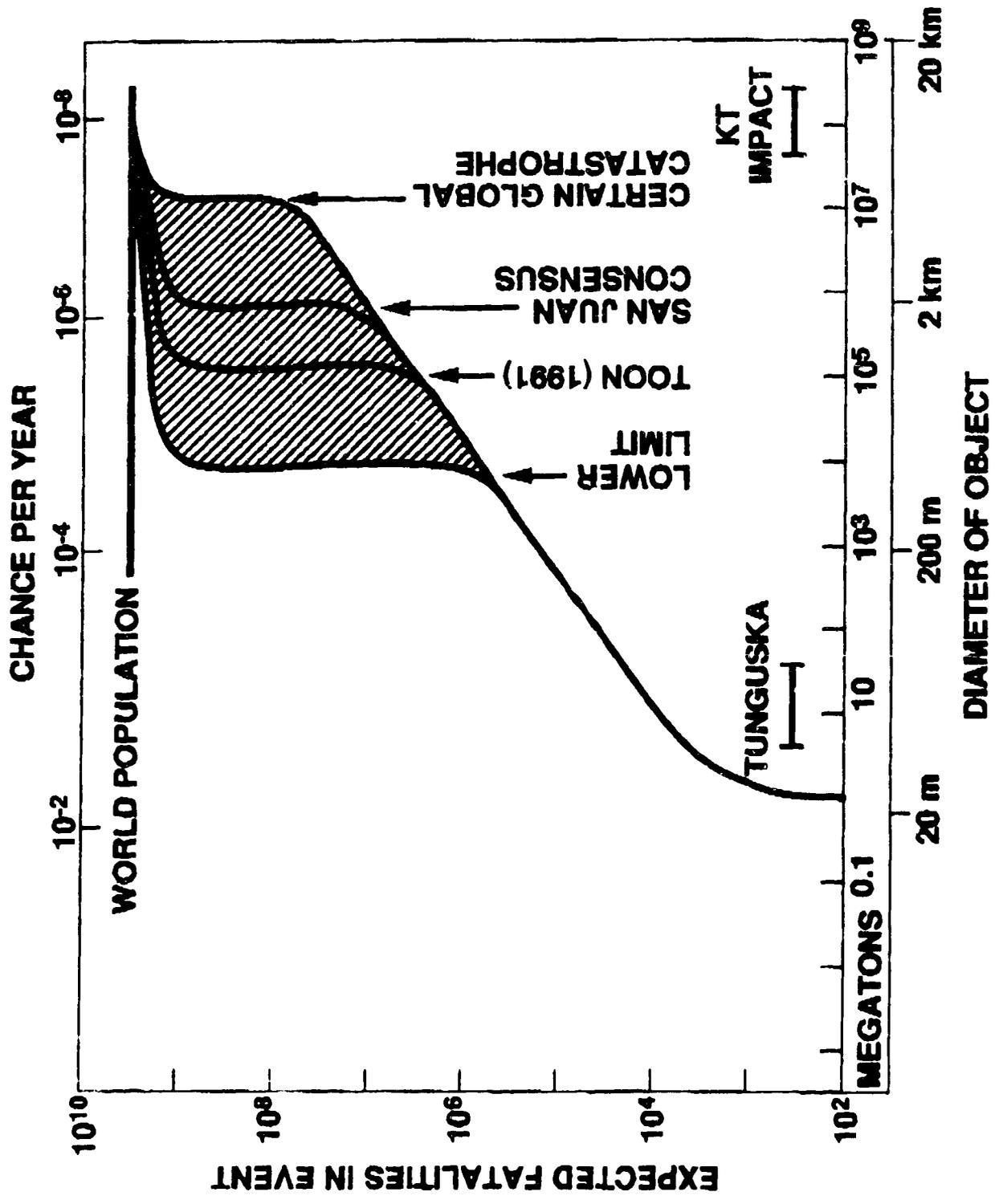


Fig. 1

FREQUENCY OF IMPACTS ON THE EARTH

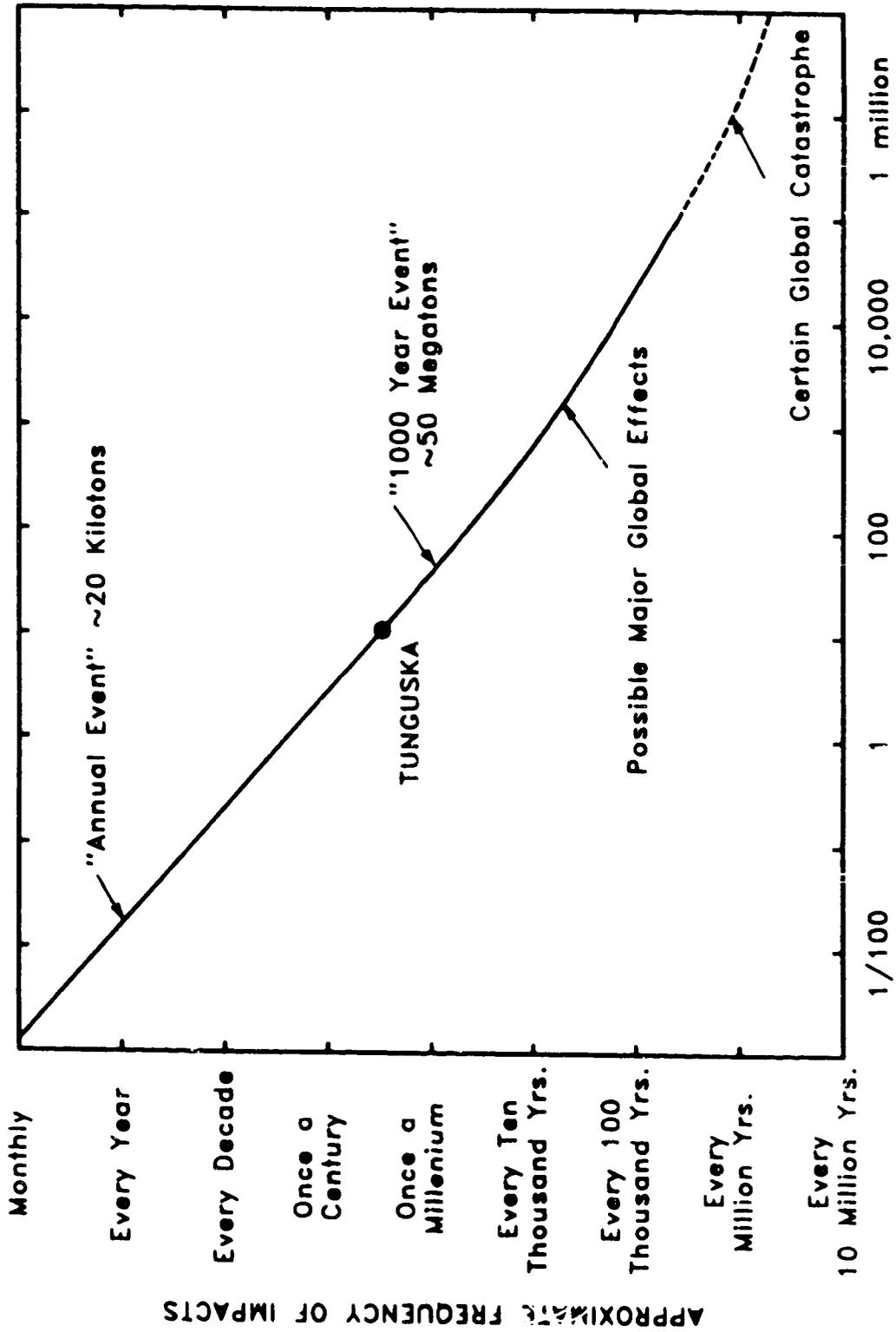


Fig. 2. MEGATONS TNT EQUIVALENT ENERGY

SOME PERSPECTIVES ON THE SEARCH FOR NEAR-EARTH OBJECTS

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Introduction

This contribution is aimed at giving some views on: (1) Presently-available techniques for searching for near-Earth objects (asteroids, comets, and fragments thereof) and how these might be enhanced at little cost; (2) The importance of objects in orbital classes about which little or nothing is known; (3) The importance of flux determinations for smaller NEOs; (4) Other areas in which added effort is required in the immediate future; and (5) Some very personal views upon the actual hazard which have not been voiced in the other documents pertaining to the NASA NEO Workshops.

1. Presently-available search techniques

Apart from the Spacewatch telescope, now performing admirably at Kitt Peak, the other three main NEO search programs use photographic techniques. Spacewatch operates by letting a large CCD chip scan across the sky at the sidereal rate¹, and this basic technique (except with faster scan rates) has been selected by the NASA NEO Detection Workshop as the method of choice for a search for large NEOs under the proposed Spaceguard Survey². The three photographic surveys use images gained with wide-field Schmidt telescopes: the Planet-Crossing Asteroid Survey (PCAS) under E. Helin and the Palomar Asteroid and Comet Survey (PACS) under E. and C. Shoemaker both use pairs of short exposures made using the 0.46 m Schmidt at Palomar Observatory, whilst the recently-started Anglo-Australian Near-Earth Asteroid Survey (AANEAS) uses single long-duration exposures made with the 1.2 m U.K. Schmidt Telescope (UKST) at Siding Spring Observatory in Australia.

These programs are all well documented² and little more will be said about them here. However, it should be noted that often a newly-discovered object may have its orbit refined to a very large degree if a previously-unrecognized observation can be found. For example, the UKST has been operating for a period of about 17 years, and very often it is possible to find earlier images of newly-recognized objects amongst the ~15,000 plates taken so far of the southern sky. The Palomar 1.2 m Oschin Schmidt has been operated for even longer, over 40 years, so that again the plate library contains invaluable data yet to be exploited. The same comment applies to many other smaller Schmidt (and other) telescopes such as the ESO Schmidt in Chile, the Uppsala Schmidts in Sweden and Australia, and so on. For example the orbit of 2060 Chiron, discovered in 1977, has been refined

with astrometric positions dating back to 1895. However, the problem in many cases is accessing the plates, and their availability: this argues for either copying or (preferably) digital scanning such that interesting objects recorded thereupon may be searched for automatically. This is in fact being carried out at this time for the UKST plate library (stored at the Royal Observatory, Edinburgh), with the data gradually coming on-line. This will allow rapid determinations of accurate orbits for many objects, especially the larger, brighter ones, as this field develops.

To give some idea of the situation I will again concentrate just on the UKST plates, although the same sort of considerations apply to Schmidt plate libraries elsewhere. From the start of routine sky survey observations in 1974 through to 1990 five NEOs were discovered by chance on UKST plates. Since May 1990 AANEAS has resulted in the discovery of about one new NEO per month; it is important to note that there has been no change in the actual data collection with the telescope, all that has happened is that the plates are rigorously scanned with binocular microscopes soon after processing. Thus it is reasonable to suppose that there are about 200 unknown NEOs which are actually recorded on old UKST plates, but have passed unnoticed. This compares with the presently-known inventory of about 190 NEOs, largely discovered as a result of the PCAS, PACS, Spacewatch and (latterly) AANEAS programs. It is entirely feasible that ~1000 or more NEOs have retrievable images spread amongst the plate libraries of the world's large Schmidts. Even if orbits for these are not calculable now, with the pointing history of the telescopes (well known for, say, the UKST) the previous 'discovery' rates of NEOs would lead to a great refinement in our knowledge of their population and flux by the Earth.

Quite apart from the above it is feasible that large NEOs could be discovered, and their orbits determined, at a greatly increased rate with a very modest increase in funding of the present programs. In the case of AANEAS no specific observations are made for discovery, due to the lack of manpower and the finances to purchase film: only plates taken as part of the routine operations are available. However, up to 30% of potential observing time on the UKST is not currently used due to poor seeing or bright-of-moon. If money and staff were available then many short exposures could be taken towards the ecliptic and opposition, and thus NEOs found more efficiently. We estimate that a discovery rate of order 100-200 per year could be achieved in this way, essentially instantaneously.

2. Objects in little-known orbital classes

It is just over 15 years since the first Aten-type (period < 1 year, aphelion > 0.9833 AU so may impact the Earth) asteroid was discovered. Since then a little more than a dozen have been found, the latest having been announced on the day this was being written (1992 BF: *IAU Circ.* 5443). These

are especially unlikely to be found since they are largely observable only at large solar elongations, whereas most planned searches concentrate on opposition. The fact that the Spaceguard Survey as presently planned will be fairly ineffective in detecting Atens is well-recognized². Therefore it is difficult at this stage to ascertain the importance of Atens with respect to the terrestrial impact hazard: is it a contribution of 1%, 5%, 10% or 50% of impacts?

However, at least this is a class of objects about which we know something; what other classes await identification? In February 1991 a new asteroid (1991 DA) was discovered in the AANEAS program, having perihelion near Mars, aphelion beyond Uranus, and a high inclination. This appears to be the first of a class of asteroids in Halley-type orbits. Its large size (5–8 km) would argue for there being hundreds or thousands of smaller, but very significant, asteroids in similar orbits. Whilst at present it has perihelion well beyond the terrestrial orbit, numerical integrations show that it may spend ~10% of its life on Earth-crossing paths^{3,4}. In the same way 2060 Chiron is likely to evolve into an orbit which makes terrestrial impact possible⁵, and the same may apply to 1992 AD, found even more recently. The huge size of the latter two objects (150–200 km) would mean that they could decay to produce a very large population of objects in near-Earth space, enhancing the present NEO population by a factor of 100 or more.

3. The importance of flux determinations for smaller NEOs

The excellent modelling done by E. Bowell and K. Muinonen in designing the optimal search strategy for the Spaceguard Survey² has demonstrated that it is not feasible to discover and determine the orbits of all NEOs smaller than about 500 m on a time-scale of less than decades; although many will be found over the course of a 20–25 year program they will still be only a small fraction of the total. The problem then arises, in connection with decisions about the sizes of object to be tackled by any space-based interception and deflection/destruction system to be planned in the shorter (5-year) term, as to whether the influx of such objects to the Earth warrants expensive attempts to intervene with these (*cf.* discussion of hazards in ref. 2).

In this respect I point out the following. My own earlier background was in the field of the radar detection of meteors. By far the largest part of the mass flux of solid objects in the near-Earth environment, if one excludes the very large objects under consideration here (NEOs), is in the form of 10^{-6} – 10^{-2} g particles which are detected as radar meteors (*e.g.* see Fig. 1 of ref. 6). At the start of the space age these were viewed as being a significant potential threat to spacecraft and therefore much money and effort was expended in detecting them and determining their *flux* (and it was found that the hazard that they posed was acceptably low). It was not until later that more emphasis was placed on their *orbits*, and that was mainly out of scientific interest (*e.g.* ref. 7). It

appears that a lesson should be learnt from this piece of history: for large NEOs the near-Earth flux is so low that it is necessary to determine the orbit of each NEO and thus calculate the influx to the planet and predict future impacts; but for the smaller objects (say, sizes < 100 m) it is feasible that suitable instruments would be able to determine the flux on a fairly short time-scale (years) without the huge effort required in order to measure their orbits. That is, the actual hazard may be categorized fairly swiftly, and then a knowledgeable decision as to the necessary steps can be taken.

Again harking back to the lessons of meteor observations, of significance here would be determinations of whether the flux of these smaller (< 100 m) NEOs changes during the year, from year to year, and also whether they arrive in showers (*cf.* section 5). It seems likely that, judging from the achievements of the Spacewatch telescope¹, the sort of instruments proposed² for the Spaceguard Survey will be able to determine the flux of small NEOs with some rapidity, without the additional problems inherent in attempting to follow these to determine their orbits.

4. Other areas requiring immediate attention

Whilst much attention has been paid to how to detect NEOs of substantial size, and how to then determine their orbits, comparatively little attention has yet been paid to the requirements of precise numerical integrations to elucidate their future dynamical history. There are, however, several groups world-wide who have performed such integrations of NEOs⁸ and other objects (*e.g.* 3-5, 9) which will eventually lead to a much better understanding than that presently available^{2,10} of which classes of NEO, and which particular objects, pose threats to the Earth. My intention here is to highlight that it is by no means possible at this time to predict the trajectory of a NEO for long periods into the future (decades) at the precision required for prognoses of Earth-impacts, especially since non-gravitational forces — notoriously difficult to model — are apparently acting on some NEOs¹¹. This area is also one which requires further investigation urgently, as indeed does the whole field of physical studies of NEOs.

5. Coherent versus stochastic catastrophism

The mainstream of thought with regard to terrestrial impacts by NEOs holds that such impacts happen randomly in time; that is, that these catastrophes occur stochastically. Contrary to this is the view held by a few that in fact the impacts to a large extent, and most certainly in the present epoch, occur coherently¹²; that is, there are periods in which there are many impacts occurring at the same time (within days to weeks) in cyclic periods as the Earth is intercepted by clusters of NEOs, mostly smaller (< 100 m) in size, produced by the disintegration of larger bodies. In

the present epoch impacts by such objects may be dominated by the influx of the products of the hierarchical decay of a giant comet over the past 20,000 years, forming the meteoroid stream termed the Taurid Complex¹³. Impacts of the Tunguska class from this complex are apparently evidenced in the historical record¹⁴. Adding to this view is the recent recognition that there were multiple impacts at the K/T boundary event¹⁵:

"Shoemaker thinks the most probably source of multiple impacts is a comet that broke up and then pummelled Earth with its debris year after year"¹⁶.

If the above contentious suggestion, or some variant upon it, in fact reflects the actual situation then any NEO defence system must be capable of dealing with multiple NEOs at one time, possibly from a near-Earth flux of several thousand objects within a few weeks, with Earth-intercept occurring at the same time of year for many years.

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TO HIT OR NOT TO HIT

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It was the view of the companion Detection Workshop that we should attempt to discover and follow up astrometrically and physically any moderately large near-earth objects (NEOs) that have the potential to collide with the earth during the next few centuries. Strict examination of this potential requires that in appropriate cases we should secure exhaustive astrometric data (optical as projected on the plane of the sky over as long a time span as possible and radar range and rate) and perform detailed numerical integrations of the future orbits, including the gravitational effects of all perturbing planets and also the nongravitational reactive effects of the vaporization of cometary ices. Particularly in the cases of comets that might be subject to both nongravitational effects and repeated encounters with Jupiter, the process is necessarily one of successive approximations as time goes by.

It has also been suggested that, at least in the case of asteroids, the application of secular-perturbation theory allows one to establish just which objects do or do not pose a long-term threat; this has led to the definition of "earth-crossing asteroids" (ECAs) as a subgroup of the general near-earth asteroids (NEAs). While the computation of secular perturbations may have merit, the procedure is not applicable to objects (mainly comets) that make frequent approaches to Jupiter, or even to objects that remain well separated from Jupiter but that have orbits strongly resonant with that of Jupiter. Nevertheless, while secular-perturbation theory may sometimes have some validity for, say, 200 000 years or more, there seems little reason to take an excessive interest in objects that have absolutely no possibility of striking the earth during the next 200 years.

I therefore maintain that, before undertaking extensive numerical integrations, and instead of applying secular-perturbation theory, it is sufficient to examine whether the orbits of the earth and a newly discovered object are *currently* close to intersecting each other. If the current osculating orbit indicates a minimum separation of, say, 0.1 AU or more, and provided that there are no large perturbations, there is obviously no cause for concern. Even if this minimum separation is 0.05 AU, there can be little threat, although one may wish to repeat the computation using orbital data integrated forward to other epochs. The principle is similar to that utilized by those astronomers who examine whether particular comets (or asteroids) are likely to produce observable meteor streams.

The most obvious point to examine is whether the object crosses the earth's orbit plane near the earth's distance from the sun, i.e., one should ascertain whether either value of

$$N = \left| \frac{q(1+e)}{1+e\cos\omega} - 1 \right| < \epsilon, \quad (1)$$

q and e being the perihelion distance (in AU) and eccentricity of the object's orbit and ω the argument of perihelion, and with $\epsilon = 0.05$ AU it is certainly reasonable to ignore the eccentricity (0.017) of the earth's orbit. All orbits with $q < 1$ AU and inclination $i < 3^\circ$ (or $> 177^\circ$) to the ecliptic obviously approach the earth's orbit within 0.05 AU, and this suggests that it is also useful to examine the component perpendicular to the earth's orbit when the object is at the earth's distance from the sun, i.e., whether either value of

$$M = |\sin(\omega \pm v)| \sin i < \epsilon, \quad (2)$$

where

$$\pm v = \arccos \left[\frac{q(1+e)}{e} - 1 \right] \quad (3)$$

(with $q < 1$ AU and $e > 0$) are the true anomalies at which this occurs; it is necessary also to perform this computation when $1 \leq q < 1 + \epsilon$ AU, supposing then the single value $v = 0$. As a general rule, criterion (2) is of greater significance than criterion (1).

Table I is a tabulation of asteroids with M and/or N meeting these criteria. To save space ϵ has been lowered to 0.04 AU, and the first 48 entries give the cases where one or both M meets the criterion, in increasing order of the smaller value; M values followed by an asterisk represent the aforementioned cases where $q \geq 1$ AU. If N also meets its criterion, the relevant values are also given, and the last seven entries in the table (still in order of increasing minimum M) show the remaining cases where the N criterion is met. The notes L and R refer to objects that were under observation for less than two or three weeks; L indicates that an object is lost, while the cases denoted with R indicate that the availability of radar observations ensures that these objects, like those with longer observed arcs, should be recoverable in the future.

On the right-hand side of Table I actual minimum separations (in AU) between the objects and the earth during the twentieth and twenty-first centuries are indicated; this list of actual approaches is not exhaustive, particularly for the twenty-first century, but it is evident that the more extreme approaches (within 0.015 AU, say) are confined to the smaller values of M . The approach of (4660) Nereus to within 0.007 AU in 2060 is the closest predicted for the future, although it is entirely possible that lost objects like 1937 UB (Hermes) could come closer than this during the time interval of concern to us. Because the earth's orbital eccentricity is ignored, there are also other objects that pass within 0.04 AU of the earth, notably (1620) Geographos, which has $M = 0.046$ AU and approaches the earth to a distance of only 0.033 AU in 1994.

It is also important to note that, although (1915) Quetzalcoatl currently has $q > 1.07$ AU, the effect of its 3:1 mean-motion resonance with Jupiter is such that $q < 1$ AU before 1940 and that in 1906 this object passed only 0.025 AU from the earth (with $M = 0.085$ AU, $N = 0.033$ AU). More to the point, we can say that, with minimum $M = 0.187$ AU, $N = 0.110$ AU, (1866) Sisyphus (which has $q = 0.87$ AU and is one of the largest NEAs) cannot possibly be a threat to the earth, a situation that was already apparent when the first orbit determination for this object was made from observations (including only approximate data) within six days of its discovery in 1972 ($M = 0.180$ AU, $N = 0.105$ AU).

Table II is a corresponding tabulation for comets. The eight comets with revolution periods of less than 200 years (six of them less than ten years, although comet Lexell was perturbed away by Jupiter long ago and now comes nowhere near the earth, and comet Biela, not observed since 1852, is generally thought no longer to exist as a coherent body) are indicated by name, and the codes M and U indicate that there are either known meteors associated with the comet or that the comet's orbit is particularly uncertain. Although comparison of the tables may be of some interest, Table II is clearly of much less significance than Table I, for the fact that short-period comets frequently approach Jupiter means that their M and N values experience rather larger changes, while the values for the comets with periods much longer than 200 years are moot because these objects will not return to the earth's vicinity during the time interval that concerns us. With a long-period comet, the significance is only whether there will be a close encounter during its discovery apparition, and even with small M or N , non-threatening cases can be completely eliminated given an orbit determination from observations within a few days of discovery. Comet Halley, which currently has $M = 0.067$ AU, $N = 0.151$ AU, does not show on the list. A millennium and a half ago, however, this comet had $M = 0.003$ AU, $N = 0.010$ AU, and there was an actual approach to within 0.038 AU of the earth in 837.

By constructing half a dozen ground-based telescopes in the 2-3-meter class and equipped with modern charge-coupled devices, and by concentrating searches each month over some 6000 square degrees of sky opposite the sun, the Detection Workshop concludes that it will be possible to find, over the course of only a couple of decades, almost all of the NEAs that pose a global threat. The proposed search will pick up most of these bodies when they are quite far from the sun, perhaps even near aphelion, and this is reasonable because that is where they spend most of their time. The same search should also be effective for short-period comets, which have rather similar orbital characteristics. The catalogues currently contain 108 asteroids and 15 short-period comets (of period less than 20 years) with $q < 1$ AU. Given that the average asteroid has a period of 3 years and the average comet one of

5 years, the known asteroids and comets pass perihelion at an annual rate of about 30 and 3, respectively. The relative threat of the short-period comets can thus be judged as about 10 percent that of the asteroids. The contribution of the one-shot, long-period comets is harder to estimate. The catalogues contain 401 such comets with $q < 1$ AU, and although the majority of them have appeared during the present century, some of the records go back more than a millennium. It is therefore difficult to select a characteristic period, but even one of only 200 years would give an annual rate of no more than 2, which is also the observed rate (excluding the tiny Kreutz sungrazing comets detected by the SOLWIND and SMM coronagraphs) during the past decade or so, or about 6 percent of that of the NEAs.

Unlike the asteroids and the short-period comets, the long-period comets have orbital poles that are distributed in an essentially random manner, and inclinations in the vicinity of 90° therefore dominate. Although there are four times as many known cases of long-period comets as asteroids with $q < 1$ AU, the number of entries in Tables I and II are comparable, suggesting that the relative threat of the long-period comets can be reduced by a further factor of four, down to at most 2 percent, say. Such a ratio is not inconsistent with the actual near-encounters listed in Tables I and II, given that the actual minimum distances for the asteroids are only representative for each object and that the list is far from exhaustive, and considering that there is really only one good case, that of 1983 VII, of the earth's near encounter with a long-period comet (the 1491 comet being uncertain and comet 1743 I in fact very probably of short period).

One can object that this argument on the relative threat of long-period comets and asteroids is flawed because I am comparing earth-approaching comets that were all bright enough to be seen with the naked eye and asteroids that were often so faint that they taxed the largest telescopes. But the intrinsic total brightness of comet 1983 VII was toward the low end of the observed distribution for long-period comets, and its nucleus, which was detected by radar, was comparable in size to the larger NEAs. Modern searches for NEAs are also rather consistently picking up comets, and for reasons that are not entirely clear, there is an apparent dearth of long-period comets that are intrinsically very faint. I am still therefore inclined to stick with my figure of 2 percent, rather than with the figures as high as 25 percent that were discussed by the Detection Workshop. Certainly, with its significantly higher velocity with respect to the earth, a typical long-period comet will be involved in a much more energetic impact than a typical NEA, but that is a separate issue.

The appreciation that earth-threatening long-period comets may represent a smaller fraction of the threatening NEOs than has previously been discussed should be counteracted by the realization that it is very difficult to discover them with a warning time of more than a few months. If comet 1991h₁ (see Table II) had been 38 days earlier in its orbit, there would have been a very near miss, but comets invariably brighten according to a higher inverse power of heliocentric distance than the square, and detection at a previous opposition would have been quite impossible. Long-period comets on collision courses with the earth spend an inordinate amount of the previous year at small angular elongations from the sun. Although the possibility of making searches from telescopes in orbit about the earth has also been discussed, this would not help unless the space instruments were large enough to make detections near opposition 100 times fainter than proposed by the Detection Workshop. Infrared searches from space have also been mentioned, but it is important to note that IRAS did not detect any discrete objects that were not or could not also be detected rather easily from optical telescopes on the ground, that its astrometric accuracy was at least 20 times worse than that of optical telescopes, that it could not observe at solar elongations significantly less than optical telescopes and that it was often difficult to distinguish between detections of discrete planetary or cometary objects and harmless dust trails. If the international community feels that it really is necessary to guarantee the early detection of long-period comets, searches would best be made using optical telescopes located far from the earth. Since the other class of potentially earth-threatening objects not easily discoverable in earth-based opposition searches are NEAs with aphelia only slightly outside the earth's orbit—or even at the earth's orbit—it might make sense to establish a surveillance system in heliocentric orbit closer to the sun, or perhaps in orbit around Venus.

Table I. Minor planets.

Object		<i>M</i>	<i>N</i>	Actual
(1981) Midas	1973 EA	0.000	0.000	0.030 1947
(2201) Oljato	1947 XC	0.000	0.009 0.002	
	L 1991 BA	0.001	0.020 0.021	0.001 1991
	1989 UP	0.002	0.040 0.003	
Hermes	L 1937 UB	0.003	0.005 0.014 0.027	0.005 1937
(4581) Asclepius	1989 FC	0.004	0.017	0.005 1989
	L 1991 VA	0.005	0.008	0.012 1991
	L 1991 TU	0.005	0.006	0.005 1991
	1988 XB	0.005	0.023	
(4660) Nereus	1982 DB	0.005	0.021 0.028	0.007 2060
(4179) Toutatis	1989 AC	0.005	0.007	0.011 2004
(2340) Hathor	1976 UA	0.007	0.029	0.008 1976
	1988 TA	0.007	0.027	0.010 1988
	R 1986 JK	0.007	0.037	0.021 1958
	R 1990 OS	0.009	0.018	0.040 1990
	1990 HA	0.010		0.036 1990
	L 1990 UA	0.012	0.017	0.020 1990
(2101) Adonis	1936 CA	0.013	0.022	0.015 1936
(3361) Orpheus	1982 HR	0.013	0.034	0.032 1982
(2135) Aristaeus	1977 HA	0.014	0.015	0.032 1977
	1989 UQ	0.015	0.021	
	L 1991 VG	0.015	0.025 0.020	0.003 1991
	R 1990 MF	0.018	0.032	0.034 1990
(3362) Khufu	1984 QA	0.018		0.016 1917
	L 1989 VB	0.019*		
	L 1990 SM	0.019		
(3757)	1982 XB	0.020*	0.030	0.038 1982
	R 1991 AQ	0.020	0.035	
	L 1990 UN	0.021	0.035	
	L 1981 CC	0.022	0.020	0.021 1981
	L 1983 LC	0.023	0.025	0.026 1915
(4034)	1986 PA	0.023		
(4769) Castalia	1989 PB	0.023		0.029 1989
	L 1991 BN	0.023		
	1988 EG	0.024	0.034	0.032 1998
(5011)	6743 P-L	0.026		
(3200) Phaethon	1983 TB	0.026		0.037 1931
(4450) Pan	1987 SY	0.027		0.036 1963
(2061) Anza	1960 UA	0.027*		
(1862) Apollo	1932 HA	0.028	0.032	0.027 1930
	L 6344 P-L	0.028		0.038 1960
	1989 QF	0.028		
(3908)	1980 PA	0.031*		
	1989 UR	0.031		
	1991 EE	0.034		
	1991 JX	0.036*		0.032 1991
	L 1954 XA	0.037		
(4183) Cuno	1959 LM	0.038		
	1991 VH	0.047	0.014	
	1991 JW	0.053	0.036	
	L 1978 CA	0.059	0.027	0.019 1910
(3671) Dionysus	1984 KD	0.095*	0.033	0.031 1984
(2102) Tantalus	1975 YB	0.117	0.029	
	1991 CS	0.140	0.032	
	L 1991 TT	0.156*	0.032	0.031 1991

Table II. Comets.

Object		<i>M</i>	<i>N</i>	Actual
1962 IV		0.000	0.000	
1991h ₁		0.001	0.002	
	Giacobini-Zinner	M 0.001	0.000	
1967 II		0.003	0.020	
1864 II		0.004	0.029	0.033
1491 II		U 0.004	0.011	0.009 1491
1680		0.005		
1882 I		0.007	0.030	
568		0.009		
1439		U 0.009	0.026	
1080		U 0.010		
1911 II		M 0.010	0.014	
1861 I		M 0.010	0.003	
1969 VII		0.011		
1833		0.013	0.034	
1976 IV		0.013	0.007	
1907 II		0.013	0.004	
	Lexell	0.013	0.023	0.015 1770
1014		U 0.014	0.014	
1743 I		0.014	0.038	0.039 1743
-146		U 0.016	0.020	
	Biela	M 0.016	0.026	0.037 1805
1969 IX		0.016	0.018	
1917 II		0.017	0.028	
1245		U 0.018	0.018	
1812 II		0.018	0.008	
	Finlay	0.019		
1763		0.020	0.027	0.028 0.022
1957 IX		0.022		
1779		0.024	0.028	
1862 IV		0.025	0.017	
1857 I		0.025	0.014	
1862 II		0.027	0.039	
1973 XII		0.028		
1939 III		0.028		
1702		0.029		
1854 III		0.030	0.024	
1368		0.030	0.030	0.040
1898 X		0.031	0.026	
1351		U 0.032*	0.028	
1910 I		0.035		
905		U 0.035		
1983 VII		0.036	0.004	0.031 1983
868		U 0.036		
1845 III		0.037		
1854 IV		0.038	0.027	
1737 II		0.040	0.021	
1925 XI		0.044	0.039	
	Tempel-Tuttle	M 0.044	0.014	0.023 1366
1911 VI		0.051	0.029	
	Grigg-Skjellerup	M 0.054	0.005	
1718		0.057*	0.029	
1977 XIV		0.070	0.011	
	Swift-Tuttle	M 0.075	0.018	
	Pons-Winnecke	M 0.077	0.026	0.039 1927
1954 X		0.077	0.014	
1849 I		0.085	0.019	
1539		0.095	0.037	
1684		0.097	0.026	
1900 II		0.191*	0.027	
1870 I		0.266*	0.035	
1947 III		0.270	0.038	

AIRBLAST DAMAGE FROM SMALL ASTEROIDS

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ABSTRACT

The fragmentation of a small asteroid in the atmosphere greatly increases its cross sections for aerodynamic braking and energy dissipation. At a typical impact velocity of 22 km/s, the atmosphere absorbs more than half the kinetic energy of stony meteoroids with diameters, $D_M < 250$ meters and iron meteoroids with $D_M < 60$ meters. Most of this energy dissipation occurs in a fraction of a scale height, which causes large meteoroids to appear to "explode" or "flare" at the end of their visible paths. The dissipation of energy in the atmosphere reduces the damage due to direct impacts (e.g., craters and tsunamis), but it produces a blast wave that can cause considerable damage to structures on the ground. The area of destruction around the impact point in which the over pressure in the blast wave exceeds 4 pounds/inch² = 2.8×10^5 dynes/cm², which is enough to knock over trees and destroy buildings, increases rapidly from zero for chondritic asteroids less than 50 meters in diameter (9 megatons) to about 2000 square km for those 80 meters in diameter (40 megatons), the approximate diameter of the Tunguska impactor of 1908. The area of destruction produced by the blast wave from the impact of stony asteroids between 70 meters and 200 meters in diameter is up to twice as great as it would be without fragmentation.

1. INTRODUCTION

Aerodynamic pressure fragments all large meteorites except iron ones that enter the atmosphere at low speed. Fragmentation greatly increases the rate at which a meteoroid dissipates its kinetic energy in the atmosphere. The fragments of a large stony meteorite are typically strewn over an area about 1 kilometer in diameter if the zenith angle of the impact is not large. The area increases for large zenith angles. An extreme example is the recently discovered Rio Cuarto meteor crater field in Argentina (Schultz and Lianza 1992) that was produced by an asteroid 300 meters in diameter. Its impact produced a series of large craters over an area about 2 kilometers wide and 30 km long.

It is evident that atmospheric fragmentation is important for any stony asteroid less than 1 kilometer in diameter since fragmentation causes its impact footprint to be of this order irrespective of its initial size. This does not imply that the atmosphere will mitigate the damage done by all stony meteorites less than 1 km in diameter. The Tunguska impactor was an ordinary stony asteroid about 80 meters in diameter that dissipated nearly all of its kinetic energy in the atmosphere, but it destroyed an area of 2000 square kilometers (Sekanina 1983). If the asteroid is larger than about 200 meters in diameter, the mass per unit area of its debris, even when spread to a diameter of 1 km, exceeds that of the atmosphere, so its debris is not significantly slowed by the atmosphere. It is clear that we must allow for fragmentation and energy dissipation in the atmosphere to fully characterize the damage done by small asteroids and to determine which asteroids we need to intercept.

The authors find that a fragmented asteroid will expand out to about twice its initial radius before significant holes appear between the fragments when viewed from the front of the meteoroid. Until this occurs, the meteoroid appears as a solid expanding object behind a single bow shock. Its mass remains constant, except for ablation, but its surface area and drag increases by a factor of four. If the meteoroid is small enough, it slows enough during this expansion after the first fragmentation that it does not undergo further fragmentation. Its various fragments proceed independently behind their own bow shocks. Larger meteoroids (small asteroids) suffer little deceleration during this first expansion, so when the fragments start to decouple from the parent body and develop their own bow shocks, they are deeper in the atmosphere, they feel more aerodynamic pressure than the original parent body, so they promptly fragment into even smaller pieces. The greater aerodynamic pressure gradient across these fragments causes their own fragments to disperse at higher velocities than the fragments of the original parent body. This higher dispersal velocity during each subsequent stage of fragmentation causes the fragments to fill in the gaps between themselves, so during this continuous fragmentation process, the

object can be treated as one body behind a single bow shock. The increase in its effective drag radius is determined by the dispersal speed of the fragments. This process continues until the debris cloud has slowed enough that the aerodynamic pressure can no longer cause further fragmentation at the time when the subfragments start to develop their own bow shocks. The subfragments then proceed as independent objects through the atmosphere.

This fragmentation model has been put into a computer code that follows the motion of the meteorite through the atmosphere allowing for changes in its aerodynamic cross section due to fragmentation and in its mass due to ablation. This code has allowed us to compute the rate of energy deposition in the atmosphere as a function of height and compute the damage due to the resulting blast wave.

2. DAMAGE DUE TO THE BLAST WAVE

Fig. 1 shows the energy deposited in the atmosphere as a function of height for an ordinary stony asteroid with a radius of 50 meters, which is a little larger than that of the Tunguska impactor of 1908. We see from the figure that the bulk of the energy deposition occurs in a fraction of a scale height, which explains why large stony meteoroids including Tunguska appear to "explode" or flare towards the end of their paths. The rapid decrease in velocity and the large increase in the rate of energy disposition in a narrow range of atmospheric height is due to the combined effect of the increasing drag area of the debris cloud resulting from fragmentation and to the exponential increase in atmospheric density.

The peak in the energy deposition curves of Fig. 1 occur near the height, h_{half} , by which half the kinetic energy has been dissipated. We saw in Fig. 1 that most of the atmospheric energy dissipation occurs in a narrow range of height around h_{half} . This allows us to approximate the energy release as a point explosion at h_{half} . There is much experimental data from the 1940's and 1950's on the effects of nuclear explosives fired at various heights, h , and yields, E. John Dale Solem (Theoretical Division, LANL) finds from this data that the radius r_4 within which the over pressure due to the atmospheric

burst exceeds 4 psi, which is enough to knock down trees and economically destroy most buildings, can be approximated by the fitting formula

$$r_4 = ah - bh^2 E^{-1/3} + cE^{1/3} \quad (1)$$

where $a = 2.09$, $b = 156 \text{ erg}^{1/3}/\text{cm}$ and $c = 0.0146 \text{ cm/erg}^{1/3}$. Here r_4 is measured along the ground from the point below the detonation. For r_4 and h in km and E in Mgtons (Megaton of TNT = 4.2×10^{22} ergs), $a = 2.09$, $b = 0.449$, and $c = 5.08$. (Similar results, in less convenient form, may be found in Glasstone and Dolan 1977, Chapter 3). Determining r_4 directly from theory is difficult because it depends on an interplay between the shock propagating directly from the point of energy release and that reflected from the ground.

Fig. 2 and 3 shows r_4 derived from Equation (1) as a function of impactor radius for stony and nickel-iron meteorites, respectively. Here E is the total kinetic energy of the impactor. For h in Equation (1) we used h_{half} , the height at which half the energy was dissipated. We assumed that the energy dissipation occurs at $h = 0$ if less than half the energy was dissipated before the meteorite hits the ground. (The values of r_4 given in these figures are somewhat larger than those given in Fig. 1-3 and 1-4 of the Summary Report of the Workshop (Rather, et. al. 1992). The error in the earlier figures was caused by a miscommunication between the authors that resulted in $0.5 E$ rather than E being put into the computer code to evaluate r_4 .)

We see from Fig. 2 that the blast waves from soft stony meteorites, which constitute about 95% of the total meteorites, only cause ground damage if their radii exceed about 25 meters. For $V = 20\text{-}25 \text{ km/s}$, the radius of destruction increases very rapidly with increasing asteroid radius. It reaches the area of Chicago for $R = 32$ meters.

There has been some controversy about the nature of Tunguska impactor (Sekanina 1983), but Fig. 2 shows that its area of destruction is consistent with the impact of an ordinary stony meteorite with a radius of about 40 meters and a probable impact energy of about 40 megatons.

The radius of destruction continues to increase rapidly with increasing asteroid radius. A stony asteroid with a radius of 150 meters, which is about the size of the one that produced the Rio Cuarto crater field in Argentina, would wipe out (at 4 p.s.i or greater) an area the size of Connecticut. This would have an impact energy of about 2 Gigatons = 2,000 Magatons with most of this energy being dissipated after the fragments hit the ground. An object of this size hits the Earth about every 3000 years. The Rio Cuarto impactor fell "considerably less" than 10,000 years ago (Shultz and Lianza 1992), after humans came to America.

We see from Fig. 3 that airblast damage from nickel-iron asteroid impacts begins at much smaller radii than that for stony ones. This is largely due to the iron meteorites fragmenting and dissipating their energy at much lower h . They are also nearly 3 times denser than stone, so they have nearly 3 times as much kinetic energy for a given radius. Fig. 3 shows that nickel-iron meteorites with radii $R > 2$ meters cause airblast damage on the ground if $V_o = 11.2$ km/s, the lowest, parabolic, velocity available to a meteorite hitting the earth. The minimum R for ground damage increases to 10 meters for $V_o = 30$ km/s due to the fragmentation and energy dissipation occurring higher in the atmosphere.

Fig. 4 and 5 show the value of r_4 as given by Fig. 2 and 3 in units of what r_4 would have been had all the energy been dissipated at $h = 0$. We see that for stony asteroids with radii in the range of 35 to 100+ meters, the radius of destruction, r_4 , is larger than it would have been had all the energy been released at $h=0$. The atmosphere forces the energy to be dissipated close to the "optimum" height that produces the maximum airblast damage. In some cases the area of destruction is more than twice as large as it would have been had the energy dissipation occurred at $h=0$.

3. CONCLUSIONS

We have found that most of the damage done by small stony asteroids (less than 100 meters in radius) results from the blast wave produced by their dissipation of energy in

the atmosphere. For larger asteroids the ground impact damage (craters, earthquakes, and tsunami) dominates over the blast wave. The authors have in preparation a paper that computes these ground effects as well as giving a much more detailed treatment of the airblast. We find that the most devastating result of the impacts of asteroids with radii in the range of 100-1000 meters is probably tsunami. Tsunami have a long range. They are basically a two-dimensional phenomena with the height of the wave dropping off only as the inverse distance from the impact. An asteroid with a radius of 200+ meters that drops anywhere in the Atlantic would wipe out the low-lying coast line on both sides of the ocean.

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FIGURE CAPTIONS

Fig. 1 The energy dissipated by an impactor as a function of height in the atmosphere. This is given for a range of initial impact velocities into the upper atmosphere. All impactors are stony asteroids with radii $R = 50$ meters.

Fig. 2 The radius of destruction around the impact point of a stony asteroid due to the atmospheric blast wave. This radius is defined to be where the overpressure is at least 4 psi, which is enough to knock down trees and economically destroy buildings. This is given as a function of the asteroid radius for several values of the impact velocity at the top of the atmosphere.

Fig. 3 Same as Fig. 2, but for nickel-iron asteroids.

Fig. 4 The radius of destruction for stony asteroids as given in Fig. 2 in units of what it would be if the same amount of energy were released at $h = 0$.

Fig. 5 The radius of destruction for nickel-iron asteroids as given in Fig. 3 in units of what it would be if the same amount of energy were released at $h = 0$.

FIGURE 1

Soft Stone

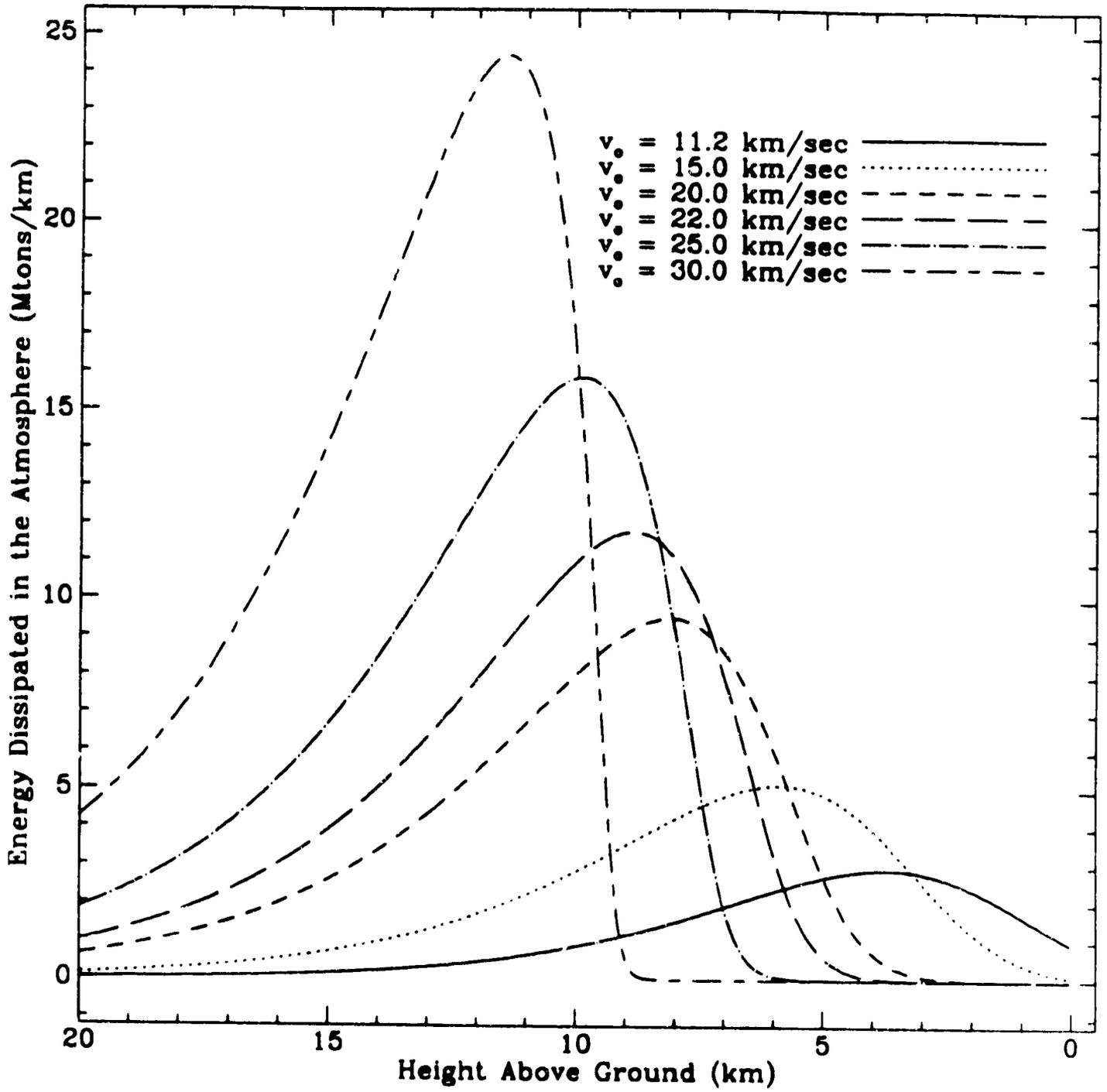


FIGURE 2

Soft Stone

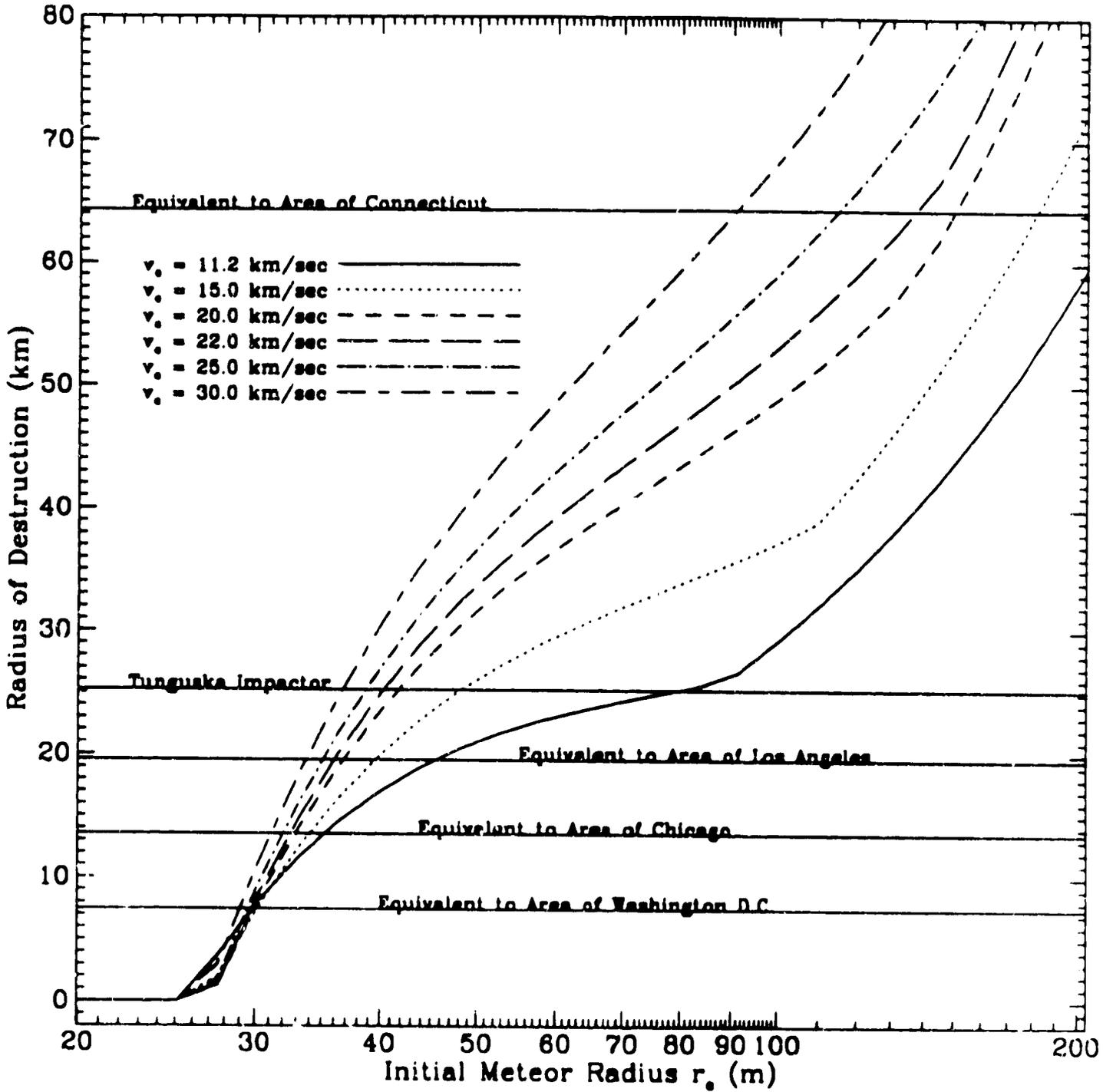


FIGURE 3

Iron

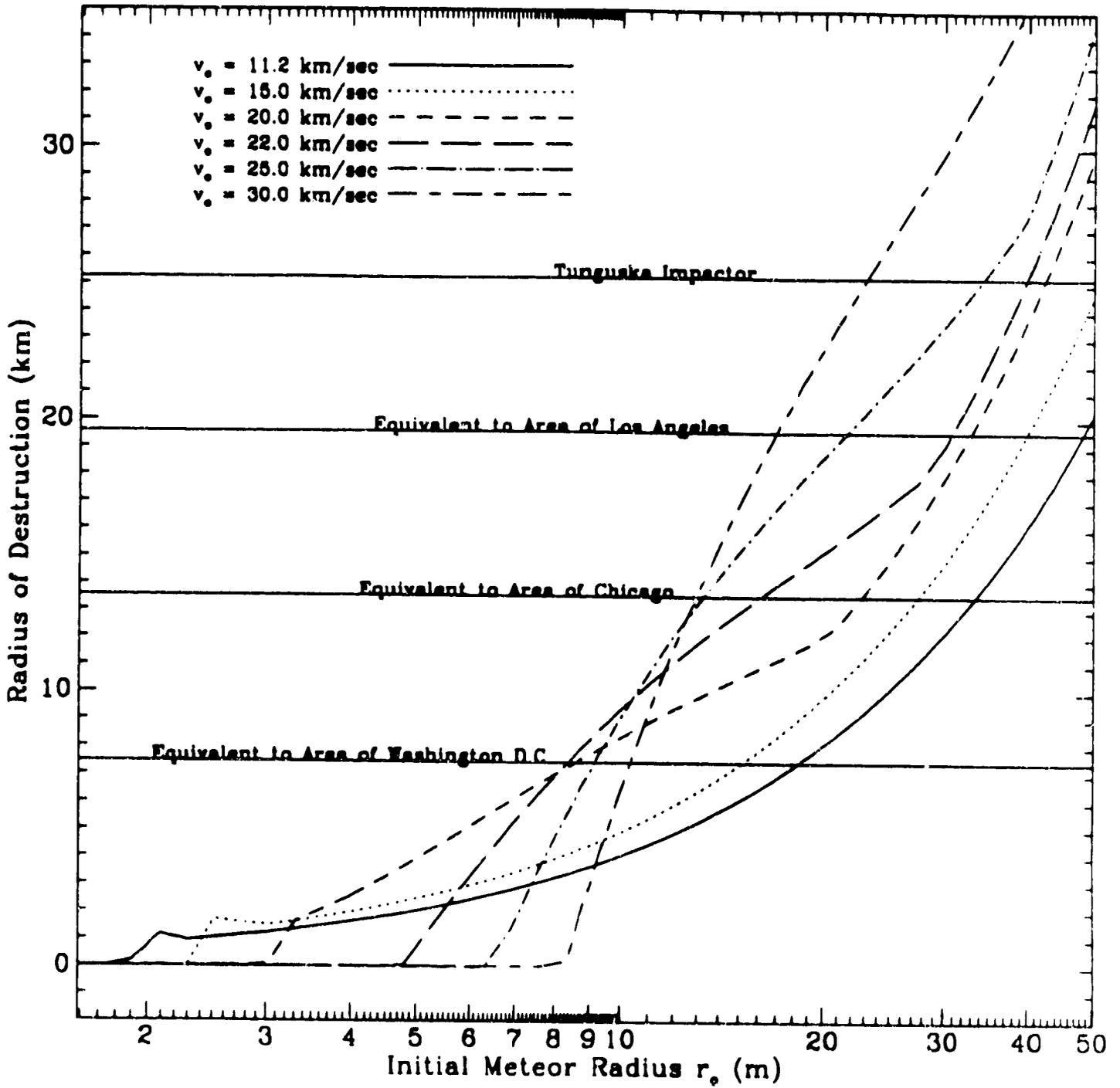


FIGURE 4

Soft Stone

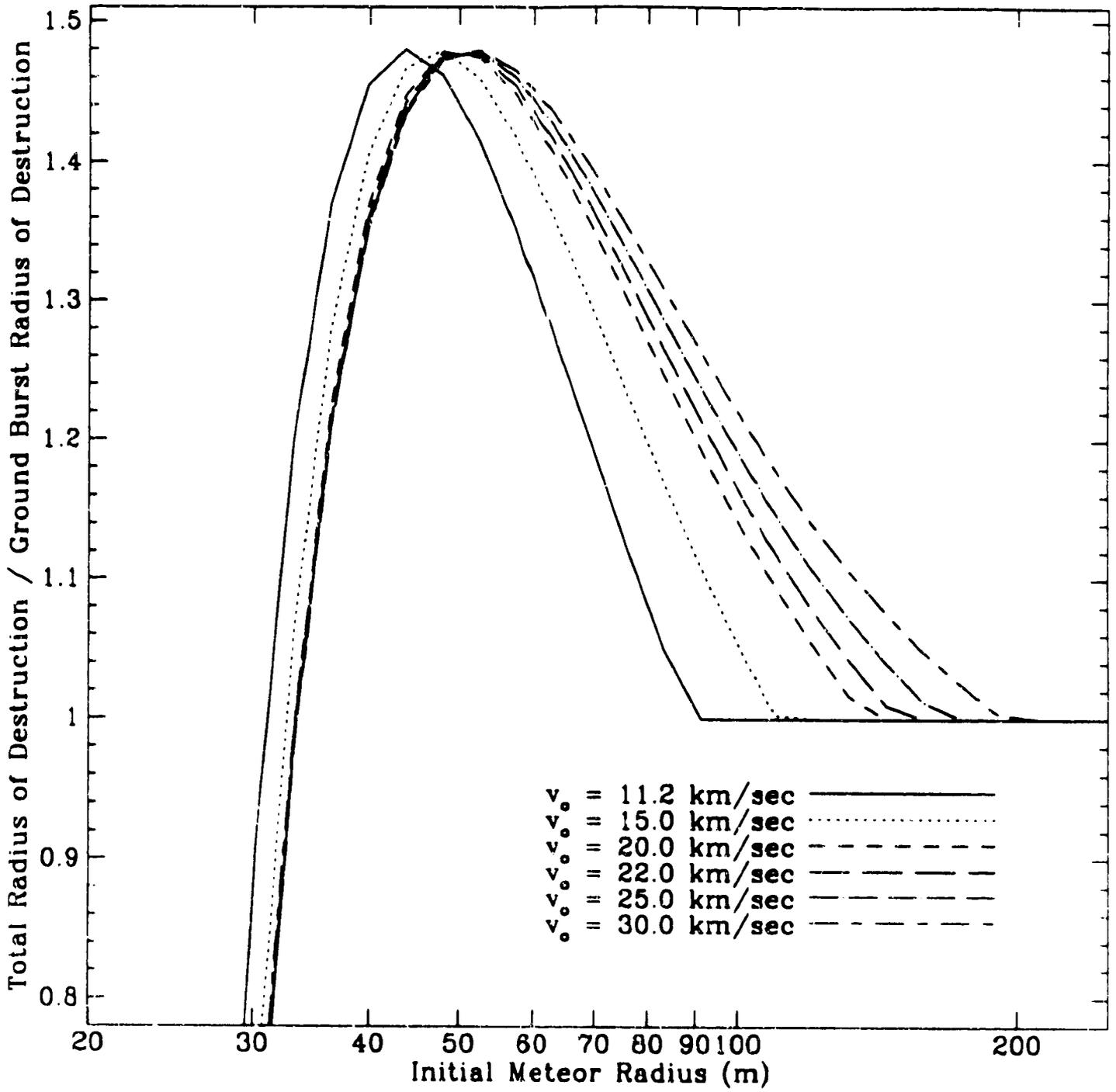
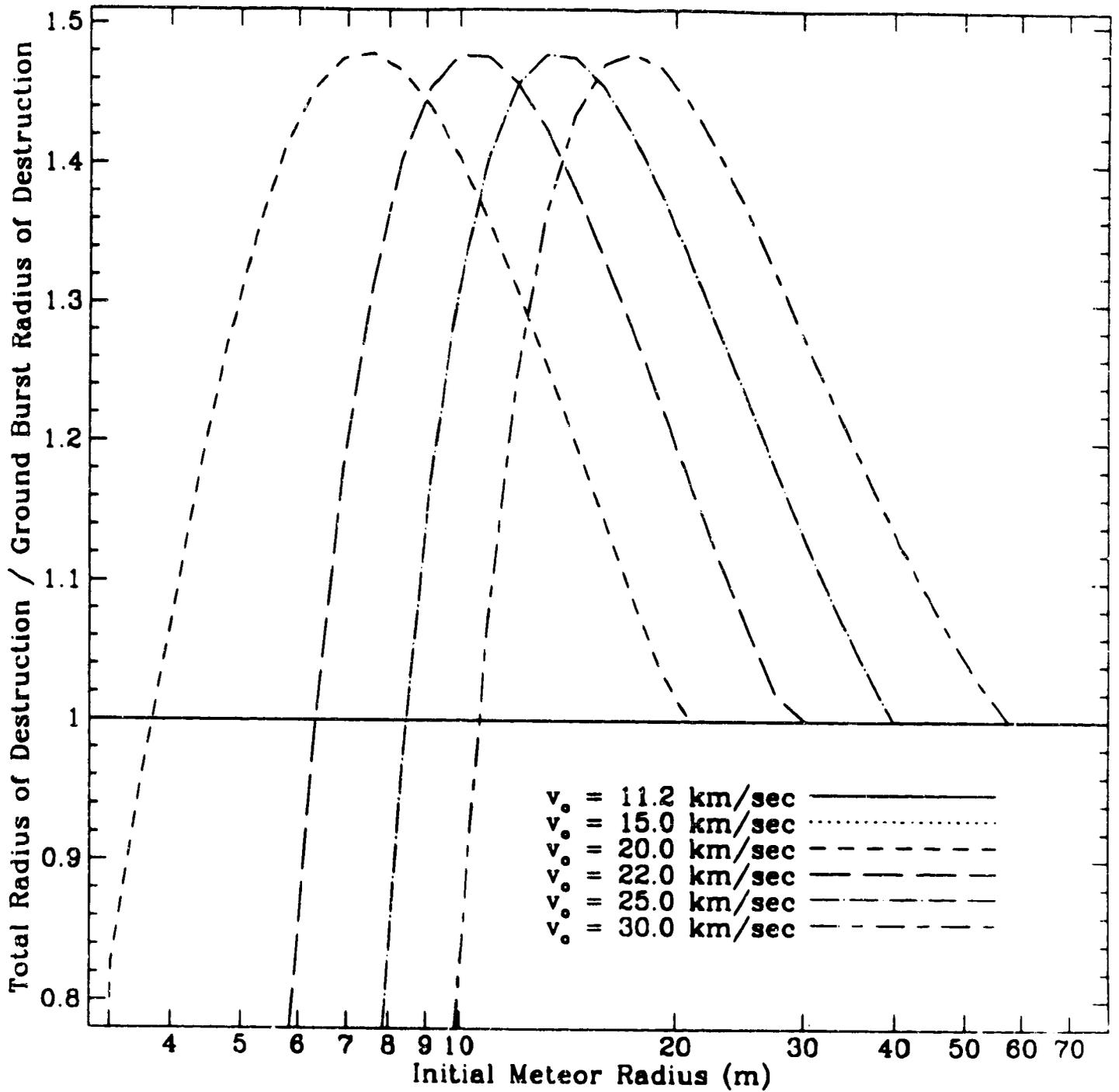


FIGURE 5

Iron



2. ASTRODYNAMICS OF INTERCEPTION

2.1 Workshop Summary

Near-Earth-objects (NEOs) are highly diverse in their intrinsic natures and in their orbital characteristics. Even the nomenclature can be confusing. Many near-Earth asteroids (NEAs), including Earth-crossing asteroids (ECAs), have been perturbed by gravitational or collisional encounters from their primordial orbits between Mars and Jupiter. Thus they are usually found in orbits of moderate eccentricity ($e \sim 0.6$), revolving about the Sun in the same sense as the Earth and the other planets, and not greatly inclined to the plane of the Earth's orbit (i.e., the ecliptic plane), although inclinations up to 70° are sometimes found. Long-period comets (LPCs), on the other hand, follow highly eccentric orbits, often highly inclined to the ecliptic. Short-period comets (SPCs) seem to have been trapped from the class of LPCs (or perhaps more directly from objects with orbits in the vicinity of the outer planets) by close passage of the giant planets (e.g., Jupiter and Saturn). With repeated passages moderately near the Sun, it is possible that some of the SPCs lose their near-surface ices that vaporize to form their glowing heads and tails, leaving only an inert regolith of material that shuts down cometary activity. They will then be classed as ECAs in spite of their sometimes more eccentric orbits, thus broadening the ECA parameter space.

A wide spectrum of possibilities exists for impacts of near-Earth objects with the Earth. The best and most likely case involves objects whose orbits are so well-known so many years in advance that threats from them can be mitigated with certainty. The worst case obviously would be an overwhelming, unpredicted disaster caused by a large object not detected in time for us to react. Warning time is the principal distinguishing factor among these different cases. Practical interest does not exceed many decades on the high side because the expected progress of humans in space will open many new options for dealing with threats far in the future, and is limited on the low side by that time interval for which no astrodynamical response is possible, essentially a few days or weeks. Table 2-1 shows how the working group partitioned the astrodynamics problem for consideration, beginning at the most favorable extreme, and working toward the less predictable case. First let us expand and clarify the definitions of the four cases identified.

Case 1. Case 1 considers Earth-crossing asteroids with well-determined orbits, which have predicted Earth-encounter position errors of the order of Earth's radius, or smaller. Therefore, it is possible to predict with reasonable confidence which orbital apparitions will bring an asteroid into Earth impact. Provided that detection resources allow them to be discovered and catalogued, the positions of these objects can be predicted precisely enough to allow warning times of decades or even centuries.

As described above, some of these threatening objects are in highly inclined, highly elliptical orbits, and will require large rocket velocities to intercept, but long warning time permits the use of minimum-energy interception orbits. Long available time also permits precursor missions to remove uncertainties from the intercept. If a high intercept velocity (e.g., 25 km/s) is acceptable, then it would be possible to fly a mission to intercept the object at the intersection of the orbits of the NEO and Earth. However, a given energy impulse will produce maximum perturbation to NEOs (other than Aten-type asteroids) if the impulse is delivered at perihelion. In the case of Aten-type asteroids, which have semi-major axes shorter than 1 AU and thus spend most of their time inside the orbit of the Earth, interception is best attempted at aphelion, where minimum energy imparted will produce maximum shift of the NEO away from the Earth.

Table 2-1. Interception case definitions

Category	Time Warning	Action	Probability of Scenario for 1-km Objects		Typical Interaction Distance (AU)	Target ΔV (cm/s)	Object
			Now	Future			
<p>1. Well-defined orbits.</p> <p>Precursor missions are strongly advisable for detailed evaluation</p>	Decades	Long-term missions	5%	95%	2	1	ECAs only
<p>2. More uncertain orbit.</p> <p>Luxury of precursor mission may be absent.</p> <p>Intermediate warning time (but still urgent).</p> <p>Object motion is affected by nongravitational forces (cometary bodies).</p>	Years	Urgent response without much room for error	Unknown		2	10 - 100 (more error)	Newly-discovered ECAs
			Unknown			(less error)	Short-period comets
<p>3. Immediate threat.</p> <p>Best scenario: discovery at 10 AU.</p> <p>Discovery initiates emergency.</p>	12 Months to 1 Month	Every available engineering measure. Continue to refine the orbit	95%	5%	0.1 (comet)	>1000 at 0.1 AU >100 at 1.0 AU	Long-period comets
			(5% of objects remain unknown after 20-year search)		0.1 - 1 (ECA)	Impact velocities 10-40 km/s	Small, newly discovered ECAs
<p>4. No warning.</p>	0 - 30 Days	Evacuate impact areas	Unknown		0		Long-period comets and unknown ECAs

Programs treating Case 1 will have beneficial spin-offs for other NASA programs and for science because the long warning times permit detailed scientific explorations and investigations of extraterrestrial resources.

Case 2. Newly discovered Earth-crossing asteroids may have poorly determined orbits. In addition, short-period comets may be perturbed by significant nongravitational forces from rocket-like outgassing, leading to unpredictable temporal variations. In either case, orbital uncertainty reduces the lead time with which we can predict probable Earth impact to a few years. Since nearly all such objects will be faint, the response must be more urgent to deal with the uncertainties and the difficulty of acquisition.

Every available means should be employed to refine the orbit. Once an object in this category is determined to be a threat, much higher intercept velocities are likely to be required because of the short mission profile. The launch energy needed, therefore, could be enormously higher than in Case 1, and there may not be the luxury of using an extra orbit for a reconnaissance flyby. On arrival at the target, the required impulse to be delivered may be an order of magnitude larger than for Case 1. It is possible that a launch window might not exist for some reason, putting the object into Case 3 (described below). Success at the first attempt is critical for the intercept mission in this case, since failure may also have the consequence of changing the interaction into Case 3.

Case 3. Here the threatening object is identified to be on a collision course with Earth with a warning time of about one year or less. The object typically will be a long-period comet approaching Earth for the first time. The most favorable scenario is discovery at a range of 10 AU at visual stellar magnitude $V = 22$, which is extremely faint and requires a large telescope for discovery. Such objects are likely to be 10 km or more in size to be visible at this distance. At 5 AU, much of the comet's light will be in the coma, making discovery much easier although localization of the nucleus may be difficult. But at 5 AU the warning time will have decreased typically to a few months.

As opposed to comets, newly discovered asteroids in this category are likely to be small bodies (less than a few hundred meters across), provided that an adequate search for ECAs has previously discovered most of the larger ones in short-period orbits. In other words, Case 3 asteroids have somehow slipped through the detection net.

Response in Case 3 requires an entirely different approach. Launch must be with shortest response time possible, and with the highest feasible velocity to make the interception as far from Earth as possible. Launch range is 0.1 to 1 AU, with a specific energy (C_2) up to 100 $(\text{km/s})^2$, associated with flight times of about 1 week to 3 months. The zone of feasible interception will often be within 0.1 AU in this case.

Case 4. This is the "horror" scenario in which a large object strikes with little or no warning. *With the present state of low observational activity, this is by far the most likely scenario because 95% of the large objects and essentially all small ones remain undiscovered at the present time.* Since an intercept is very difficult or impossible in such a case, evacuation from impact areas may be the only possible approach, and this may be futile.

3.3 Possible Interception Trajectories

The unique feature of the astrodynamical problem of intercepting an Earth-impact-threatening NEO is that the orbits of the NEO and of the Earth intersect at the ascending or descending node of the NEO orbit where the impact is predicted to occur.

Figure 2-1 shows a maneuver to achieve a rendezvous with an NEO, starting from low-Earth orbit (LEO). A large launch impulse, essentially equal to the difference between the predicted Earth-impact velocity of the NEO and the Earth orbital velocity of the spacecraft, must be applied at the time Earth passes the nodal longitude where the two orbits intersect. This injects the spacecraft into an orbit approximately matching that of the NEO, except for orbital phase and a small orbital period mismatch. This period difference is chosen so as to cause the two bodies to drift together, at which point an orbit trim maneuver completes the rendezvous. The total launch velocity, ΔV , for such missions is typically in the range 7 to 18 km/s. The Case 2 threat, with a warning time of only a few years, may require this type of interaction, perhaps modified to increase the drift rate at the cost of a higher orbit trim ΔV ; this modification will decrease the time spent in the drift phase of the mission.

Figure 2-2 shows an alternative interception trajectory which reduces the mission ΔV by relaxing the rendezvous requirement and using a high-velocity approach, typically in the range 10 to 20 km/s. The interceptor is injected into a heliocentric orbit with a period slightly under or over one year, at a point near the node of the NEO orbit (the point where impact with Earth is predicted to occur). Interception occurs at that same nodal point, several years later. A modified version of this strategy may be useful against Case 2 threats, where mission ΔV is to be minimized, and the time available is tightly constrained.

An alternative low- ΔV strategy (Figure 2-3) uses multiple planetary gravity assist maneuvers to approximate a globally optimal transfer from LEO to a rendezvous with the target asteroid. This strategy is appropriate for high-impact-velocity Case 1 (long warning time) threats, whenever the defensive system requires either a rendezvous with the target object, or an interception far from Earth's orbit, e.g., at the perihelion point. For a rendezvous, the final gravity-assist maneuver will generally be an Earth flyby at the node of the NEO orbit, to inject the spacecraft into a matching rendezvous orbit. The mission ΔV for this type of trajectory is the sum of the impulse needed to inject the vehicle into an interplanetary trajectory to the first flyby planet (probably Venus or Mars: estimated $\Delta V = 4$ to 5 km/s), and a small amount (probably < 0.5 km/s) for guidance and orbit trim maneuvers.

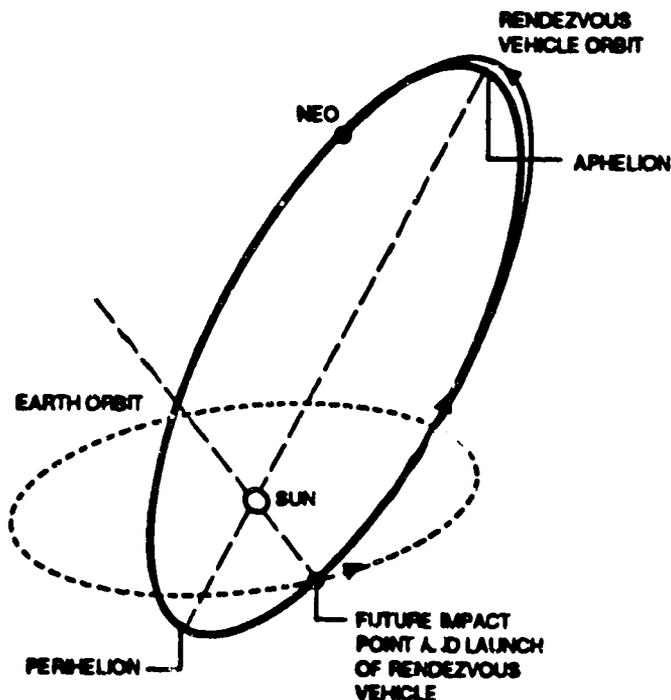


Figure 2-1. High- ΔV NEO rendezvous mission

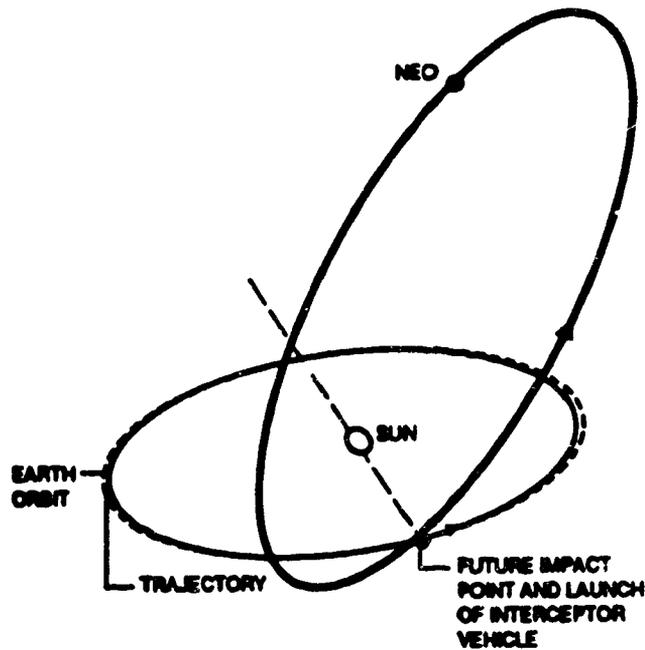


Figure 2-2. Low- ΔV , high-closing velocity interception. Interceptor orbital period is slightly greater or less than one year in order to achieve phasing needed for interception. Several NEO orbital periods must be available before Earth impact

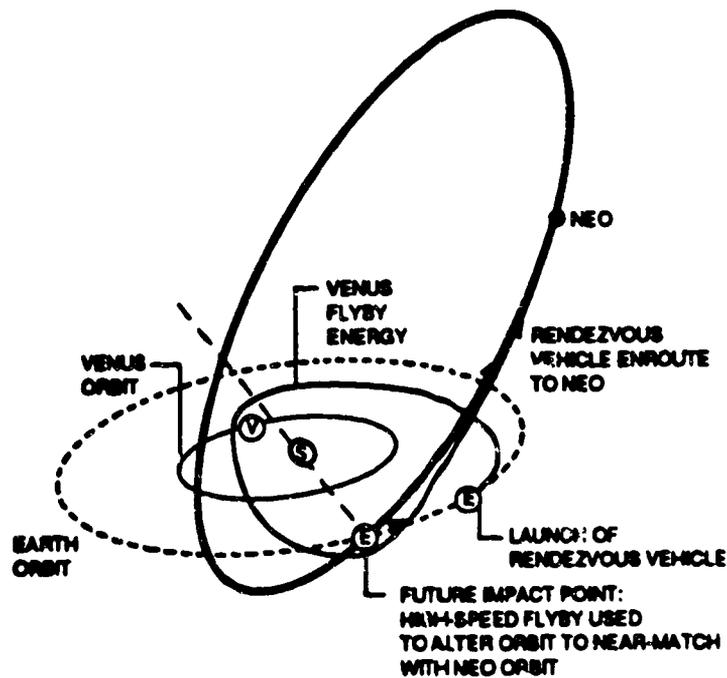


Figure 2-3. Moderate- ΔV rendezvous mission, using planetary flyby (in this case, Venus first and then Earth)

DEFLECTION AND FRAGMENTATION OF NEAR-EARTH ASTEROIDS

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ABSTRACT

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 with a populated region of the Earth, could potentially be diverted with a velocity of ~1 cm/sec from an Earth impacting trajectory by impact (at 12 km/sec) by a rocket launched, 10^2 to 10^3 Kg impactor. For larger bodies, the use of kinetic energy impactors appear 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.

1. INTRODUCTION

Several hundred asteroids and comet nuclei with diameters $> 10^2$ m, in Earth crossing orbits, have been discovered. Upon extrapolating this known population of near Earth objects (NEO's) 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. The largest earth crossing asteroids have diameters in the ~ 10 km range. It is unlikely that any still larger objects remain undiscovered, however, it is likely that additional objects as large as 3-5 km in diameter may remain undiscovered.

Scientific interest in NEO's is great because it appears that many of these objects are main belt asteroids which have been perturbed into terrestrial planet crossing orbits, and thus give rise to a large fraction of impactor flux on terrestrial planet surfaces [Binzel et al., 1992]. Objects as small as 5-10 m in diameter, can be telescopically observed. Recently 1991 BA, in the 5-10 m size was detected. This object passed within $\sim 10^5$ km of the earth [Scotti et al., 1991]. Small objects with diameters > 0.6 and 0.2 m for stony and iron objects are believed to be representative of the terrestrial meteorite collection. Since the number distribution of different meteorite classes correlates poorly with asteroid type as inferred from reflectance spectra of main belt 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 (NEA's) are currently being planned by NASA [Veverka and Harris, 1986]. Moreover, the composition of NEA's is of great interest since these represent possible minable resources which, in principle, could supply raw materials, including water, and hence, oxygen and hydrogen for extended space flights in the future.

New comets are brought into the swarm of NEO's by gravitational perturbation from their orbits in the Kuiper belt and/or Oort cloud [Weissman, 1990]. Some objects currently classed as near-earth asteroids may be devolatilized comets.

Planet crossing objects are removed from the population either via collision with a

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planet or by gravitational perturbation which causes them to be ejected into hyperbolic orbits.

Although earth-crossing asteroids have been recognized telescopically since 1932, when Karl Reinmuth discovered 1862 Apollo, it was the American geologist, G. K. Gilbert whose work on Meteor Crater, Arizona, and many later workers, made it apparent 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.

The concept that the impact of any asteroid or comet with the earth could, in principle, have a catastrophic effect on life on the earth logically followed from the 1980 discovery of Alvarez et al. [Alvarez et al., 1980] of the worldwide platinum group element-rich impact ejecta dust layer at the Cretaceous-Tertiary (K-T) boundary. The gradual great acceptance of the Alvarez hypothesis that the impact of ~10 km or larger bolide with the earth at the K-T boundary (65 Ma ago) gave rise to a great extinction of more than 50% of the known genera and probably 90% of all species, recently motivated several technical meetings, focussed on this topic, in several countries. Sparked by public concern, the United States House of Representatives in 1991 requested that the National Aeronautics and Space Administration to conduct a (workshop) series of studies of the asteroid-impact threat to the earth [Morrison, 1992], and the means to prevent it [Rather et al., 1992]. The recent Near-Earth Object Detection Workshop [Morrison, 1992], quantified the hazards to populations of different size earth impactors based, in part, on the results of an earlier, 1981, workshop [Shoemaker, 1983]. Using the estimated population of NEO's 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. Objects of about 100 m diameter include the 1908 Tunguska event (~10 Mton) energy. This size impactor has a frequency of about once every ~300 years. The Tunguska bolide did not hit the earth's surface and yet did great damage. These objects, although inducing local areas of

devastation of $\sim 5 \times 10^3 \text{ km}^2$, have an annual probability of leading to the deaths of a given individual of only 3×10^{-8} /year. Although less frequent, once every 0.5 Ma, earth impactors of the $\sim 2 \text{ km}$ diameter size are inferred to be the minimum size which can produce global catastrophic effects (25% human mortality). Thus the annual individual death probability from such an event is of the order of 5×10^{-7} , which is comparable to the annual worldwide probability of an individual succumbing in a commercial airplane accident. When viewed in this way, it appears to us that for society to deal with this problem rationally, it ought to expend not more than perhaps a fraction of the amount 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 ground-based and possibly space-borne telescopes. The technologies which might be employed to divert asteroids can be expected to change so rapidly that it appears premature to conduct detailed engineering studies or build prototypes.

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., 1992] and impact ejecta scaling [Housen et al., 1983], which were not available to earlier studies [MIT Students, 1968; Solem, 1992].

In the present paper we examine the orbit perturbation requirements to deflect objects from the Earth, which upon astronomical orbit determination are found to have earth impacting trajectories. We then examine several physical means for both deflecting and explosively fragmenting such objects. We consider NEO's in three size ranges, 0.1, 1, and 10 km in diameter. Their fluxes, on the total area of the earth per year are respectively, 10^{-3} , 10^{-5} , and 10^{-8} . It is unlikely that any undiscovered objects $> 5 \text{ km}$ exist. Significantly smaller objects pose very little threat, because they do not penetrate the

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atmosphere intact. Short duration responses, which might be considered for new comets, have recently been described by Solem [1991; 1992]. This study addresses the physical means of encountering NEO's with spacecraft-bearing energetic devices many years, or even decades, before projected earth impact.

2. NEAR EARTH ASTEROID ORBIT DEFLECTION CONSIDERATIONS

Two possible approaches to orbit deflection are perturbation perpendicular to orbital motion and perturbation along the trajectory of motion, e.g. either speeding up or slowing down the orbital velocity relative to the Sun.

An increment of velocity, Δv applied transversely to a circularly orbiting particle induces an eccentricity or inclination which results in an oscillation about the original orbiting point of amplitude.

$$\delta \sim \frac{\Delta v}{v_0} a \quad (1)$$

where v_0 is the orbit velocity (30 km/s for the Earth) and a is the semimajor axis. Thus to perturb a particle by $\delta \sim 1 R_{\oplus}$. The Δv required is

$$\Delta v \sim \frac{v_0 R_{\oplus}}{a} = 1 \text{ m/s} \quad (2)$$

To perturb a body on a time t short compared to the orbit period, a simple linear estimate suffices:

$$\delta = \Delta v t \quad (3)$$

To perturb a body $1 R_{\oplus}$ in time, t , requires

$$\Delta v \sim \frac{R_{\oplus}}{t} \sim \frac{75 \text{ m/s}}{t, \text{ days}} \quad (4)$$

Note that the linear estimate reduces to the orbital oscillation after ~ 1 radian of orbital motion.

In contrast, an increment of velocity Δv applied parallel to the orbit motion changes

the orbital semimajor axis, but more importantly, changes the orbit period which results in a secular drift of the perturbed body from its original path. For an initially circular orbit, the mean drift velocity, $\Delta v'$ is in the opposite sense and larger than Δv :

$$\Delta v' = -3\Delta v \quad (5)$$

An even larger amplification occurs if the impulse is applied at the perihelion of an eccentric orbit. For an eccentricity of 0.5, $\Delta v' = -5\Delta v$. Thus, over a time long compared to the orbit period, an increment Δv applied parallel to v produces a deflection of

$$\delta \sim 3\Delta v t \quad (6)$$

Hence, for 1 R_{\oplus} deflection

$$\Delta v \sim \frac{R_{\oplus}}{3t} \sim \frac{0.07 \text{ m/s}}{t, \text{ years}} \quad (7)$$

Thus, with a lead time of the order of a decade, a velocity increment as small as ~ 0.01 m/sec could suffice to divert an asteroid from a collision course with the Earth.

3. 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.

A. DIRECT IMPACT DEFLECTION

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

(1) The kinetic energy delivered for even a modest encounter velocity (~ 12 km/sec) 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/sec is 70×10^{10} ergs per g of impactor. This is much greater than typical chemical explosive energies (4×10^{10} ergs/g), and as demonstrated below the ejecta throw-off from such an impact will suitably perturb the NEO.

(2) The cratering efficiency on a small (100 m diameter) asteroid (escape velocity 5 cm/sec) is unmeasured. However, extrapolating small scale studies (at high and low gravities) it is expected to be $\sim 10^4$ times [Holsapple, 1992; Housen et al., 1983] the earthly value of 2.8 tons of rock per ton of equivalent explosive yield [Cooper, 1977]. For example, we calculate the impact of a 200 kg projectile onto 100 m diameter, 10^6 ton, 2 g/cm^3 asteroid, induces a gravity limited crater with 10^5 tons of ejecta having greater than escape velocity. This will perturb the velocity object ~ 0.6 cm/sec even if a (30 bar) strength controlled crater formation is assumed [Holsapple and Schmidt, 1982] and $\sim 10^2$ tons per equivalent ton of explosive is calculated.

It is possible that for small asteroids, an impactor device, e.g., the U.S. Space Defense Initiative's technology derived from the Boeing Company's Lightweight Exoatmospheric Projectile, could be utilized.

At larger asteroid diameters of 1 km, the increase in asteroid mass by a factor of 10^3 reduces the resulting perturbation velocity by the same factor. Moreover, the cratering efficiency declines on account of the increased gravity of the asteroid and thus direct impact deflection in this size range becomes impractical.

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. A lead time of three decades, prior to earth encounter would, from Eq. 7, require a $\Delta v \sim 0.2$ cm/s. 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/sec, the ejected mass necessary to produce a recoil of 0.2 cm/sec is

$$\Delta m \sim \frac{0.2 \text{ cm / sec}}{0.3 \text{ km / sec}} m_a \sim 7000 \text{ tons}$$

where m_a is the asteroid mass. 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. NUCLEAR EXPLOSION RADIATION DEFLECTION

By detonating a nuclear explosive which emits a large portion of its yield via neutrons, a large area of the asteroid/comet surface can be irradiated [Hyde, 1984]. Subsequent blow-off of surface material in excess of the escape velocity can provide the necessary impulse for orbital deflection as sketched in Fig.1. We have found that by detonating a charge at a normalized altitude $h/R = \sqrt{2}-1 \approx 0.4$, where h and R are the altitude of the charge above the asteroid surface and R is the radius of the asteroid, a maximum dose of $f_{\max} = 0.27$ times the total radiative yield is delivered to 0.296 times the unit area of an assumed spherical asteroid. For a mean neutron cross section of 10^{-24} cm², an assumed asteroid density of 2 g/cm³ and mean atomic weight of 25, a characteristic neutron penetration depth of ~ 20 cm is inferred. Thus an asteroid volume corresponding to a 20 cm deep surface shell covering 0.296 of the surface area is irradiated, which for a 50 m radius

object with a density of 2g/cm^3 will have an irradiated shell of mass 3.7×10^9 g. We further assume that the fraction, $e=0.3$, of the explosive yield is delivered as neutron or other radiation and this radiation is completely converted to internal energy, ΔE , per unit mass in the irradiated shell. The energy per unit kiloton of explosive yield delivered to the irradiated shell is thus

$$\Delta E = f_{\text{max}} e (4 \times 10^{19}) \text{ ergs} \quad (8)$$

where 4×10^{19} is the equivalent number of ergs in a kiloton of explosive yield. This heating at constant volume of the shell will result in an increase in the pressure (per kiloton), ΔP of

$$\Delta P = \gamma \rho \Delta E \quad (9)$$

where γ is the thermodynamic Gruneisen ratio. We assume γ to be unity, and ρ is the asteroid/comet density which we assume is 2g/cm^3 . This irradiation occurs in less than the $\sim 10^2 \mu\text{s}$ required for the sonic wave travel time through the shell. From Eq. 9, this energy density will raise the shell thermodynamic pressure to ~ 1.7 kbar (per kiloton). As depicted in Fig. 1, this pressure increase accelerates the irradiated shell to the right and a stress wave pulse is propagated to the left within the asteroid. The right moving irradiated shell and left propagating stress wave causes the irradiated shell to break away from the asteroid (to conserve momentum) as depicted in Fig. 1. The stress wave propagating to the left in the asteroid appears to be sufficiently low amplitude such that little further destruction of the object is expected to occur. By assuming a compressional wave velocity, C_p , of 2km/sec , we find

$$\Delta v_r = \Delta P / \rho C_p \quad (10)$$

in the asteroid material, the resulting outward particle velocity of the shell material is 44m/sec/Kton . Considering only the component of velocity along the direction between the explosive and the asteroidal center yields a reduced velocity of $\sim 31 \text{m/sec/Kton}$. For the 50m radius asteroid, this velocity is much greater than the escape velocity of 5.3cm/sec . By conservation of momentum, the rebounding surface material translates into an asteroidal

perturbation velocity of 11 cm/sec/Kton. For 1 and 10 km diameter objects, the comparable rebound velocities are 11×10^{-3} and 11×10^{-6} cm/sec/Kton. However, if $e = 0.03$ rather than 0.3, these velocities will decrease by a factor of 10. Thus we conclude that to achieve deflection velocities on the order of 1 cm/sec requires detonation of 0.01 to 0.1 Kton, 0.01 to 0.1 Mton, and 0.01 to 0.1 Gton nuclear explosives, for asteroids of diameter 100 m, 1 km, and 10 km, respectively.

D. DEFLECTION BY SURFACE NUCLEAR EXPLOSIVE

Another approach to the use of nuclear explosives employs the use of a surface charge to induce cratering on the asteroid. The thrown-off ejecta effectively induces a velocity change in the asteroid 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 asteroid 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 asteroid velocity in the case that gravity limits ejecta production, and the asteroid is weak. For the case of a 0.1 km asteroid, it is conceivable that cratering processes are limited by asteroid yield strength. We examine this case, also. The mass of ejecta cratered per unit mass of explosive, when cratering is limited by gravity, is given by Housen et al.[1983]

$$\pi_v = \{0.16-0.24 (d/a) \pi_2^{0.194} + 2.11 [(d/a) \pi_2^{0.194}]^2 - 2.38 [(d/a) \pi_2^{0.194}]^3 + 0.663 [(d/a) \pi_2^{0.194}]^3\} / [\pi_2^{0.581}] \quad (11)$$

Eq. 11 was obtained on the basis of small-scale laboratory centrifuge experiments under high gravity, reduced pressure, and large-scale nuclear explosive tests. Equation 11 also describes a limited number of small scale experiments conducted by Johnson et al. [1969] at reduced gravity and reduced atmospheric pressures. Here π_v is the mass of material ejected from the crater per unit mass of explosive. It is assumed that nuclear explosives can be assigned an equivalent TNT (high explosive) mass based on their yield. Here d and a

are explosive depth and equivalent explosive mass radius. Also, π_2 is defined as the gravity scaling parameter

$$\pi_2 = (m/\delta)^{1/3} g/Q \quad (12)$$

where m is the equivalent charge mass and δ is charge density. For simplicity, we again assume that charge density and asteroid density are equal at a value of 2 Mg/m^3 . Q is the energy per unit mass of TNT which is $4 \times 10^6 \text{ J/kg}$ and g is asteroid surface gravity. Since the only ejecta which will alter the orbit of an asteroid must be thrown off the object at a velocity exceeding the escape velocity, we use the generalized equations of Housen et al. [1983] to calculate the mass of ejecta, m_e launched at speeds greater than escape velocity

$$m_e/(\rho R_c^3) = 0.32 [2R/R_c]^{-0.61} \quad (13)$$

where R_c is the final crater radius. The mass of ejecta escaping the asteroid and the resulting asteroid velocity perturbation versus surface explosive charge are shown in Fig.

2. To relate R_c to m_e , we assume a conical-shaped crater with a depth to diameter ratio of 5. Thus far for surface explosions ~ 0.1 , 10^2 and 10^4 Kton of explosive energy, detonated at the asteroid surface, are required to perturb 0.1, 1, and 10 km diameter asteroidal or cometary object's orbital velocity by $\sim 1 \text{ cm/sec}$. Moreover, for a 100 m asteroid strength scaling [Holsapple and Schmidt, 1982] may apply. In the case of an effective yield strength of 30 bars, Fig. 2 indicates only 500 kg would be required to perturb a small asteroid by 1 cm/sec.

Thus at best, surface explosions are no better than radiative stand-off explosions, and the requirements are subject to greater uncertainty.

5. FRAGMENTATION AND DISPERSAL

Small scale fragmentation experiments on solid rocks demonstrate that the bulk of the fragments of a collisional disruption have velocities of $\sim 10 \text{ m/s}$. However, the "core" or largest fragment has been demonstrated to have a differential velocity of no more than $\sim 1 \text{ m/s}$ (e.g. Nakamura and Fujiwara [1991]). From equation 4, if the body is fragmented

~75 days before earth encounter then most of the ≥ 10 m fragment 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 ≥ 10 m are allowed. For a really large object (> 1 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. 7 and in the transverse direction according to Eq. 2. For a characteristic velocity of ejecta of 10 m/s, the debris cloud would be $\sim 10R_{\oplus}$ in radius (with some oscillation about the orbit) and grow in length by $\sim 200 R_{\oplus}$ per orbit period. Thus, if the asteroid 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 $\Delta v \leq 1$ m/s 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 still hit the Earth.

"Catastrophic disruption" is generally defined as fragmentation where the largest fragment is $\leq 1/2$ the total mass. The energy density to accomplish this decreases with increasing size of body, and becomes rather uncertain when extrapolated to 1-10 km size bodies (e.g. Housen & Holsapple [Housen and Holsapple, 1990]). However, for the present purpose, we are interested in the energy density necessary to break up an asteroid so that all fragments are ≤ 10 m in size. This is obviously a higher energy density than that to just "break it in two," and we suggest should be of the order of the energy density needed to "break in two" a 10 m object, $\sim 10^7$ ergs/gm.

Because of the large energy requirements to fracture a well consolidated asteroid, only nuclear explosives are considered. In order to relate the energy density as a function of radius for a completely coupled (buried) nuclear charge, we employ the empirical relations of shock-induced particle velocity, v , versus energy scaled radius ($r/kT^{1/3}$) of Cooper [1977]. For hard (mainly igneous) terrestrial rocks of Cooper finds

$$\ell n_{10} v(\text{m/s}) = 5.233 - 2 \ell n_{10} (r/kT^{1/3}) \quad (14)$$

where the r , radius is hydrodynamically scaled by the one-third power of explosive yield ($kT^{1/3}$). Similarly, for soft rocks, Cooper finds

$$\ell n_{10} v(\text{m/s}) = 4.590 - 2 \ell n_{10} (r/kT^{1/3}) \quad (15)$$

Since the shock wave energy per unit mass is equal to v^2 , the quantity

$$E_{\text{frac}} = v^2(r, kT^{1/3}) \quad (16)$$

where v^2 can be specified via Eq. (14) or (15) and $E_{\text{frac}} = 10^3 \text{ J/kg} = 10^7 \text{ ergs/g}$. Upon substituting Eq. (15) into Eq. (16) for 1 kT, we find $r = 35 \text{ m}$. Thus, a 1 kT explosive is expected to fragment a 35 m radius sphere of rock, if the explosive is placed well within the asteroid. Also, a 1 megaton charge of explosive will fragment 350 m radii of rock and 1 Gton of explosive will fragment 3.5 km of rock. In contrast, for hard rock (Eq. 14), which describes less attenuative rock, gives the radius of fracture of 74 m for 1 Kton explosion. From Eq. 15, to deliver 10^7 ergs/g to 0.1, 1, and 10 km diameter asteroids requires 3 kT, 3 Mtons, and 3 Gtons, centrally placed.

The above discussion is based on the premise that the charge is buried to sufficient depth so as to obtain optimum fragmentation. 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 [Schmidt et al., 1986], whereas the large fraction of the energy of a deeply buried charge is coupled into rock.

Figure 3 shows the charge depth for different d/a values and yield required to completely excavate asteroids of 100, 1,000, and 10,000 m diameter. The yield values required for an excavating charge are less by a factor of 3×10^3 to 4 in going from 0.1 to a 10 km asteroid, than those calculated for fragmentation. These charges are in the 0.15 to 3 kton range for 100 m asteroid, 0.007-3 Mton for a 1 km asteroid, and 0.3 to 3 Gton for a 10 km diameter asteroid. 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 asteroid size and surface gravity. Fig. 3 also shows the radius of excavated volumes between craters on the Earth and a 10 km asteroidal object differ by a factor of up to 5 in going from the gravity of a 10 km diameter object, 0.3 cm/sec^2 to that of the Earth (982 cm/sec^2). Dispersal seems to require about the same energy as deflection, and also is benefitted by charge burial. Hence, asteroid deflection rather than destruction, via fragmentation, appears the favorable choice.

CONCLUSIONS

We have examined the velocity criteria for perturbation of the orbits of earth-crossing objects (asteroids and comets) so as to cause objects which 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/sec. Energy levels are prohibitive for larger bodies, and the required perturbation impulse would disrupt the body.

We also note that perturbation of an object perpendicular to its orbit is more effective by applying a change in velocity, (Δv) along its original orbit and thereby inducing a change in orbital period, and hence the radius of the orbital axes. Upon applying an impulse at perihelion, gives rise to a Δv , which, in turn, provides a larger deflection δ , after time, t , of the order of $3\Delta vt$, than can be achieved for perpendicular deflection.

For a ~100 m diameter asteroid, the kinetic energy of 10^2 to 10^3 kg impactors, intercepting at $\sim 2 \text{ km/sec}$ 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/sec. For larger diameter asteroids, 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 asteroidal material to deflect from the Earth impact a 1 km asteroid over an interval of 30 years prior to encounter. Nuclear explosive irradiation may be used to blow-

off a 20 cm shell encompassing (~ 0.3 times) the asteroid surface area by exploding a charge at an optimum height of $h/R = \sqrt{2} - 1$. Minimum charges of 0.01, 10^2 , and 10^4 Kton of explosives are required to cause this shell to blow-off and perturb the velocity of 0.1, 1, and 10 km asteroids by 1 cm/sec. However, less radiatively efficient explosives may require an order of magnitude more explosive yields. Surface charges of 10^{-2} , 10, and 10^5 Kton may be used to eject crater material to greater than local escape velocity, and hence, perturb 0.1, 1, and 10 km diameter asteroids by a velocity increment of ~ 1 cm/sec. 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 completely excavate (working only against local gravity) 0.1, 1, and 10 km diameter asteroids require energies of ~ 1 ton, 30 Kton and 0.8 Gtons, 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) asteroid, 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 range asteroids 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 an asteroid may be warranted, we do not believe it is appropriate to conduct engineering designs of systems because:

- 1) low earth impact probability of hazardous asteroids;
- 2) high cost compared to low probability;
- 3) rapid changes in defense systems technology.

10/5/92

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FIGURE CAPTIONS

Figure 1. Sketch of the use of nuclear explosive radiation to induce a (~1 cm/sec) velocity perturbation in a near earth asteroid. (a) Nuclear explosive designed to provide a substantial fraction, e , of its yield as energetic neutrons and γ gamma rays is detonated at an optimum height, $(\sqrt{2} - 1) R$, above an asteroid. At this elevation asteroid subtends 0.27 of the area of a unit sphere around the explosive and explosive irradiates 0.296 of the asteroid surface area (b) Irradiated to a depth of ~20 cm, surface material subsequently expands and spalls away from the asteroid, inducing a several kilobar stress wave in the asteroid. (c) Blow-off of the irradiated shell induces a cm/sec velocity perturbation in the asteroid.

Figure 2. Mass ejecta accelerated to greater than escape velocity (left) for cratering explosive charges on surface and 0.1, 1, and 10 km diameter asteroid as a function of explosive yield. Plotted on right is the resultant asteroid velocity change resulting from momentum conservation. G, indicates gravity scaling and S, strength scaling of crater size and dynamics. The curvature of the velocity curve for strength scaling for a 0.1 km diameter asteroid, arises from the substantial fraction of the asteroid ejected by an explosive crater in the 30 bar strength material.

Figure 3. Radius of excavated sphere of asteroidal material for 0.1, 1, and 10 km asteroids, versus, normalized charge depth. Effect of nominal yield explosive for each size asteroid 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 0.83 Gton explosive charge yields a radius of excavated volume of crater of 5 and 1 km on the asteroid and Earth, respectively.

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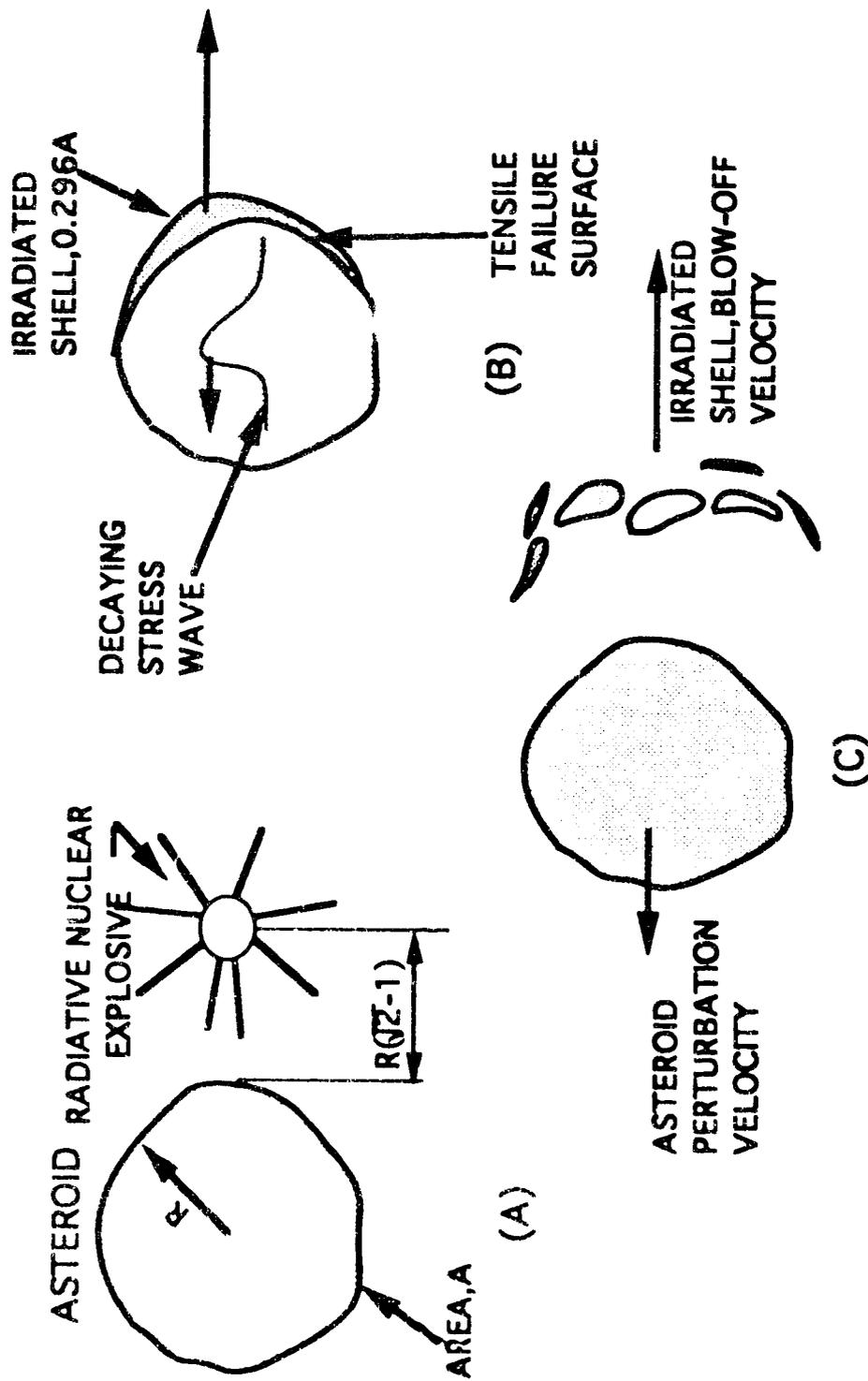


Fig. 1.

Asteroid Velocity Change (cm/sec)

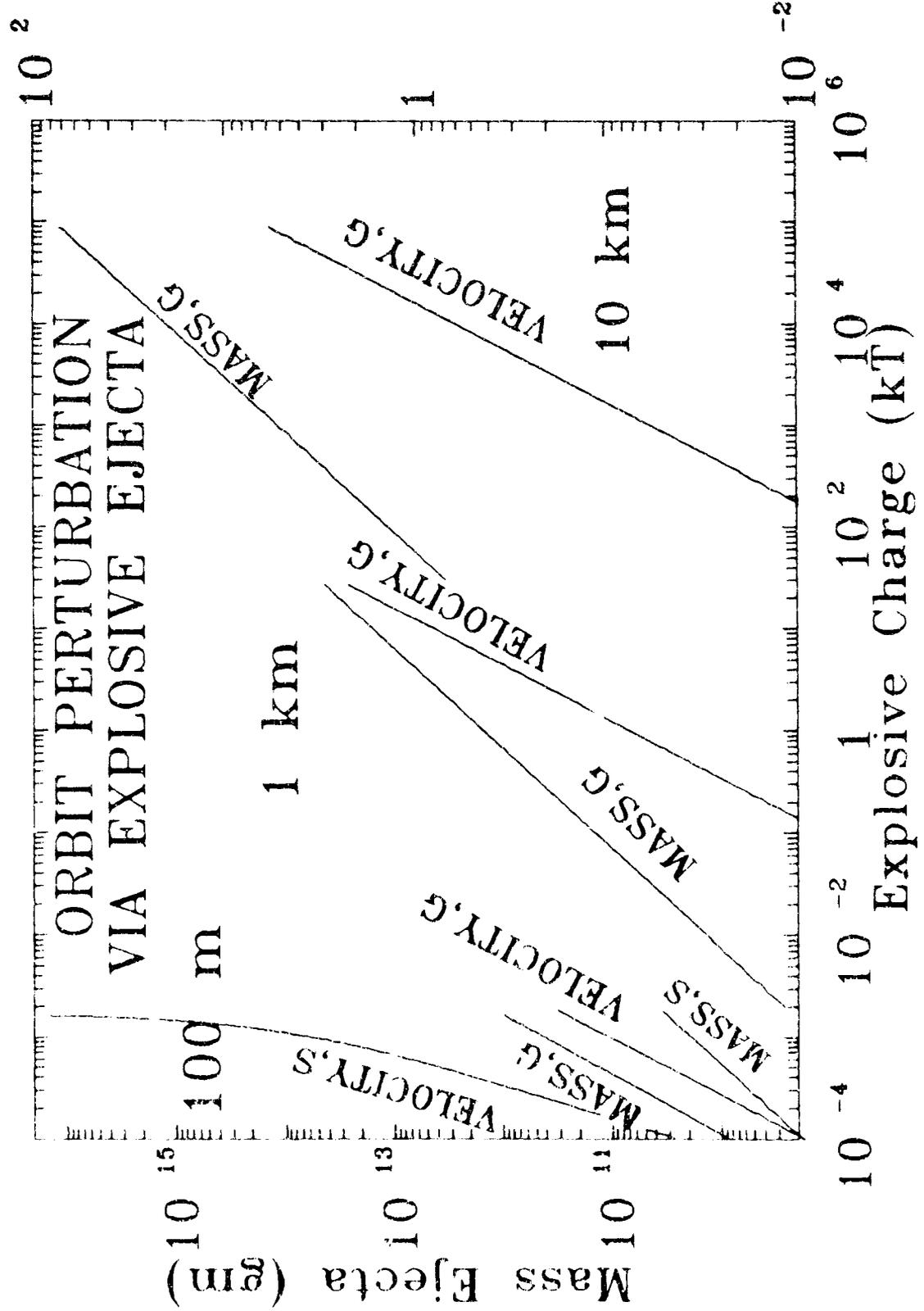


Fig. 2.

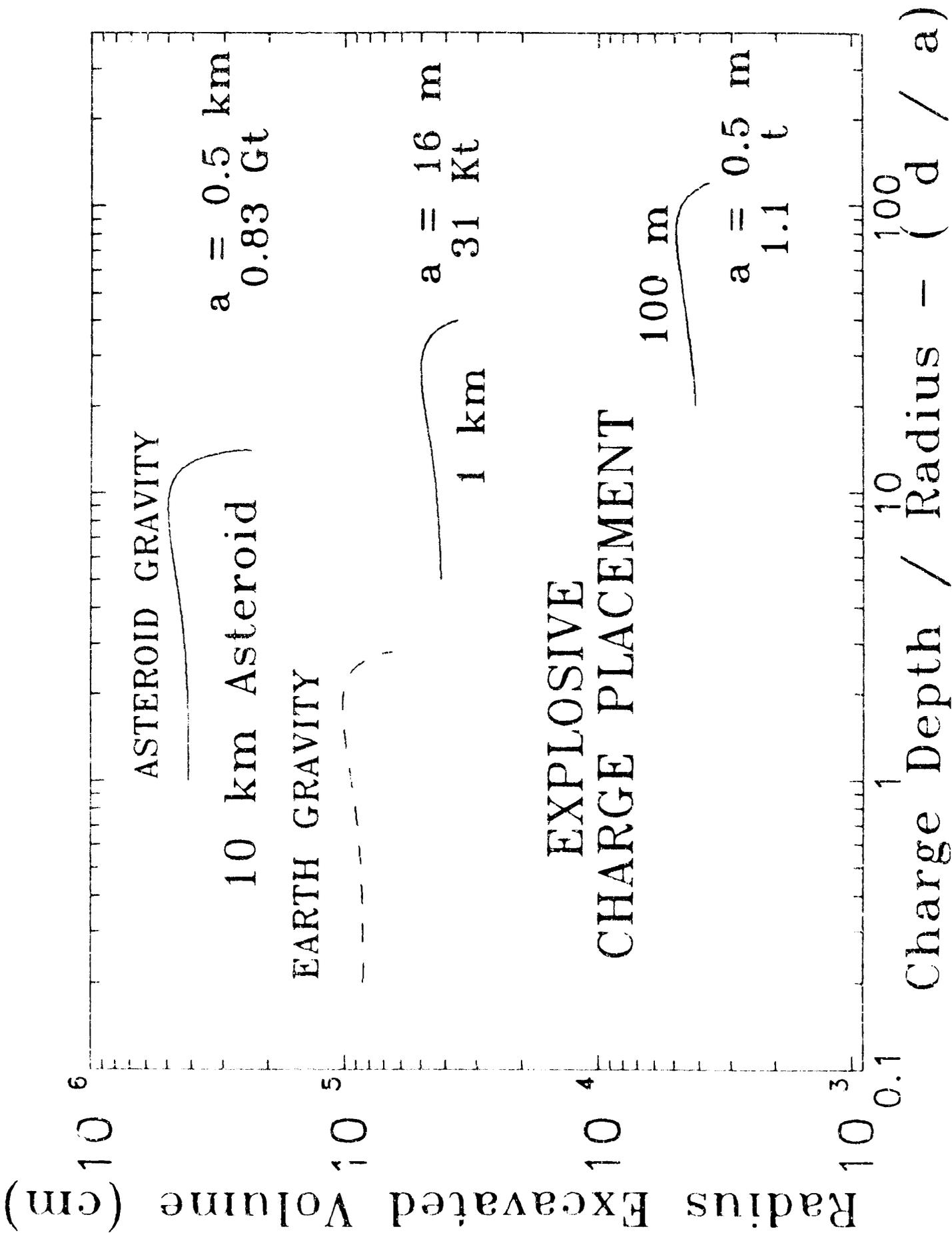


Fig. 3.

DYNAMICS OF NEO INTERCEPTION

Claude Phipps, Los Alamos National Laboratory

NASA Near Earth Object Interception Workshop

Paper C1, Tutorials and Technology Summaries, J. D. G. Rather, presiding

The energy density of kinetic objects with relative velocities in the 5 – 50 km/s range typical of NEO's is quite large, being greater than hot chemical reactions, and more like that of plasmas created by laser ablation. Especially when warning time is short (as it will normally be prior to accurate NEO orbit determinations), efficient response suggests addressing the NEO with an energy density similar to its own.

COMPARING SPECIFIC KINETIC ENERGY WITH CHEMICAL AND NUCLEAR

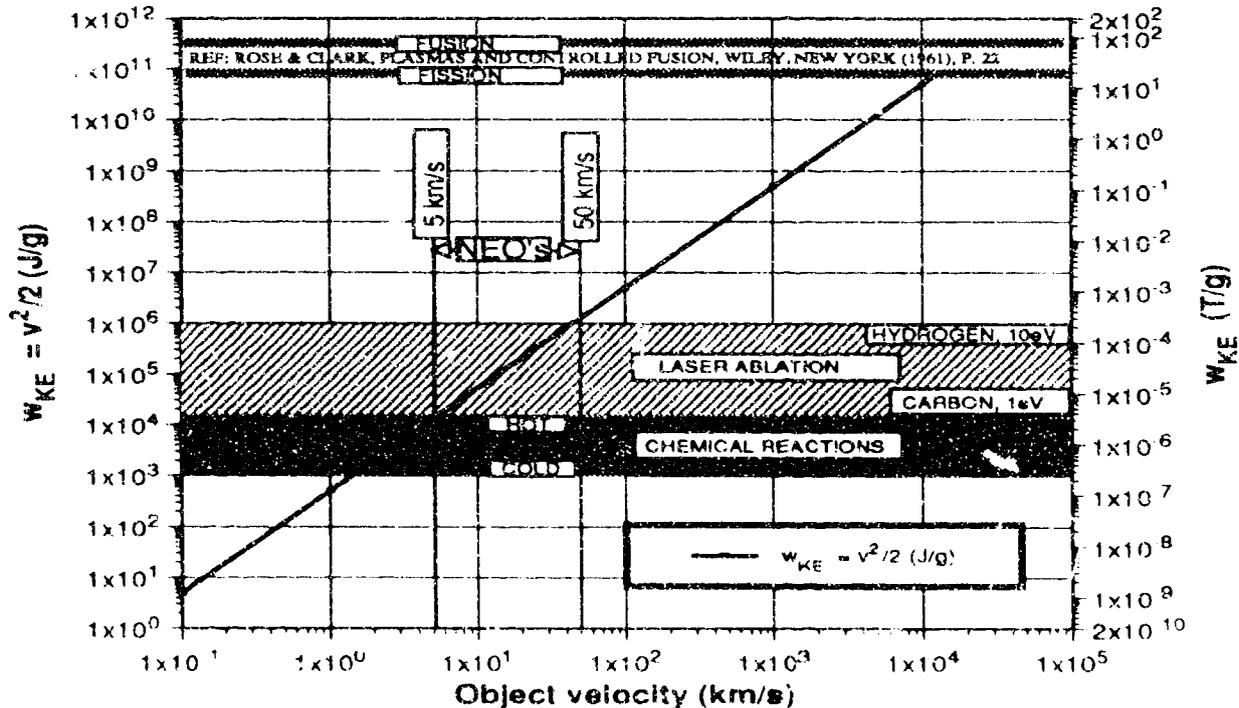


Figure 1

The question comes, how to inter-relate the various parameters of interception in a way that shows the amount of deflection energy required in various situations.

Detection

The first step is to relate detection distance z_{det} to the object diameter D_o . We will illustrate how this works for the simplest scheme: using scattered solar radiation at night to make the object stand out against its background. If we use a diffraction-

limited telescope against a field with background irradiance i_b watts/(cm²-sterrad-nm) then the background power collected by the telescope P_b is aperture-independent,

$$dP_b/d\lambda = 3.67 \lambda^2 i_b \quad \text{watts/nm} \quad [1]$$

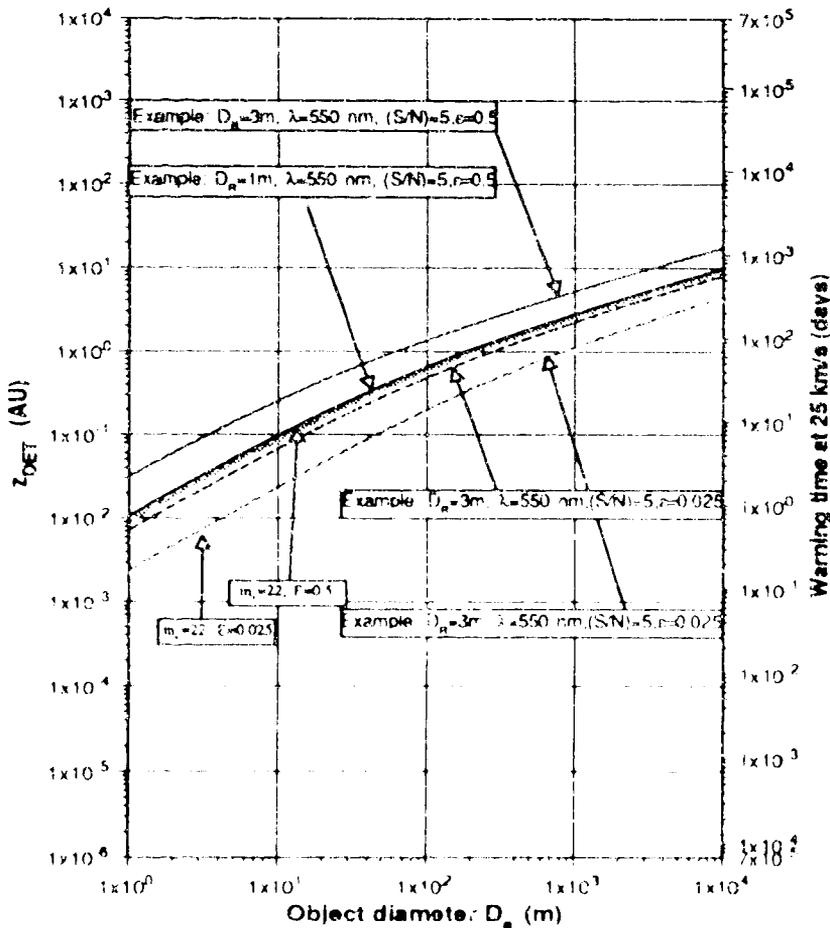
since the diffraction-limited solid angle decreases at the same rate as aperture increases. In the night sky near 550 nm, $i_b = (4 \times 10^{-11} / S)$ watts/(cm²-sr-nm)^a, where S is the effective width of the visual star-color response curve (about 60 nm). Observational experience is consistent with $i_b \Rightarrow 6 \times 10^{-13}$ watts/(cm²-sr-nm)^b. The peak solar spectrum^c near Earth is $I_s = 1.85 \times 10^{-4}$ watts/(cm²-nm), so solar flux on the NEO surface is

$$I_{NEO} = I_s (1 + Z_{DET})^{-2} \quad \text{watts/(cm}^2\text{-nm)} \quad [2]$$

where $Z_{DET} = z_{DET}$ expressed in A.U. Taking both spectra as flat near peak visual acuity at 550 nm, detection occurs for an optical signal-to-noise ratio (SN) when received power $P_R = (SN)P_b$. If the NEO has scattering coefficient ϵ into 2π sterrad, the result is:

$$(1 + Z_{DET})Z_{DET} = 1.89 \times 10^{-10} \frac{D_a D_R}{\lambda} \sqrt{\frac{\epsilon}{(SN)}} \quad [3]$$

Detection distance in AU for the solar illumination scheme



where D_a and D_R are the asteroid and receiver diameters. Equation [3] is plotted in **Figure 2**, at left. Note $m_v = 24$ is consistent with about 1 photon/sec per 1-m-diameter aperture, within the visual star-color response curve. The gray curves in **Figure 2** represent that distance at opposition at which an object with the indicated albedo would become visual magnitude 22. It is seen that warning time may be a few days for the smallest, darkest objects which can penetrate

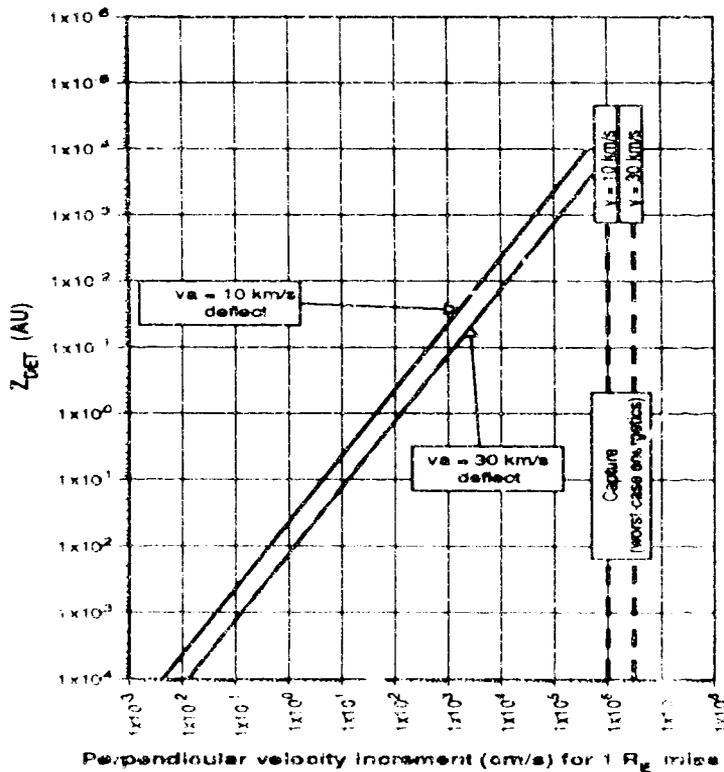
the atmosphere. Here, we have implicitly considered the most difficult case in which the object is first detected when it is already on a collision course, *because this case is currently most probable*. See "Astrodynamics of Interception" working group report

Velocity Vector Change

Having determined z_{DET} we now need to relate it to the required perpendicular velocity change required to produce a $1 R_E$ miss. To do this, we make a linear approximation to the true Keplerian velocity vector and take

$$\theta_d = \frac{v_{\perp}}{v_{\parallel}} = \frac{R_E}{z_{LxET}} \quad [4]$$

The required perpendicular velocity change from Equation [4] is shown in **Figure 3**, following, along with parallel velocity change required to capture, for comparison.



Here, we note that the actual z_{DET} to be used in Equation [4] is z_{DET}' , reduced from the original value due to finite interceptor velocity v_{INT} according to:

$$z_{DET}' = v_{INT} t_{INT} = \frac{z_{DET}}{1 + (v_a/v_{INT})} \quad [5]$$

Energy-Momentum Coupling

The final step is to estimate the energy required to be delivered to the NEO in order to produce this velocity change. Although a very wide range of interception and energy-coupling phenomena are involved, the plasma temperatures

will probably lie in the 1-100 eV range. Accordingly, we choose to follow laser-interaction work by relating interception energy to the NEO momentum produced using an energy-momentum coupling coefficient C_m . This relates the momentum produced by the surface-ablation-rocket effect to the delivered energy needed to cause the ablation:

$$C_m = \frac{mv}{W} \quad \text{dyne-sec/J.} \quad [6]$$

In fact,

$$C_m = \frac{\eta_{AB}}{(v_{AB}/2 \times 10^7)} = \frac{2.04 \times 10^4 \eta_{AB}}{I_{sp}} \quad [7]$$

where η_{AB} is the energetic efficiency of the ablation, v_{AB} is its velocity and I_{sp} is the specific impulse. In most situations, C_m will range from 0.5 to 5.

Roadmap

The density ρ and diameter D_a of the NEO give its mass, which, combined with the required velocity change and the correct coupling coefficient C_m gives the required interaction energy, the goal of this presentation. This calculation is contained in a third graph, which is combined with Figures 2 and 3 in a general roadmap for determining deflection energy, in the **Figure** following this page. The Figure treats a 100-m-diameter object moving toward Earth at 30 km/s. It is detected just beyond 1AU, but -- with an interceptor whose velocity is only 1/6 that of the NEO (5 km/s) -- Z_{DET} (the distance at interception) is just 0.2 AU. Because the object is so close, it must be given a transverse velocity increment of about 500 cm/s. The NEO density is 8 g/cm³ and the C_m we are counting on at its surface is 2 dyne-s/J, so the shift between the second and last graphs is a factor of 2. Intersection with the 100-m-diameter line gives a required energy of about 200 kT. However, note that the application of this energy in one pulse will likely rupture the object, since 15kT is sufficient to rupture a density-1 object this size. The nearly vertical shaded "rupture" line in the Figure is a plot of the relationship

$$W_{rupture} = 0.29 D_a^{3.33} \rho_a^{1.11} \quad J \quad [8]$$

which derives from blastwave theory^d. To halt the same object would require 1.5 GT.

Importance of Small Objects

Below the size-threshold for threatening life on Earth, it is important to note that the same blastwave theory together with a likely size-frequency plot demonstrate that the smaller objects produce more damage by blast. Several data sources^{e, f} seem to indicate $N(D_a) = 80 D_a^{-2.5}$ for the cumulative probability of a size $\geq D_a$ over the range from about 2 m to about 10 km. Since theory predicts destroyed area $A_{dest} = \alpha W_{blast}^{2/3} = \gamma D_a^2$,

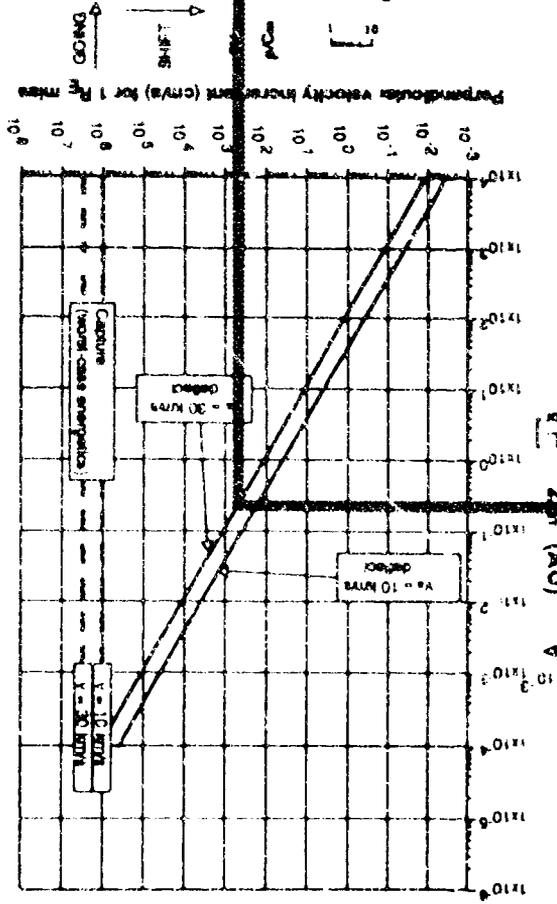
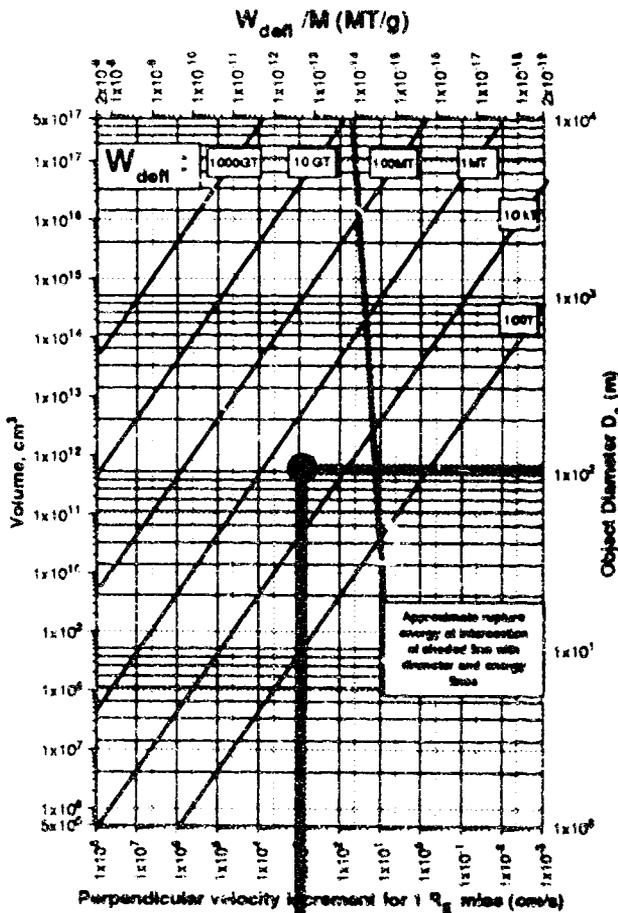
the differential probability for each size type is $f = \frac{dN}{dD_a} = 200 D_a^{-3.5}$ and one obtains

$$\int_0^{\infty} f A_{dest} d\xi = 400 D_a^{0.5} \quad [9]$$

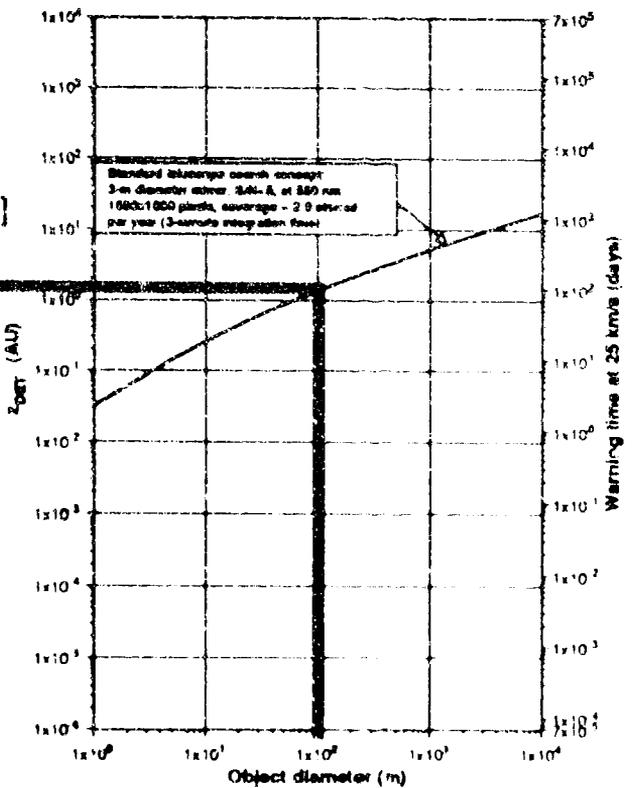
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ILLUSTRATING THE USE OF DEFLECTION CARPET CHARTS TO CALCULATE DEFLECTION ENERGY



Summary: detection distance in AU vs. NEO diameter in m



3. ENERGY DELIVERY/MATERIALS INTERACTION

Workshop Summary

The working group on energy delivery and materials interactions deliberated on the variety of options offered for deflection or pulverization of comets and asteroids on collision course with Earth. A consensus was reached on the best course of action. A summary of the associated observations and opinions is given below.

Similar to the approach taken by the working group on the astrodynamics of interception, described in Chapter 2, we segregated the problem of preventing a collision with a comet or asteroid into two characteristic domains: (1) actions to be taken if the collision can be predicted several orbital periods in advance and can be averted by imparting a small change in velocity, most effectively at perihelion, and (2) actions to be taken when the object is less than an astronomical unit (AU) away, collision is imminent, and deflection or disruption must be accomplished as the object closes on Earth. For this report, we call the first domain of actions, *remote interdiction* and the second domain of actions *terminal interception*.

3.1 Use of Nuclear Explosives

Nuclear explosives may be used in three modes depending on the location of the explosive at the time of detonation: (1) buried below the surface of the object either at an optimum depth for cratering or an optimum depth for pulverizing; (2) right at the surface, or more practically, slightly below the surface; and (3) above the surface at an optimum height for imparting a uniform impulse—generally called the "stand-off" mode. All three modes are applicable to both the remote-interdiction and terminal-interception domains.

3.1.1 Buried Nuclear Explosives. An optimally buried nuclear explosive will expel about an order of magnitude more mass from its crater than a nuclear explosive detonated at the surface, thus transferring proportionately larger momentum to the object.

In the terminal-interception case, the interceptor could use its kinetic energy to penetrate the object, requiring a heavy probe or billet to displace the matter in front of the nuclear explosive. The billet will erode as it passes into the object, and its required mass will be determined by the relative velocity at intercept, the desired depth and the composition of the object. It will increase the mass that the interceptor must deliver to the object by about an order of magnitude, and accordingly it is not obvious that total-system advantage is realized by using a buried explosive in lieu of a surface explosive. The buried explosive is believed best for pulverization in the case where the expected optimum crater would be near the size of the object (i.e., an attempt to totally disrupt the object). In that case, burial near the center of mass of a reasonably homogeneous object should produce the most uniform pulverization with closest to isotropic expansion (i.e., uniform in all directions).

In the remote-interdiction case, where years are available to design specialized payloads, a lightweight drill might allow the explosive to be emplaced at arbitrary depth, with less weight penalty. This requires a vehicle with an engine for maneuvering and landing on the object and an auger tip for boring beneath the surface with power supply attached. This option requires more study.

A severe difficulty with the subsurface explosion option is that to use it effectively and in a predictable manner requires some fairly detailed knowledge of the object's morphology. While this might be done relatively easily with precursor missions if time permits, it could be extremely difficult if performed only by a vanguard spacecraft for the terminal-interception case. To control the direction and magnitude of the imparted momentum, it will be necessary to know the object's rigid-body mechanical properties (mass, center of mass, angular

momentum, and rotational characteristics) as well as its composition and topography. Of these properties, the mass, center of mass, and molecular composition are very important, but a number of fundamental structural characteristics are even more important. Is it dirty ice, a snowball with a rocky core, iron-rock, chondrite, or nickel-iron? Is it one big chunk, two chunks bound by microgravity, many loosely bound small fragments, or a solid core with regolith?

In the terminal-interception case, knowledge of these properties is not only important to plan and predict the effect of the explosion, but also important to planning the path of the penetration vehicle. In the remote-interdiction case, a robotic auger, as described above, might also have the facility to carefully prepare the surface and characterize the material in which the explosive is embedded. This technique might direct the thrust vector most accurately toward the center of mass, minimizing the angular momentum imparted to the object (i.e., the intent is to displace the NEO, not to impart rotation to it).

In summary, the buried-explosive deflection mode offers no strong advantage in interceptor weight over the surface burst and demands the greatest knowledge of the NEO's properties. It is probably best for pulverization, a mode in which mechanical and geological information requirements are much reduced because it is well known from hundreds of underground nuclear tests that a large enough blast can disperse any solid object into very small fragments.

3.1.2 Surface-burst Nuclear Explosives. The surface-burst mode can be utilized with less knowledge about the interior of the object, but requires more knowledge about the surface contours and composition in the vicinity of the explosion. The subsurface composition is less critical both to estimates of the blow-off mass and to estimates of the imparted momentum. *The surface-burst mode eliminates the demand for geological information necessary to predict the performance of a penetration vehicle. The surface-burst mode, however, suffers from the same problems of unwanted fracture as the burial mode. If the crater is too large, the object may split into a few big chunks, each of which could do substantial damage. Such a hapless break would likely deny the opportunity for deflection by subsequent interceptors.*

3.1.3 Stand-off Nuclear Explosives. The fracture problem can be much mitigated by detonating the nuclear explosive some distance from the object. Rather than forming a crater, the neutrons, x-rays, gamma-rays, and some highly ionized debris from the nuclear explosion will blow-off a thin layer of the object's surface. This will spread the impulse over a much larger area and lessen the shear stress to which the object is subjected. Of these four energy transfer mechanisms, the most effective (at reasonable heights of burst) is neutron energy deposition, suggesting that "primarily fusion" explosives would be most effective because they produce maximum neutron yield. Neutrons are more effective than x-rays for transferring energy, owing to their depth of penetration.

For the same imparted momentum, there is far less deep mass expulsion when the energy is imparted in the stand-off mode. This mode is less sensitive to the details of topography and less demanding of compositional information. A precursor reconnaissance spacecraft may not be required because the effect on the NEO is believed to be highly predictable. The main drawback of the stand-off mode is that it requires one to two orders of magnitude more energy yield than the surface burst for the same imparted momentum, and high yield implies higher payload weight.

3.2 *Use of Interceptor Kinetic Energy*

For sufficiently small objects and sufficiently long warning times, it may be possible to produce the required orbital deflection by non-nuclear kinetic impacts on the NEO. (The threshold for this capability depends upon many parameters. For detailed explanations, the reader should refer to the technical discussion in the Proceedings of the NEO Interception Workshop, available from Los Alamos National Laboratory). If for some reason it is deemed undesirable to use a nuclear explosive, the kinetic-energy of the interceptor rocket could be used to provide deflection in the surface-burst mode described above or to attempt to produce pulverization of smaller objects. An object traveling at 25 km/s has about 75 times the kinetic energy of the same mass of high explosive, so that placing a mass in the way of the oncoming object would provide energy for its deflection or destruction. Obviously, the use of chemical explosives is ineffectual and unnecessary because the kinetic energy of impact is so much greater than the explosive yield per unit mass. If the interceptor were traveling toward the object also at 25 km/s, the energy released on collision would be 300 times the interceptor's mass in high explosive. *While this kinetic energy is substantial, the specific energy of a nuclear explosive is 10^6 to 10^7 times greater, making the nuclear option the only choice for large objects and late interceptions.*

3.2.1 *Kinetic-energy Deflection.* Knowledge requirements for both mechanical and geological properties of the NEO target are similar in kinetic energy encounters to those for a nuclear surface burst. For the propellant invested, terminal deflection is most effective because the interceptor velocity is usually diametrically opposed to the object velocity, but the intercept point must still be far enough away to cause the NEO to miss the Earth. For remote interdiction, the impulse is most effectively imparted at perihelion, as described in Chapter 2. If the object is detected long enough in advance, the interceptor might take advantage of planetary flybys to dramatically increase the energy at interception. Since the interceptor can be injected into a retrograde orbit, both interceptor and object will be traveling at their highest orbital speeds if they collide at perihelion.

In terminal defense, the fracture probability is quite high for smaller objects, even if they are only to be diverted to an unpopulated area of the Earth. Furthermore, for objects whose diameters are greater than about 100 m, required interceptor masses approach 1,000 tons. A practical object-size cutoff for terminal non-nuclear kinetic-energy deflection appears to be about 70 m.

3.2.2 *Kinetic-energy Pulverization.* Kinetic-energy pulverization may be possible for small objects (less than 100 meters diameter). An array of spears (darts) is an intriguing concept, and such apparatus might be deployed with a minimum investment of kinetic energy in the interceptor. The spears let the object impale itself. However, the intercept must take place far enough from the Earth to ensure separation of the debris. If the chunks of debris all follow the same trajectory, the conglomerate energy imparted to the Earth's atmosphere may produce damage on the Earth's surface.

The scheme is a bit complicated, and some knowledge of the mechanical and geological properties of the object may be necessary. It would be relatively ineffective against nickel-iron asteroids.

3.3 *Attached-thrust Deflection*

To attach a thruster to the threatening object involves a necessarily complicated process of rendezvous, matching velocities, landing, preparing footings in the microgravity environment, characterization of the various mechanical parameters of the object, and finally

deploying the propulsion apparatus. Practical considerations preclude its use in the terminal-interception domain

3.3.1 Mass Drivers. Steam rockets, conveyer belts, electron agnetic guns, etc. seem viable in principle, but involve much more sophisticated engineering and far greater expense than the impulsive approaches.

3.3.2 Solar Sails. Being passive, huge solar sails deployed so as to tow the asteroid enjoy some simplicity over the mass drivers, but are equally formidable engineering tasks. Despite the ecologically oriented appeal of the solar sail, we did not find it attractive because the impulsive approaches all seemed simpler and cheaper.

3.3.3 Crack Outgassing. Some asteroids are believed to contain volatiles in their cores. A novel deflection technique would be to drill to the core, generate some subsurface fractures (as is done for geothermal energy), and use the outgassing to propel the object to a new orbit. But this also involves exceedingly complicated engineering, and would be restricted to objects endowed with such a volatile core. It would require a great deal more knowledge than we presently possess.

3.4 Laser Deflection

Perhaps the most conspicuous advantage of laser deflection by induced surface blow-off is that it would be Earth- (or Moon-) based. It is therefore unnecessary to fly out to meet the object. A second advantage is that it is easy to "fire for effect" (i.e., fire and observe the velocity change). The beam could be applied for a while and the reaction could be measured from Earth. Thus, precise knowledge of the object's mechanical and geological properties is unnecessary. Although we admired this technique for its originality, we felt that it would be limited to remote interdiction on a prior orbit passing near Earth, and would be a gargantuan engineering project, even for deflecting modest-sized objects.

3.5 Consensus of the Energy Delivery/ Materials Interaction Group Members

General agreement was reached that the "primarily fusion" stand-off nuclear explosive was by far the most robust and defensible option for all aspects of the NEO defense problem. It is relatively insensitive to mechanical and geological properties and obviates the need for a precursor reconnaissance spacecraft necessary for surface and sub-surface bursts. It imposes less fracture probability. It can be applied in both remote interdiction or terminal intercept domains. For technical reasons, the most cost-effective "primarily fusion" device will be about 100 MT as detailed in the Proceedings (available from Los Alamos National Laboratory) If an object were encountered that was larger than could be adequately deflected by the device in stand-off mode, it could be switched to the surface-burst mode to impart a factor of ten to one hundred times more momentum, at somewhat exacerbated fracture probability. (The details of stress and fracture versus range and yield of the explosion should be a topic of extensive theoretical study and eventual experimentation. In the terminal intercept domain, the larger the object, the smaller the fracture probability.)

The Energy Delivery/Materials Interactions working group also concluded that, *if the defense of our planet is really taken seriously, and we consider terminal defense to be as important as remote interdiction, then it will be imperative to have ground-based interceptors available for use on relatively short notice. The most versatile and effective interception system might consist of several large ground-based rockets which could be quickly brought from storage and armed with the required explosive devices under the appropriate international controls. The number is somewhat arbitrary, but it should allow for a reasonable level of redundancy, should there be a malfunction. Furthermore, having a number of interceptors would allow*

operation in a "fire-for-effect" mode; i.e., careful measurement of the response of the first interceptor could provide a great deal of information on how to apply the second interceptor. It would allow repetitive deflection should such be necessary, and it would allow switching to surface-burst mode at any stage of the engagement.

This group felt, further, that if any other option is selected, it must be with a motive beyond the most straightforward defense of our planet. A key consideration is the very serious political implications of maintaining such a potentially devastating fleet of interceptors, even though it would still have miniscule threat potentials compared both with the thousands of war rockets and warheads now still maintained in the world's arsenals or with the devastation of a single large NEO impact. Clearly, there is a need for a well thought out policy with regard to these matters. It is particularly important to keep the above recommendations for (presently hypothetical) interceptors in perspective in comparison with the existing vastly larger nuclear defense forces. Contrary to uninformed criticisms that a small number of specialized interceptors would entail enormous cost and hazard of accident or misuse, such interceptors could be notably straightforward to create and safe to maintain because they derive from vast research and development expenditures and experience accumulated during the forty-five years of the Cold War.

Combining an interdiction mission with a scientific research program might be another agenda item. Conversion of the threatening object into space assets of some sort might also be considered, e.g. a benchmark accomplishment for human space flight, rosetta stone for solar system history, space station, remote outpost, supply source for valuable materials, etc. But if the serious objective is robust and cost-effective defense of the Earth, members of this working group generally agreed that the "primarily fusion" nuclear explosive is the option of choice.

To further assess the efficacy of such a defense system, we recommend a research program incorporating the following elements: (1) detailed numerical simulation of the response of representative NEO geometries to stand-off and surface-burst nuclear explosions; (2) optimization of the deflection astrodynamics problem combined with the detection and tracking problem; and (3) establishment of a data base in support of the numerical simulations, including mechanical properties, thermal properties, equation of state, opacity, and nuclear properties of the NEO material.

**Nuclear Explosive Propelled Interceptor
For Deflecting Comets and Asteroids
On A Potentially Catastrophic Collision Course With Earth**

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ABSTRACT

Nuclear explosive spacecraft propulsion offers the high specific impulse required for intercepting interplanetary intruders (comets or asteroids) rapidly closing on Earth. The exceedingly high relative velocities provide sufficient kinetic energy to deflect these malignant astral bodies without resorting to an explosive warhead, nuclear or otherwise.

I. Introduction

Since Alvarez¹ announced evidence for asteroid impact as the putative cause of the cretaceous-tertiary extinction, there has been a heightened awareness that our fair planet is and always has been in a state of merciless cosmic bombardment. Not all this cannonade has been deleterious, for example, the event Alvarez suggests may have cleared the way for the rise of homo sapiens. But being a selfish sub-species, we would rather hold on to our domination of the Earth, and deny a chance to any more well adapted creature for as long as we can. Less facetious is the possibility of a strike from an interplanetary body with radius on the order of 100 m. If an asteroid, such an object would likely have a relative velocity of about $25 \text{ km} \cdot \text{sec}^{-1}$, which would give it a kinetic energy of about 1000 megatons. In a populated area, the damage would be catastrophic. If it were a comet, the relative velocity would be more like $50 \text{ km} \cdot \text{sec}^{-1}$ and the energy would quadruple. The Tunguska Event² (1908) offers sobering evidence that such potentially catastrophic collisions are not so infrequent that they can be ignored. That impact was about 10 megatons and could be expected every few hundred years. Recent estimates³ indicate that a 20-kiloton (Hiroshima-size) event should occur every year. This would be conspicuous, apparently much of the energy is dissipated in penetrating the atmosphere. That such cataclysms are not generally recorded in the archives of natural disaster seems somewhat of a mystery. Perhaps it can be attributed to the fact that until the 20th century, very little of the Earth's surface was populated.⁴ Nevertheless, the risk of being killed as a result of asteroid impact is somewhat greater than the risk of being killed in an airplane crash.⁵

The problem naturally divides into two parts: (1) detection of these relatively small astral intruders; and (2) smashing or deflecting them should they be on an endangering course.

If all of the Earth-threatening asteroids were known, the orbits could be calculated and the process of deflection could be carried out in a leisurely manner. But 99% have not

yet been discovered.⁶ Furthermore, there are an enormous number of unknown comets for which a thorough search is completely impractical.

Asteroids in the 100-m size range are exceedingly difficult to detect unless they are very close. Comets are more conspicuous owing to their coma, but they will be moving a lot faster and can be in retrograde orbits or out of the plane of the ecliptic. In either case, it seems likely we will have little time to respond to a potential collision. It therefore appears that deflection at relatively close range is one of the most important issues.

In 1984, Hyde⁷ suggested using nuclear explosives to counter the intruders. In 1990, Wood, Hyde, and Ishikawa⁸ showed that defense against small intruders could be accomplished with non-nuclear interceptors, largely using the kinetic energy of the intruder itself. In this paper, I show that large intruders could be deflected using an extremely high-specific-impulse interceptor. The effectiveness of using nuclear-explosive propelled interceptors derives mainly from the fact that the deflection could be accomplished further from the Earth.

II. Interceptor Flight and Intruder Deflection

The final velocity of an interceptor missile relative to the Earth, or the orbit in which it is stationed, is given by the rocket equation,

$$V = gI_{sp} \ln \frac{M_i}{M_f}, \quad (1)$$

where M_i and M_f are the initial and final mass of the interceptor and I_{sp} is the specific impulse of the rocket fuel. In general, the time required to reach this relative velocity will be short compared to the total flight time, so the range at which the intruder is intercepted will be given by

$$\mathfrak{R}_i = \mathfrak{R}_l \left(1 - \frac{v}{v + V} \right), \quad (2)$$

where \mathfrak{R}_l is the range when the interceptor is launched and v is the speed at which the intruder is closing on the Earth. If the impact gives the intruder a transverse velocity component v_{\perp} then the threatening intruder will miss its target point by a distance

$$\epsilon = \mathfrak{R}_l \frac{v_{\perp}}{v} \left(\frac{V}{v + V} \right), \quad (3)$$

where I have neglected the effect of the Earth's gravitational field. To obtain the transverse velocity component, we would use the kinetic energy of the interceptor to blast a crater on the side of the intruder. The momentum of the ejecta would be balanced by the transverse momentum imparted to the intruder. From Glasstone's empirical fits⁹, the mass of material in the crater produced by a large explosion is

$$M_e = \alpha^2 E^{\beta}, \quad (4)$$

where $\beta \simeq 0.9$ and $\alpha \simeq 8.4 \times 10^{-4} \text{ gm}^{\frac{1}{2}(1-\beta)} \cdot \text{cm}^{-\beta} \cdot \text{sec}^{\beta}$ for an explosive buried at the optimal depth for maximum ejection of dirt. For a surface burst, Glasstone uses the same value of β but takes $\alpha \simeq 1.6 \times 10^{-4} \text{ gm}^{\frac{1}{2}(1-\beta)} \cdot \text{cm}^{-\beta} \cdot \text{sec}^{\beta}$. This depends on gravity, density, EOS and other parameters. Seebaugh¹⁰ suggests the same value of β , but $\alpha \simeq 5.2 \times 10^{-5} \text{ gm}^{\frac{1}{2}(1-\beta)} \cdot \text{cm}^{-\beta} \cdot \text{sec}^{\beta}$ for a surface burst, about half that used by Glasstone. Kreyenhagen and Schuster¹¹ have noted that impacts in the $20 \text{ km} \cdot \text{sec}^{-1}$ range couple 50-80% of their energy to the ground, while surface bursts couple only 1-10%. The correct value of α is somewhere between a surface burst and an optimally buried explosion. For the purpose of the estimates in this paper, I will take $\alpha \simeq 2 \times 10^{-4} \text{ gm}^{\frac{1}{2}(1-\beta)} \cdot \text{cm}^{-\beta} \cdot \text{sec}^{\beta}$, but the reader is invited to choose any value in the range, the essential conclusions will not be significantly altered.

The kinetic energy available when the interceptor collides with the intruder is

$$\frac{1}{2} M_i (V + v)^2. \quad (5)$$

About half this energy goes into the dirt ejected from the crater. So the transverse velocity imparted to the intruder is

$$v_{\perp} = \frac{1}{M_i} \sqrt{\frac{M_i M_f (V + v)^2}{2}} = \frac{\alpha}{M_i} \left(\frac{M_f (V + v)^2}{2} \right)^{\frac{\beta+1}{2}}, \quad (6)$$

where M_i is the mass of the comet or asteroid. We can combine Eqs. (3) and (6) to obtain

$$\epsilon = \alpha M_f \frac{V(V + v)^{\beta}}{M_i v} \left(\frac{M_f}{2} \right)^{\frac{\beta+1}{2}}. \quad (7)$$

Equation (7) reveals the importance of the intercept velocity V , which is proportional to specific impulse I_{sp} . If $V \ll v$, the deflection is proportional to V , and if $V \gg v$, the deflection is proportional to $V^{\beta+1} \sim V^2$.

III. Optimum Mass Ratio

Substituting Eq. (1) into Eq. (7), setting $d\epsilon/dM_f = 0$, and solving, we find the mass ratio that produces the largest value of ϵ ,

$$\frac{M_i}{M_f} = e^Q, \quad (8)$$

where

$$Q = 1 - \frac{v}{2gI_{sp}} + \sqrt{1 + \frac{1-\beta}{1+\beta} \frac{v}{gI_{sp}} + \left(\frac{v}{2gI_{sp}} \right)^2}. \quad (9)$$

In the limit of very high specific impulse, the optimum mass ratio is

$$\frac{M_i}{M_f} = e^2. \quad (10)$$

The maximum displacement of the impact location on Earth is then given by

$$\epsilon = \frac{\alpha v^\beta \mathcal{R}_I}{M_a} \left(\frac{M_i e^{-Q}}{2} \right)^{\frac{\beta+1}{2}} \frac{g I_{sp} Q}{v} \left(1 + \frac{g I_{sp} Q}{v} \right)^{\beta} \quad (11)$$

Figure 1 plots the dimensionless parameter $\epsilon M_a / \alpha v^\beta \mathcal{R}_I M_i^{\frac{1}{2}(\beta+1)}$ versus the dimensionless parameter $g I_{sp} / v$ for $\beta = 0.8, 0.9,$ and 1.0 . It shows the increasing advantage to higher specific impulse derived from Eq. (11).

Which size asteroid is most threatening remains a controversial question. By dint of their frequency of occurrence and the damage they could do, I believe the most threatening asteroid is about 100 m in radius, and I will use it for my example. With a specific gravity of three, such an asteroid weighs 1.25×10^{13} g, and at a relative velocity $v = 2.5 \times 10^6$, its impact energy would be about 1000 megatons. To divert the asteroid to a nearby ocean would generally require a deflection of no more than a Mm. While it would churn up quite a wave, the damage would be trivial compared to impact in a populated area. The nearest range at which we might commit to launch the interceptor would be about $\frac{1}{100}$ A.U. = 1.5 Gm.

Equation (11) can be rearranged to give the required initial mass of the interceptor,

$$M_i = 2e^Q \left[\frac{M_a v \epsilon}{\alpha \mathcal{R}_I g I_{sp} Q} \left(\frac{1}{v + g I_{sp} Q} \right)^{\beta} \right]^{\frac{2}{\beta+1}} \quad (12)$$

The best chemical fuels might have a specific impulse as high as 500 sec. Thus if we choose a chemically propelled interceptor in the scenario described above, the initial mass of the rocket would have to be

$$M_i = 4.74 \times 10^9 \text{ g.}$$

An adequate interceptor would have to weigh nearly 5,000 tons. Clearly this is not a very viable option.

IV. Nuclear Explosive Propulsion

Nuclear explosive propulsion was first considered in the late 50s and early 60s under the ORION¹² program at Los Alamos¹³ and General Atomics Corporation¹⁴. To get a feel for the tremendous potential of nuclear-explosive propulsion we need an estimate of the specific impulse, obtained by calculating the pressure impulse imparted by a bomb exploded in a vacuum. Pursuant to this estimate, we must find the density and velocity distribution of the sudden expansion of a sphere of gas. There is no exact analytic solution to this problem, but an approximate solution can be constructed on the basis of an analogous plane problem¹⁵. At high temperatures we can let the adiabatic exponent $\gamma = 5/3$ and the debris density is given by

$$\rho = \frac{15m_b}{8\pi R^3} \left(1 - \frac{r^2}{R^2} \right), \quad (13)$$

where

$$R = t \sqrt{\frac{10E}{m_b}}, \quad (14)$$

and E and m_b are the energy and mass of the bomb respectively. In the limit $R \rightarrow \infty$, the velocities of the fluid particles approach constant values and $u \simeq r/t$.

Say the interceptor pusher plate is at a distance r from the bomb. The debris stagnates against the pusher plate, which in the frame of the debris, acts like a piston moving at velocity u . The piston produces a shock in the colliding debris. The pressure behind this shock¹⁶ is

$$\rho u^2 \left(\frac{\gamma + 1}{2} \right), \quad (15)$$

and because it is a shock, the density will increase a factor of $(\gamma + 1)/(\gamma - 1)$, and the impulsive pressure is

$$P = \frac{4}{3} \rho u^2. \quad (16)$$

An additional thrust will be imparted by the re-expansion of the debris. The largest possible impulsive pressure including all effects would be $P = 2\rho u^2$, but because the debris will radiatively cool during stagnation, we will ignore the impulse from re-expansion.

Then the approximate pressure applied to the plate is

$$P = \frac{1}{8\pi} \sqrt{\frac{2m_b^5}{5E^3}} \frac{r^2}{t^3} \left(1 - \frac{m_b r^2}{10Et^2} \right). \quad (17)$$

Of course, the thrust is zero until the first debris arrives at the canopy, which occurs at a time $t_0 = r\sqrt{m_b/10E}$. The velocity imparted by a single explosion is

$$\begin{aligned} \Delta V &= \frac{A_p}{m} \int_{t_0}^{\infty} P \, dt \\ &= \frac{25A_p}{24\pi r^2} \sqrt{\frac{2m_b E}{5}}, \end{aligned} \quad (18)$$

where m is the mass at the time of the explosion and A_p is its projected area of the pusher plate.

If we use n bombs, the final velocity of the interceptor is

$$V = \frac{25 A_p}{24 \pi r^2} \sqrt{\frac{2m_b E}{5}} \sum_{j=0}^n \left(\frac{1}{M_i - j m_b} \right), \quad (19)$$

where M_i is the initial mass of the interceptor. In the limit of a very large number of bombs ($n \rightarrow \infty$), we can approximate

$$V \simeq \frac{25 A_p}{24 \pi r^2} \sqrt{\frac{2E}{3m_b}} \ln \frac{M_i}{M_f}, \quad (20)$$

where $gM_f = g(M_i - nm_b)$ is the "dry weight" of the interceptor. By analogy with Eq. (1), we have

$$I_{sp} = \frac{25}{24g} \frac{A_p}{\pi r^2} \sqrt{\frac{2E}{5m_b}} \quad (21)$$

The specific impulse goes as the square root of the yield-to-weight ratio. If the pusher plate subtends a solid angle of 2π , a bomb weighing 25 kg with a yield of 2.5 kilotons $\approx 10^{20}$ ergs would produce a specific impulse $I_{sp} \approx 4.25 \times 10^4$ sec, assuming most of the energy goes into debris motion. The best chemical fuels have specific impulses of ~ 500 sec, nuclear furnaces such as Rover-NERVA could approach ~ 1000 sec, and gas-core reactors, perhaps ~ 2000 sec.

V. Performance of the Nuclear-Explosive Propelled Interceptor

If we assume the specific impulse given above, then from Eq. (12) for a typical asteroid,

$$M_i = 2.46 \times 10^6 \text{ g.}$$

The interceptor need weigh a mere $2\frac{1}{2}$ tons.

From Eqs. (8) and (9) we obtain $M_i/M_f = 7.19$, so the interceptor consists of about 2150 kg of nuclear explosives and about 350 kg of inert components: pusher plate, shock absorbers, missile body, guidance, etc. The 86 nuclear explosives would have a total yield of 215 kilotons. From Eq. (1), the interceptor velocity at impact is

$$V = gI_{sp} \ln \frac{M_i}{M_f} = 821 \text{ km} \cdot \text{sec}^{-1}.$$

The energy of impact is

$$\frac{M_f(V+v)^2}{2} = 1.23 \times 10^{21} \text{ erg} = 29 \text{ kilotons}, \quad (22)$$

which would probably be enough to shatter the intruder as well as deflect it. From Eq. (3), the range at intercept is

$$\mathfrak{R}_i = \mathfrak{R}_l \left(\frac{V}{v+V} \right) = 1.46 \text{ Gin.} \quad (23)$$

The time from launch to intercept is about a half hour. Thus there would be ample time to launch a second interceptor, should the first malfunction. From Eq. (4), the mass of the ejecta is about 3.82×10^{11} g or about 3% of the asteroid's mass. The interceptors would most likely be stationed at an Earth-Moon Lagrange point so the fission-products from the nuclear-explosive propellant would be dispersed well outside of Earth's magnetosphere.

Table I compares the chemical- and nuclear-propelled interceptors if launched when the asteroid is $\frac{1}{100}$ A.U. from Earth. If detected at that range, about 17 hours would remain

before the intruder collides with our dear planet. The chemical-propelled interceptor would have only one chance.

VI. Tentative Conclusions

It is fair and appropriate to haggle over the numbers I have used for the sake of example. But the dramatic advantages of nuclear explosive propulsion are clear. A lingering question: Why I have avoided giving the interceptor a nuclear warhead? I submit that an interceptor with an inert warhead would be perceived by world politics as far less threatening, even though it is propelled by nuclear explosives. And it is sufficient to do the job.

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Table I

Comparison of chemical- and nuclear-propelled interceptors. Assumed 100-m radius asteroid with density $3 \text{ g} \cdot \text{cm}^{-3}$, mass $M_a = 12.6 \text{ MT}$, velocity $v = 25 \text{ km} \cdot \text{sec}^{-1}$. Crater parameters: $\beta = 0.9$ and $\alpha = 2 \times 10^{-4} \text{ gm}^{\frac{1}{2}(1-\beta)} \cdot \text{cm}^{-\beta} \cdot \text{sec}^{\beta}$. Interceptors launched when the asteroid is $\frac{1}{100}$ A.U. from Earth.

	Chemical	Nuclear
Specific Impulse (I_{sp})	500 sec	42,500 sec
Mass Ratio (M_i/M_f)	3.44	7.19
Initial Mass (M_f)	4,740 tons	2.56 tons
Final Mass (M_i)	1,375 tons	342 kg
Rocket Velocity (V)	6.06 $\text{km} \cdot \text{sec}^{-1}$	821 $\text{km} \cdot \text{sec}^{-1}$
Intercept Range (R_i)	29.3 Mm	1.46 Gm
Intercept Time	13.4 hours	30 min
Collision Energy	$6.63 \times 10^{21} \text{ erg}^\dagger$	$1.23 \times 10^{20} \text{ erg}$
	158 kT H.E.	29 kT H.E.
Ejecta Mass (M_e)	1.74 MT	382 kT
Fraction Ejected (M_e/M_a)	13.8%	3.03%

[†] Collision will probably cause asteroid to break up.

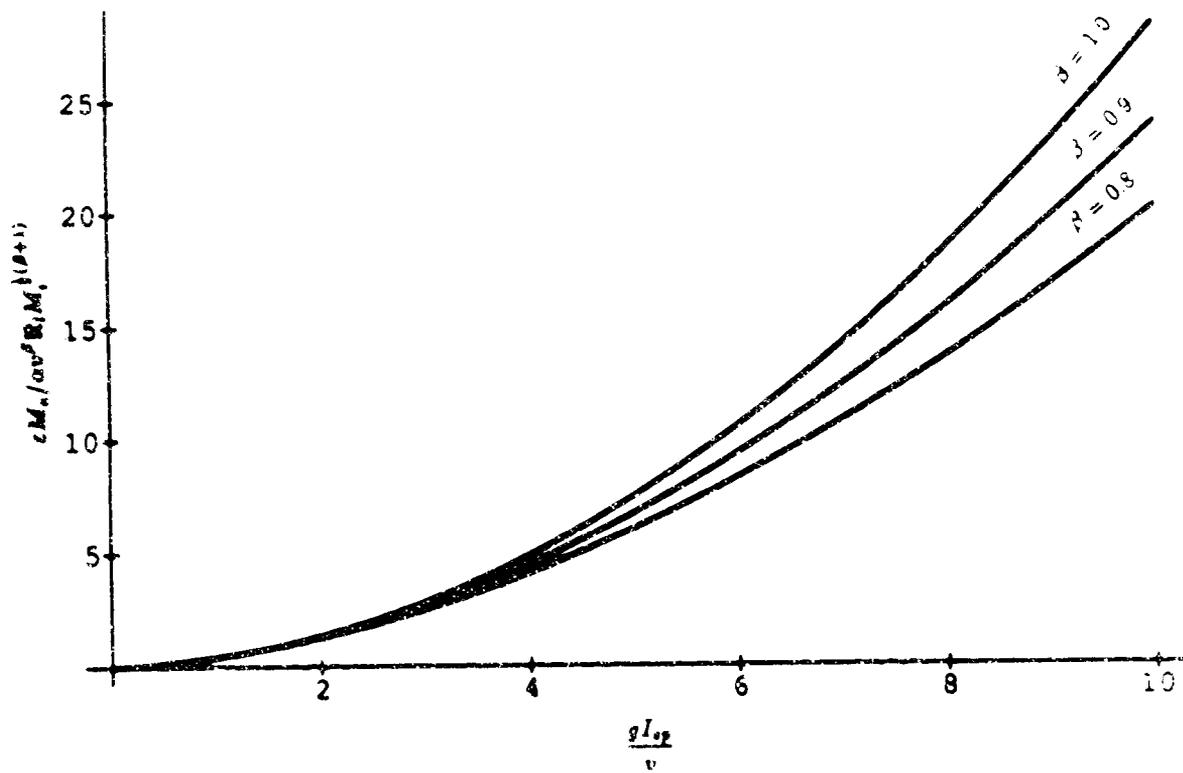


Figure 1

Interception of Comets and Asteroids on Collision Course with Earth

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ABSTRACT

I derive a series of expressions to delineate the utility, performance, and range of applicability of rocket interceptors designed to deflect or pulverize comets or asteroids on collision course with Earth. The two quantities of greatest interest are: (1) the *mass in orbit* or initial mass of the interceptor, which will usually dominate the cost of the system; and (2) the *blow-off fraction*, the fraction of the assailant object's mass expelled to impart transverse momentum, which also provides a measure of the probability that the object will fracture. The interaction is calculated for both kinetic-energy deflection and nuclear-explosive deflection and uses a fairly general relationship between the energy deposited and the blow-off mass. In the nuclear-explosive case, I calculate the interceptor mass and cratering effect for detonations above the surface and below the surface as well as directly on the surface of the assailant. Because different assailants could possess a wide range of densities and material properties, the principal value of this work is to show the relationships among the salient parameters. However, using typical values for the various physical properties, I make the following observations. (1) Kinetic-energy deflection is effective for ocean diversion of assailants smaller than about 70 m, if the interceptor is launched when the range to the assailant is more than $\frac{1}{30}$ AU. At shorter range, interceptors become impractically massive. Probability of fracture also increases rapidly with diminished range. An interceptor with an order-of-magnitude larger mass is required to cause the assailant to miss the planet rather than *splash-down* in an ocean. The more massive interceptor introduces a larger probability of fracturing the assailant. Higher specific impulse interceptors are more effective at increasing deflection and reducing fracture probability, mainly because they divert the assailant at a greater distance. Objects less than 10 m are better pulverized by interception at short range with special mass arrays. (2) Nuclear-explosive deflection is imperative for assailants greater than about 100 m detected closer than $\frac{1}{30}$ AU because of interceptor size. Nuclear-surface-burst deflection offers a three-to-four order of magnitude reduction in interceptor mass over kinetic-energy deflection. The advantage of nuclear-explosive deflection decreases slightly with specific impulse and decreases dramatically with assailant velocity. Fragmentation is a problem for nuclear explosive intercepts launched closer than about $\frac{1}{3}$ AU. (3) Nuclear penetrators offer no advantage for deflection, but are better for pulverization. (4) Nuclear stand-off deflection greatly reduces fragmentation probability, but with a substantial increase in interceptor mass.

1. Introduction

The problem of preventing a collision with a comet or asteroid can be considered two domains: (1) actions to be taken if the collision can be predicted several orbital periods in advance, and can be averted by imparting a small change in velocity (most effectively at perihelion) and (2) actions to be taken when the object is less than an astronomical

unit (AU) away, collision is imminent, and deflection or disruption must be accomplished as the object closes on Earth. I call the first domain of actions, "remote interdiction" and the second domain of actions "terminal interception."

If all of the Earth-threatening asteroids were known, the orbits could be calculated and the process of deflection could be carried out in a leisurely manner. Remote interdiction would be the option of choice. But 99% have not yet been discovered.¹ Furthermore, there are an enormous number of unknown long-orbit comets for which a thorough search is completely impractical.

Asteroids in the 100-m size range are exceedingly difficult to detect unless they are very close. Comets in this size range are more conspicuous owing to their coma, but they will be moving a lot faster and can be in retrograde orbits or out of the plane of the ecliptic. In either case, it seems likely we will have little time to respond to a potential collision. It therefore appears that terminal interception, disruption or deflection at relatively close range, is likely the most important issue.

In 1984, Hyde² suggested using nuclear explosives to counter the comets or asteroids, which I collectively call "astral assailants" at the risk of creating a pathetic fallacy. In 1990, Wood, Hyde, and Ishikawa³ showed that defense against small assailants could be accomplished with non-nuclear interceptors, largely using the kinetic energy of the assailant itself. In this paper, I consider the dynamics of the terminal intercept problem. I explore the possibility of using kinetic-energy deflection as well as nuclear explosives. Nuclear explosives can be employed in three different modes depending on their location at detonation: (1) buried below the assailant's surface by penetrating vehicle; (2) detonated at the assailant's surface; or (3) detonated some distance above the surface

Figure 1 shows the interception scenario. The asteroid or comet is headed toward Earth at a velocity v . The interceptor traveling at velocity V is about to engage the assailant object. The assailant has a mass M_a , and the interceptor, because it has long since exhausted its fuel, it has its final mass M_f . We cannot hope to deflect the assailant like a billiard ball because $M_a \gg M_f$. So the interceptor must supply energy to *blow-off* a portion of the assailant's surface, that blow-off material being very massive compared to the interceptor, $M_a \gg M_e \gg M_f$. One might think that a conventional high explosive would suffice, but the energy it would supply would be relatively insignificant. Standard high explosive releases 10^3 calories = 4.184×10^{10} ergs per gram. An asteroid moving at $25 \text{ km} \cdot \text{sec}^{-1}$ has a specific energy of 3.125×10^{12} ergs per gram -- about 75 times the specific energy of high explosive. If the interceptor is moving at the same speed in the opposite direction ($V = v = 25 \text{ km} \cdot \text{sec}^{-1}$), the interceptor would impact with a specific energy 300 times that of high explosive. There is a whole lot of kinetic energy available; a chemical energy release would be in the noise. However, even this tremendous kinetic energy would be completely swamped by a nuclear explosive. The yield-to-weight ratio of nuclear explosives is generally measured in kilotons per kilogram, that is, tons per gram. A typical specific energy is a million times that of chemical high explosive, or about four orders of magnitude higher than the kinetic energy of the interceptor collision.

2. Kinetic-Energy Deflection

The final velocity of an interceptor missile relative to the Earth, or the orbit in which it is stationed, is given by the rocket equation,

$$V = g I_{sp} \ln \frac{M_i}{M_f}, \quad (1)$$

where M_i and M_f are the initial and final mass of the interceptor and I_{sp} is the specific impulse of the rocket fuel. In general, the time required to reach this relative velocity will be short compared to the total flight time. The time elapsed from launch to intercept is

$$\Delta t = \frac{\mathfrak{R}_i}{v + V}, \quad (2)$$

where \mathfrak{R}_i is the range when the interceptor is launched and v is the speed at which the assailant is closing on the Earth. So the range at which the assailant is intercepted will be given by

$$\mathfrak{R}_i = \mathfrak{R}_i \left(1 - \frac{v}{v + V} \right), \quad (3)$$

If the impact gives the assailant a transverse velocity component v_{\perp} then the threatening assailant will miss its target point by a distance

$$e = \mathfrak{R}_i \frac{v_{\perp}}{v} \left(\frac{V}{v + V} \right), \quad (4)$$

where I have neglected the effect of the Earth's gravitational focussing and used a linear approximation to Keplerian motion. To obtain the transverse velocity component, we would use the kinetic energy of the interceptor to blast a crater on the side of the assailant. The momentum of the ejecta would be balanced by the transverse momentum imparted to the assailant. From Glasstone's empirical fits⁴, the mass of material in the crater produced by a large explosion is

$$M_e = \alpha^2 E^{\beta}, \quad (5)$$

where α and β depend on the location of the explosion, the soil composition and a myriad of other parameters. Clearly the crater constant α and the crater exponent β will vary depending on whether we are considering an assailant composed of nickel-iron, stony-nickel-iron, stone, chondrite, or dirty snow. For almost every situation, however, we find $\beta \simeq 0.9$.

The kinetic energy available when the interceptor collides with the astral assailant is

$$E = \frac{1}{2} M_f (V + v)^2. \quad (6)$$

Only a fraction of the interceptor's kinetic energy is converted to kinetic energy of the ejected or "blow-off" material. Let this fraction be equal to $\frac{1}{2} \delta^2$, or

$$\delta = \sqrt{2 \frac{\text{ejecta kinetic energy}}{\text{interceptor kinetic energy}}}. \quad (7)$$

The reason for this strange definition is that it greatly simplifies the algebra. I will call the parameter δ the *energy fraction*. Then the transverse velocity imparted to the assailant is

$$v_{\perp} = \delta \frac{\sqrt{M_e E}}{M_a} = \frac{\delta}{M_a} \sqrt{\frac{M_e M_f (V+v)^2}{2}} = \frac{\alpha \delta}{M_a} \left(\frac{M_f (V+v)^2}{2} \right)^{\frac{\beta+1}{2}}, \quad (8)$$

where M_a is the mass of the comet or asteroid. We can combine Eqs. (4), (5), and (8) to obtain

$$\epsilon = \alpha \delta \mathfrak{R}_I \frac{V(V+v)^{\beta}}{M_a v} \left(\frac{M_f}{2} \right)^{\frac{\beta+1}{2}}. \quad (9)$$

Equation (9) reveals the importance of the intercept velocity V , which is proportional to specific impulse I_{sp} . If $V \ll v$, the deflection is proportional to V , and if $V \gg v$, the deflection is proportional to $V^{\beta+1} \sim V^2$.

2.1. Optimum Mass Ratio for Kinetic Energy Deflection

The energy on impact is proportional to the final mass of the interceptor and the square of its relative velocity as given in Eq. (6). The smaller its final mass, the higher its relative velocity, so there is some optimum mass ratio that produces the greatest deflection for a given initial mass. This would be the optimal interceptor design, the most bang for the buck.

Substituting Eq. (1) into Eq. (9), setting

$$\frac{d\epsilon}{d(M_i/M_f)} = 0, \quad (10)$$

and solving, we find the mass ratio that produces the largest value of ϵ ,

$$\frac{M_i}{M_f} = e^Q, \quad (11)$$

where

$$Q = 1 - \frac{v}{2gI_{sp}} + \sqrt{1 + \frac{1-\beta}{1+\beta} \frac{v}{gI_{sp}} + \left(\frac{v}{2gI_{sp}} \right)^2}. \quad (12)$$

We note that this optimal mass ratio depends only on the velocity of the assailant relative to earth v and the interceptor's specific impulse I_{sp} . The value of β is a constant of the assailant's soil composition and is very close to 0.9, and $g \simeq 980 \text{ cm sec}^{-2}$ is a constant of Planet Earth. In the limit of very high specific impulse, the optimum mass ratio is

$$\frac{M_i}{M_f} = e^2. \quad (13)$$

The maximum displacement of the impact location on Earth is then given by

$$\epsilon = \frac{\alpha \delta v^{\beta} \mathfrak{R}_I}{M_a} \left(\frac{M_i e^{-Q}}{2} \right)^{\frac{\beta+1}{2}} \frac{g I_{sp} Q}{v} \left(1 + \frac{g I_{sp} Q}{v} \right)^{\beta}. \quad (14)$$

Figure 2. plots the dimensionless parameter $\varepsilon M_a / \alpha \delta v^\beta \mathfrak{R}_i M_i^{\frac{1}{2}(\beta+1)}$ versus the dimensionless parameter gI_{sp}/v for $\beta = 0.8, 0.9,$ and 1.0 . It shows the increasing advantage to higher specific impulse derived from Eq. (14).

A great deal of physical insight can be obtained just by studying the axis labels of the dimensionless plot. From the ordinate, we see that for the same value of gI_{sp}/v , which is more or less fixed by interceptor design, the asteroid deflection ε is

- Proportional to the range of the assailant at launch (\mathfrak{R}_i).
- Inversely proportional to the mass of the assailant (M_a).
- Nearly proportional to the velocity of the assailant relative to Earth ($v^\beta \simeq v^{0.9}$).
- Nearly proportional to the initial mass of the interceptor ($M_i^{\frac{1}{2}(\beta+1)} \simeq M_i^{0.95}$).
- Proportional to the crater constant (α).
- Proportional to the square root of the fraction of interceptor kinetic energy converted to blow-off kinetic energy ($\frac{1}{2}\delta^2$).

Equation (14) can be rearranged to give the required initial mass or mass in orbit of the interceptor,

$$M_i = 2e^Q \left[\frac{M_a v \varepsilon}{\alpha \delta \mathfrak{R}_i g I_{sp} Q} \left(\frac{1}{v + g I_{sp} Q} \right)^\beta \right]^{\frac{2}{\beta+1}} \quad (15)$$

The mass given by Eq. (15) will generally be the largest single factor in the cost of a defensive system of this sort. To appreciate the magnitude of the problem, it is now necessary to put in a few numbers. The best chemical fuels might have a specific impulse as high as 500 sec, which I will use to make the point. The density of potential astral assailants varies greatly, from less than $1 \text{ gm} \cdot \text{cm}^{-3}$ for a snow-ball comet to a little over $1 \text{ gm} \cdot \text{cm}^{-3}$ for a dirty-ice comet to about $3 \text{ gm} \cdot \text{cm}^{-3}$ for a chondrite to about $8 \text{ gm} \cdot \text{cm}^{-3}$ for a nickel-iron asteroid. An agreeable average is $3.4 \text{ gm} \cdot \text{cm}^{-3}$. The velocity of the assailant relative to Earth could range from $5 \text{ km} \cdot \text{sec}^{-1}$ for an asteroid in nearly coincident orbit with Earth to $70 \text{ km} \cdot \text{sec}^{-1}$ for a long-period comet in retrograde orbit near the plane of the ecliptic. I will take $25 \text{ km} \cdot \text{sec}^{-1}$ for this example.

Because the material properties of asteroids and comets vary so widely, an estimate of the crater constant and crater exponent is somewhat arbitrary. Here I will make an estimate for impact cratering of medium hard rock. Glasstone uses $\beta \simeq 0.9$ and $\alpha \simeq 8.4 \times 10^{-4} \text{ gm}^{\frac{1}{2}(1-\beta)} \cdot \text{cm}^{-\beta} \cdot \text{sec}^\beta$ for an explosive buried at the optimal depth for maximum ejection of dry soil. For a surface burst, Glasstone takes $\alpha \simeq 1.6 \times 10^{-4} \text{ gm}^{\frac{1}{2}(1-\beta)} \cdot \text{cm}^{-\beta} \cdot \text{sec}^\beta$. The correct value of α for the impact crater is somewhere between a surface burst and an optimally buried explosion. For the purpose of the estimating the crater size for kinetic energy deflection, I will take $\alpha \simeq 2 \times 10^{-4} \text{ gm}^{\frac{1}{2}(1-\beta)} \cdot \text{cm}^{-\beta} \cdot \text{sec}^\beta$. Kreyenhagen and Schuster⁵ have noted that impacts in the $20 \text{ km} \cdot \text{sec}^{-1}$ range couple 50-80% of their energy to the ground, while surface bursts couple only 1-10%. I will assume about 60% coupling and about half that goes to the blow-off. Thus about 30% of the interceptor's kinetic energy is converted to kinetic energy of the blow-off, corresponding to $\delta \simeq 0.775$.

Figure 3 shows the initial mass of the interceptor required to deflect the astral assailant by 1 Mm, as a function of the assailant's diameter and its range when the assailant is launched. The one-megameter deflection is typical of the course change required to divert an assailant from impact in a populated area to a nearby ocean. To interpret Fig. 2 for a ten-megameter deflection, which would be conservative for missing the planet entirely ($R_{\odot} = 6.378$ Mm), we need to multiply the masses by about a factor of ten*. Figure 3 makes a clear statement about the applicability of kinetic-energy deflection. Kinetic-energy deflection is practical only for assailants considerably less than 100 m in diameter. To handle a 100-m assailant would require a 1000 ton interceptor even if launched when the assailant was still $\frac{1}{10}$ AU away. The mass would go to 10,000 tons if the assailant were deflected to miss the planet entirely rather than diverted to an ocean. Thus dealing with 100-m assailants requires another technology. For practical purposes, the kinetic-energy interceptor is limited to the 3- to 30-m assailant, which would require an interceptor mass of 1 to 100 tons.

3.2. Kinetic-Energy Fragmentation and Pulverization

Equation (15) gives the initial mass of an optimally designed interceptor for deflecting an astral assailant by blowing-off its surface. It was derived under the assumption that the amount of mass blown off is small compared to the assailant's mass. If the ejected mass is too large, the crater will have dimensions a significant fraction of the assailant's dimension, and it is more likely that the assailant will break up. If the fragments are too large and are scattered at random, they may still be able to penetrate the Earth's atmosphere and do damage. A two-meter fragment of a nickel-iron asteroid has about the same average ρr as the atmosphere measured vertically from sea level, and thus will penetrate the atmosphere losing only about half its energy. A ten-meter chondrite, however, will probably break-up owing to the dynamic stress of traversing the atmosphere. Shock from the energy of its explosion may still do damage. In order to ensure that no damage is done, it will be necessary to pulverize the assailant, that is, break it into very small pieces that are sure to dissipate all of their energy in the atmosphere.

To get a handle on the problem of whether the assailant will be deflected, fragmented, or pulverized, we need an estimate of what fraction of the assailant will be blown off in the collision. By combining Eqs (1), (5), (11), and (15), we find that the fraction of the assailant blown-off is given by

$$\begin{aligned}
 f &= \frac{M_a}{M_i} = \frac{\alpha^2}{M_a} \left(\frac{M_i}{2cQ} \right)^{\beta} (gI_{sp}Q + v)^{2\beta} \\
 &= M_a^{\frac{\beta-1}{\beta+1}} \left\{ \alpha \left[\frac{\epsilon v}{\mathfrak{R}_i \delta} \left(1 + \frac{v}{gI_{sp}Q} \right) \right]^{\beta} \right\}^{\frac{\beta+1}{\beta}}
 \end{aligned} \tag{16}$$

where Q is again given by Eq.(12). Some qualitative features of the blow-off fraction are immediately apparent.

* From Eq.(15), $M_i \propto \epsilon^{\frac{\beta+1}{\beta}}$, so a factor of 10 in ϵ corresponds to a factor of 11.3 in M_i .

- blow-off fraction is nearly independent of assailant mass ($M_a^{\frac{L+1}{L+1}} \approx M_a^{-0.0526}$).
- blow-off fraction is nearly proportional to the crater constant ($\alpha^{\frac{1}{L+1}} \approx \alpha^{1.03}$).
- blow-off fraction is nearly inversely proportional to the energy coupling ($\delta^{\frac{2L}{L+1}} \approx \delta^{0.947}$).
- blow-off fraction is decreases asymptotically with specific impulse.

Using the parameters above, Fig. 4 shows the blow-off fraction for ocean diversion as a function of assailant diameter for three different ranges to the assailant at interceptor launch. If more than 10% is blown-off, the assailant will probably break-up. What we learn from Fig. 4 is that if we cannot launch the interceptor at about $\frac{1}{30}$ AU or better, we cannot deflect the assailant without fracturing it. Under those circumstances it is better to try to pulverize it with an array of masses, probably resembling spears for maximum penetration.

Equation (16) suggests a way to beat the fracture problem. The blow-off fraction can be reduced by increasing the specific impulse. Figure 5 shows the blow-off fraction as a function of specific impulse for a 100-m assailant with the mission launched at a range of $\frac{1}{100}$ AU. With a specific impulse of 500, over 14% of the assailant mass is blown-off, whereas at a specific impulse of 5000, less than 4% is blown-off.

3. Nuclear Explosive Deflection

Much more deflection can be obtained if a nuclear explosive is used to provide the cratering energy. In this scenario, most of the weight after the rocket fuel is expended would be the nuclear explosive, which produces a yield of

$$E = \varphi M_f \quad (17)$$

where φ is the yield-to-weight ratio. Again, $\delta^2/2$ of this energy goes into the dirt ejected from the crater, so the transverse velocity imparted to the assailant is

$$v_{\perp} = \frac{\delta}{M_a} \sqrt{\varphi M_f M_a} = \frac{\alpha \delta}{M_a} (\varphi M_f)^{\frac{L+1}{2}} \quad (18)$$

We can combine Eqs. (4), (5), and (18) to obtain

$$\epsilon = \frac{\alpha \delta \mathcal{R}_1 V (\varphi M_f)^{\frac{L+1}{2}}}{M_a v V + v} \quad (19)$$

3.1. Optimum Mass Ratio for Nuclear Explosive Deflection

Substituting Eq. (1) into Eq. (19) and solving Eq. (10), we find the logarithm of the mass ratio that produces the largest value of ϵ ,

$$Q = -\frac{v}{2gI_{sp}} + \frac{1}{2} \sqrt{\frac{8v}{(1+\beta)gI_{sp}} + \left(\frac{v}{gI_{sp}}\right)^2} \quad (20)$$

In the limit of very high specific impulse, the optimum mass ratio is

$$\frac{M_i}{M_f} = 1. \quad (21)$$

In the limit of very low specific impulse, the optimum mass ratio is

$$\frac{M_i}{M_f} = \exp\left(\frac{2}{1+\beta}\right). \quad (22)$$

The maximum displacement of the impact location on Earth is then given by

$$e = \frac{\alpha \delta R_i g I_{sp} Q (\varphi M_i e^{-Q})^{\frac{2+\beta}{1+\beta}}}{M_e v g I_{sp} Q + v}. \quad (23)$$

For a surface burst, Glasstone uses $\beta = 0.9$, but takes $\alpha \approx 1.6 \times 10^{-4} \text{ gm}^{\frac{1}{2}(1-\beta)} \cdot \text{cm}^{-\beta} \cdot \text{sec}^{\beta}$. He describes the medium as dry soil. Medium strength rock would be more consistent with $\alpha \approx 10^{-4} \text{ gm}^{\frac{1}{2}(1-\beta)} \cdot \text{cm}^{-\beta} \cdot \text{sec}^{\beta}$, and, in the 20-kt range, would roughly agree with Cooper⁶. If about 5% of the nuclear explosive energy goes into kinetic energy of the blow-off, then $\delta = 1/\sqrt{10} \approx 3.16$.

Equation (23) can be rearranged to give the required initial mass of the interceptor,

$$M_i = \frac{e^Q}{\varphi} \left[\frac{M_e v e}{\alpha \delta R_i} \left(1 + \frac{v}{g I_{sp} Q} \right) \right]^{\frac{1+\beta}{2+\beta}}, \quad (24)$$

where now Q is given by Eq. (20).

It is generally known that nuclear warheads can be a few kilotons per kilogram if they weigh more than about a hundred kilograms. For the purpose of these estimates, I will take the conservative of $\varphi = 1 \text{ kiloton} \cdot \text{kilogram}^{-1}$. Figure 6. is analogous to Fig. 3, using the values of α and δ given above.

A good way to compare kinetic-energy deflection with nuclear-explosive deflection is to look at the ratio of the initial masses of the interceptors. If we divide Eq. (24) by Eq. (15), we see that all variables drop out except specific impulse (I_{sp}), the assailant's velocity (v), the energy fraction (δ), and the cratering constant (α). For a comparison of the techniques, we would keep the same values of I_{sp} and v . We define the ratio

$$R_m = \frac{M_i \text{ given by Eq. (24)}}{M_i \text{ given by Eq. (15)}}. \quad (25)$$

The the appropriate dimensionless ratio for the comparison is

$$R_m \frac{\alpha_n \delta_n}{\alpha_k \delta_k}, \quad (26)$$

where the subscripts n refer to the parameters for nuclear-explosive deflection and the subscripts k refer to the parameters for kinetic-energy deflection. This is the actual ratio of initial interceptor weights for kinetic-energy versus nuclear-explosive deflection. Figure 7a shows this ratio as a function of assailant velocity (v) for specific impulse $I_{sp} = 500$ sec. Figure 7b shows the same ratio as a function of specific impulse (I_{sp}) for assailant velocity $v = 25 \text{ km} \cdot \text{sec}^{-1}$. Figure 7c shows the same ratio as a function of both specific impulse and assailant velocity. For the numerical examples we have chosen, we have

$$\frac{\alpha_n \delta_n}{\alpha_k \delta_k} = \frac{10^{-4} \times 0.316}{2 \times 10^{-4} \times 0.775} = 0.204. \quad (27)$$

So for my particular selection of parameters, we can read the mass ratios in Figs. 7a, 7b, and 7c by multiplying the number on the vertical axis by 0.204.

From Figs. 7a, 7b, and 7c, we learn the following qualitative features.

- The interceptor weight is about three orders of magnitude less for nuclear-explosive deflection than for kinetic-energy deflection.
- The advantage of nuclear-explosive deflection decreases significantly with assailant velocity.
- The advantage of nuclear-explosive deflection decreases slightly with specific impulse.

3.2. Nuclear-Explosive Fragmentation and Pulverization

By combining Eqs (1), (5), (11), and (24), we find that the blow-off fraction is given by

$$\begin{aligned} f &= \frac{M_e}{M_i} = \frac{\alpha^2}{M_e} \left(\frac{\varphi M_i}{cQ} \right)^\beta \\ &= M_e^{\frac{\beta-1}{\beta+1}} \left\{ \alpha \left[\frac{cv}{R_i \delta} \left(1 + \frac{v}{g I_{sp} Q} \right) \right]^\beta \right\}^{\frac{1}{\beta+1}}, \end{aligned} \quad (28)$$

where Q is given by Eq. (20). Somewhat remarkably, Eq. (28) is independent of φ and has the same form as Eq. (18). The only differences are: (1) the different form of Q , (2) the value of the energy fraction δ , and (3) the value of the cratering constant α .

Figure 8 shows the blow-off fraction for planetary miss (10 Min) as a function of assailant diameter for two different ranges to the assailant at interceptor launch. If the interceptor is launched at a range much closer than $\frac{1}{2}$ AU, the assailant will be fragmented rather than deflected.

3.3. Penetrators

The biggest crater is not produced by a surface burst, but by an explosive buried some distance below the surface. Clearly if it is buried too deeply, it will produce no crater at

all. The optimum depth for cratering is a function of all the usual parameters describing material properties, but most importantly, gravity, which, to a large extent, can be ignored for comets and asteroids. For dry soil on the surface of the Earth, Glasstone gives the optimum depth as $150 E^{0.3}$ feet and he would obtain the crater constant and exponent as $\beta \approx 0.9$ and $\alpha \approx 8.4 \times 10^{-4} \text{ gm}^{\frac{1}{2}(1-\beta)} \cdot \text{cm}^{-\beta} \cdot \text{sec}^{\beta}$ for use in Eq. (5). For the moment, let us say that the value of α is increased an order of magnitude.

Looking at Eq. (24), we might expect the initial mass to decrease an order of magnitude, but in order to penetrate to the optimal depth the explosive has to be fitted with a weighty billet: a cylinder of metal (probably tungsten) that will erode during penetration of the assailant's soil. In general, this will increase the weight by about an order of magnitude, or decrease the yield-to-weight φ by about an order of magnitude. Thus in Eq. (24), the decrease in initial interceptor mass M_i owing to the increase in the cratering constant α is just about compensated by the decrease in yield-to-weight φ .

However, the blow-off fraction given in Eq. (28) becomes an order of magnitude larger, because it does not depend on yield-to-weight φ . The conclusion is that a penetrator has no value enhancing deflection, but may be of great value if we choose to pulverize the astral assailant.

3.3. Stand-off Deflection

The fracture problem can be much mitigated by detonating the nuclear explosive some distance from the astral assailant. Rather than forming a crater, the neutrons, x-rays, γ -rays, and some highly ionized debris from the nuclear explosion will blow-off a thin layer of the assailant's surface. This will spread the impulse over a larger area and lessen the shear stress to which the assailant is subjected. Of these four energy transfer mechanisms, by far the most effective (at reasonable heights of burst) is neutron energy deposition, suggesting that primarily-fusion explosives would be most effective.

The problem of calculating the momentum transferred from a stand-off detonation is sufficiently complicated that it is difficult to address analytically. Computer simulations seem the most effective approach. However some general statements can be made. At an optimal height of burst, about 2 to 8% of the explosive's energy is coupled to the assailant's surface, again depending on the assailant's actual composition and the neutron spectrum and total neutron energy output of the explosive. This corresponds to an energy fraction δ of 0.2 to 0.4. Most of the energy is deposited in the first 10 cm of the soil. The cratering constants can still be used as in Eq. (5), but for this surface blow-off, $\beta \approx 1$ and α ranging from 10^{-6} to $2 \times 10^{-8} \text{ cm}^{-1} \cdot \text{sec}$. If we select an assailant for which $\delta = 0.3$ and $\alpha = 1.5 \times 10^{-6} \text{ cm}^{-1} \cdot \text{sec}$, we find from Eq. (24) that the blow-off fraction will be about a factor of 35 times smaller than the surface burst. The blow-off fraction given in Fig. (8) would be in the range of 1% for $R_i = \frac{1}{10}$ AU and in the range of $\frac{1}{3}$ % for $R_i = \frac{1}{3}$ AU. Similarly, from Eq. (28) we find that the initial mass of the interceptor would have to be about 40 times as large. So in Fig. (6) the mass would be multiplied by 40, i.e. ranging from about 28 tons to about 28 kilotons. The latter would not be very practical.

4. Comments, Summary, and Tentative Conclusions

Since Alvarez⁷ announced evidence for asteroid impact as the putative cause of the cretaceous-tertiary extinction, there has been a heightened awareness that our fair planet is and always has been in a state of merciless cosmic bombardment. Not all this cannonade has been deleterious, for example, the event Alvarez suggests may have cleared the way for the rise of homo sapiens. But being a selfish sub-species, we would rather hold on to our domination of the Earth, and deny a chance to any more well adapted creature for as long as we can. Less facetious is the possibility of a strike from an interplanetary body with radius on the order of 100 m. If an asteroid, such an assailant would likely have a relative velocity of about $25 \text{ km} \cdot \text{sec}^{-1}$, which would give it a kinetic energy of about 1000 megatons. In a populated area, the damage would be catastrophic. If it were a comet, the relative velocity would be more like $50 \text{ km} \cdot \text{sec}^{-1}$ and the energy would quadruple. The Tunguska Event⁸ (1908) offers sobering evidence that such potentially catastrophic collisions are not so infrequent that they can be ignored. That impact was about 10 megatons and could be expected every few hundred years. Recent estimates⁹ indicate that a 20-kiloton (Hiroshima-size) event should occur every year. This would be conspicuous, apparently much of the energy is dissipated in penetrating the atmosphere. That such cataclysms are not generally recorded in the archives of natural disaster seems somewhat of a mystery. Perhaps it can be attributed to the fact that until the 20th century, very little of the Earth's surface was populated.¹⁰ Nevertheless, the risk of being killed as a result of asteroid impact is somewhat greater than the risk of being killed in an airplane crash.¹¹

The problem naturally divides into two parts: (1) detection of these relatively small assailants; and (2) smashing or deflecting them should they be on an endangering course. In this paper, I have addressed the latter issue. The relationships I have derived should guide thinking on how to counter such assailants. Their main value is to show the functional relationship among the parameters. This paper is not intended to be an exhaustive study, and much research will be required to evaluate the constants in the equations I have derived. But the following observations are compelling and unavoidable.

- Kinetic-energy deflection is effective for ocean diversion for assailants smaller than about 70 m, if the interceptor is launched when the assailant is further than $\frac{1}{30}$ AU
 - At shorter range, interceptors become impractically massive and the probability of fracture increases rapidly
 - Ocean impact is probably unacceptable for larger assailants, and an order-of-magnitude larger interceptor is required for missing the planet with concomitant increase in fracture probability
 - Higher specific impulse interceptors are more effective at increasing deflection and reducing fracture probability, mainly because they divert the assailant at a greater distance.
 - Objects less than 10 m are better pulverized at short range.
- Nuclear-explosive deflection is imperative for assailants greater than about 100 m detected closer than $\frac{1}{30}$ AU because of the enormous mass of the interceptor required for kinetic-energy diversion.

- Nuclear-surface-burst deflection offers a three-to-four order of magnitude reduction in interceptor mass.
 - Advantage decreases slightly with specific impulse
 - Advantage decreases dramatically with assailant velocity
 - Fragmentation is a problem for intercepts closer than about $\frac{1}{3}$ AU.
- Nuclear penetrators offer no advantage for deflection, but better for pulverization.
- Nuclear stand-off deflection greatly reduces fragmentation probability, but involves a substantial increase in interceptor mass

The assailant object depicted in Fig. 1 is roughly spherical in shape. In fact, comets or asteroids are generally quite aspherical, a "potato" or "peanut" being the most popular descriptions. All the deflection techniques except the stand-off nuclear burst make a crater that is small compared to the characteristic dimension of the assailant. The linear momentum impulse will be imparted along a line connecting that crater and the center of mass — with corrections for local geology and topography. An aspheric object will also receive some angular momentum, depending on the location of the crater and the object's inertial tensor. The size of the impulse will depend on material properties, geology, and topography.

Thus, it will be necessary to characterize the geology and mechanical properties of the assailant when using the cratering deflection techniques. Such characterization could be accomplished by a vanguard spacecraft. Stand-off deflection is much less sensitive to these details. In general, linear momentum will be imparted along the line connecting the detonation point with the center of mass, a larger lever arm. Little angular momentum will be imparted, depending on projected areas compared to the inertial tensor. Thus, beside its fracture-mitigation virtues the stand-off deflector requires less information about the object it is deflecting.

5. References

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Figure Captions

Figure 1. *Interception Scenario.* (a) The asteroid or comet is headed toward Earth at a velocity v . The interceptor, traveling at a diametric velocity V , is about to engage the assailant. The assailant has a mass M_a , and the interceptor, because it has long since exhausted its fuel, it has its final mass M_f . (b) The interceptor supplies energy to blow-off a portion (mass M_o) of the assailant's surface to impart a transverse velocity v_{\perp} . The blow-off material is very massive compared to the interceptor, $M_a \gg M_o \gg M_f$.

Figure 2. *Dimensionless Plot of Kinetic-Energy Deflection.* Dimensionless parameter $\epsilon M_o / \alpha \delta v^{\beta} R_i M_i^{\frac{1}{2}(\beta+1)}$ versus the dimensionless parameter $g I_{sp} / v$ for $\beta = 0.8, 0.9$, and 1.0 .

Figure 3. *Initial Masses of Optimally Designed Interceptors Using Kinetic-Energy Deflection for Ocean Diversion (1 Mm).* Initial mass of the interceptor required to deflect the assailant by 1 Mm, as a function of the assailant's diameter and its range when the assailant is launched. Assumed quantities: $\rho = 3.4 \text{ gm} \cdot \text{cm}^{-3}$, $v = 25 \text{ km} \cdot \text{sec}^{-1}$, $\beta = 0.9$, $\alpha = 2 \times 10^{-4} \text{ gm}^{\frac{1}{2}(1-\beta)} \cdot \text{cm}^{-\beta} \cdot \text{sec}^{\beta}$ and $\delta \simeq 0.775$. The one-megameter deflection is typical of the course change required to divert an assailant from impact in a populated area to a nearby ocean. To interpret a ten-megameter deflection, which would be conservative for missing the planet entirely ($R_{\odot} = 6.378 \text{ Mm}$), multiply the masses by about a factor of ten ($M_i \propto \epsilon^{\frac{2}{\beta+1}}$, so a factor of 10 in ϵ corresponds to a factor of 11.3 in M_i).

Figure 4. *Blow-off Fraction for Ocean Diversion (1 Mm) using Kinetic-Energy Deflection.* Assumed quantities: $\rho = 3.4 \text{ gm} \cdot \text{cm}^{-3}$, $v = 25 \text{ km} \cdot \text{sec}^{-1}$, $\beta = 0.9$, $\alpha = 2 \times 10^{-4} \text{ gm}^{\frac{1}{2}(1-\beta)} \cdot \text{cm}^{-\beta} \cdot \text{sec}^{\beta}$ and $\delta \simeq 0.775$. If more than 10% is blown-off, the assailant will probably break-up.

Figure 5. *Asymptotic Decrease of Blow-off Fraction with Specific Impulse.* The blow-off fraction as a function of specific impulse for a 100-m assailant with the mission launched at a range of $\frac{1}{100}$ AU. With a specific impulse of 500, over 14% of the assailant mass is blown-off, whereas at a specific impulse of 5000, less than 4% is blown-off.

Figure 6. *Initial Masses of Optimally Designed Interceptors Using Nuclear-Explosive Deflection.* Ocean deflection of 1 Mm is sought. Assumed quantities: $\rho = 3.4 \text{ gm} \cdot \text{cm}^{-3}$, $v = 25 \text{ km} \cdot \text{sec}^{-1}$, $\beta = 0.9$, $\alpha = 10^{-4} \text{ gm}^{\frac{1}{2}(1-\beta)} \cdot \text{cm}^{-\beta} \cdot \text{sec}^{\beta}$ and $\delta \simeq 0.318$.

Figure 7. *Ratio of Kinetic-Energy Interceptor Mass to Nuclear-Explosive Interceptor Mass.* (a) As a function of assailant velocity (v) for specific impulse $I_{sp} = 500 \text{ sec}$. (b) As a function of specific impulse (I_{sp}) for assailant velocity $v = 25 \text{ km} \cdot \text{sec}^{-1}$. (c) As a function of both specific impulse and assailant velocity. For the present numerical examples we have chosen, $\alpha_n \delta_n / \alpha_k \delta_k = 0.204$. So figures can be read by multiplying the number on the vertical axis by 0.204.

Figure 8. *Blow-off Fraction for Collision Avoidance (10 Mm) using Nuclear-Explosive Deflection.* If the interceptor is launched at a range much closer than $\frac{1}{3}$ AU, the assailant will be fragmented rather than deflected.

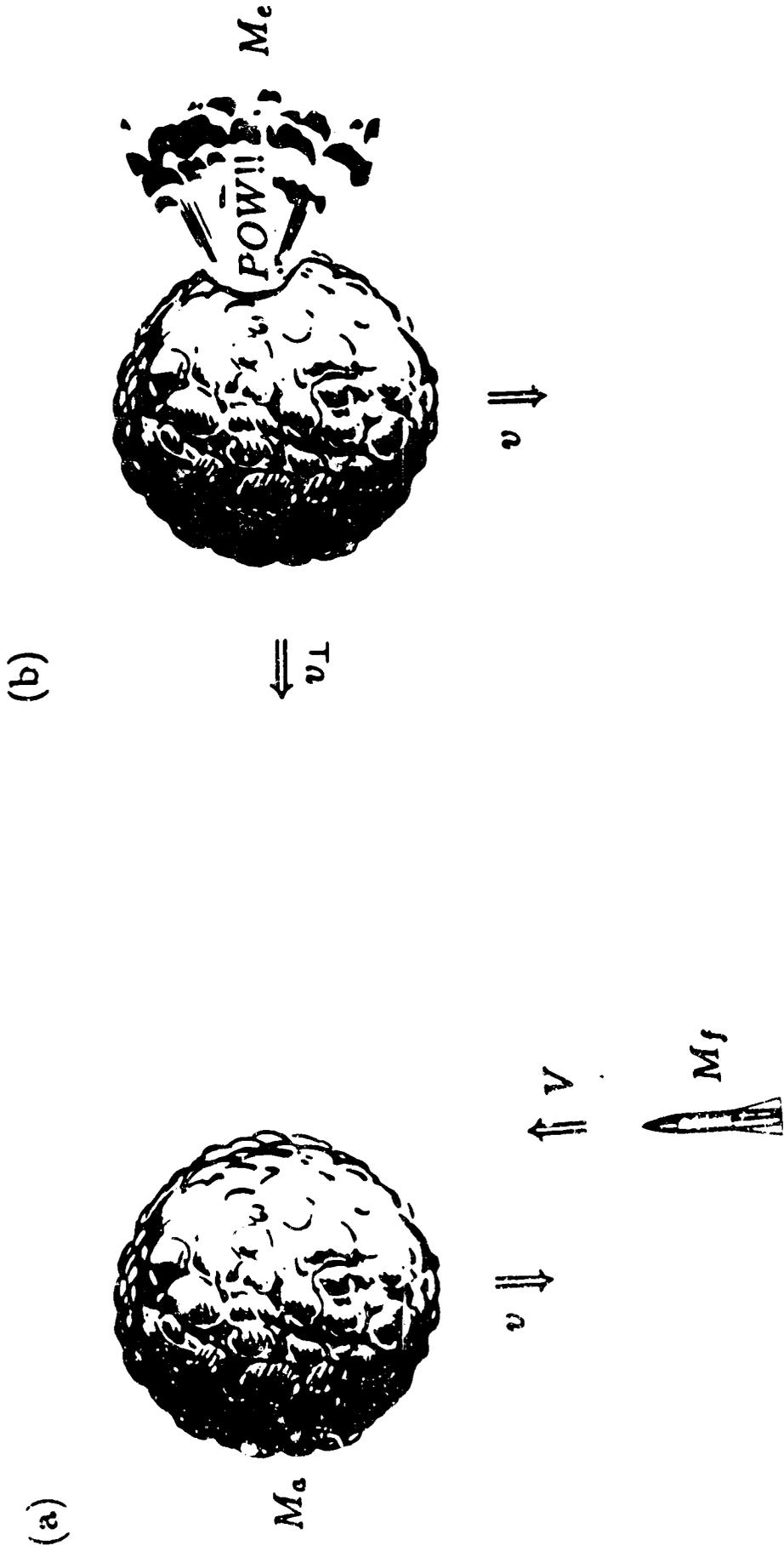


Figure 1.

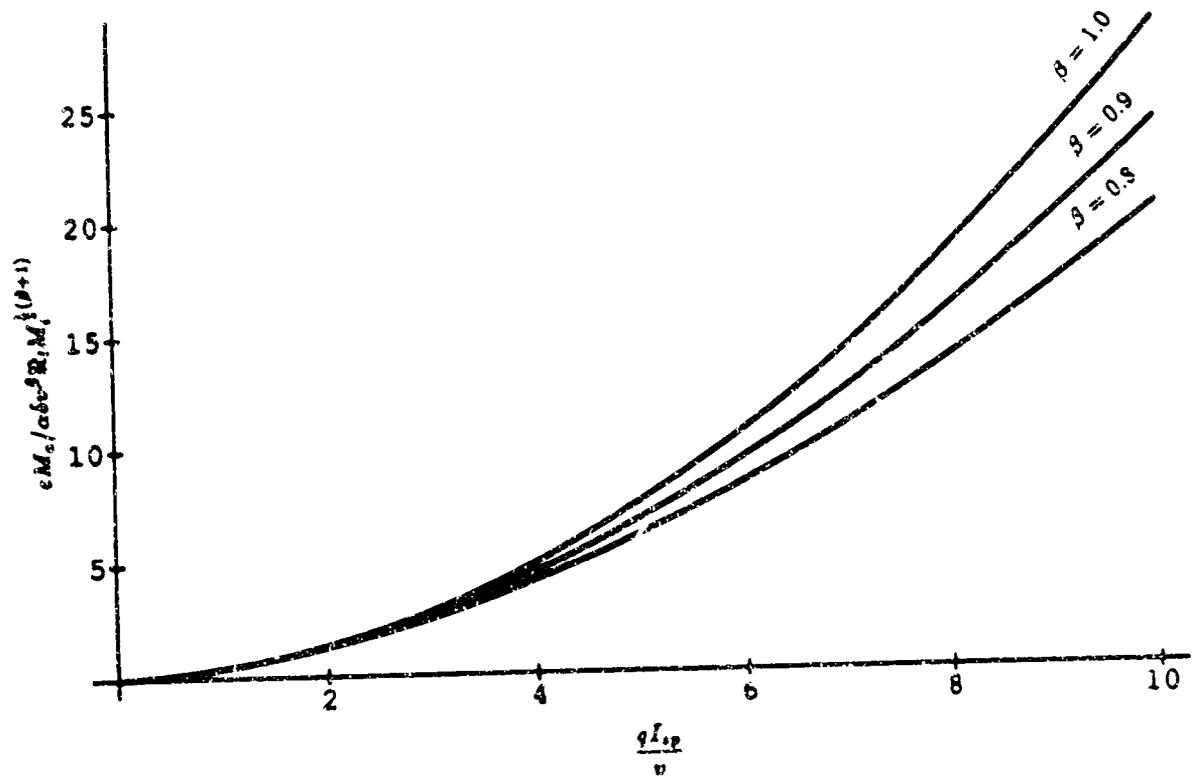
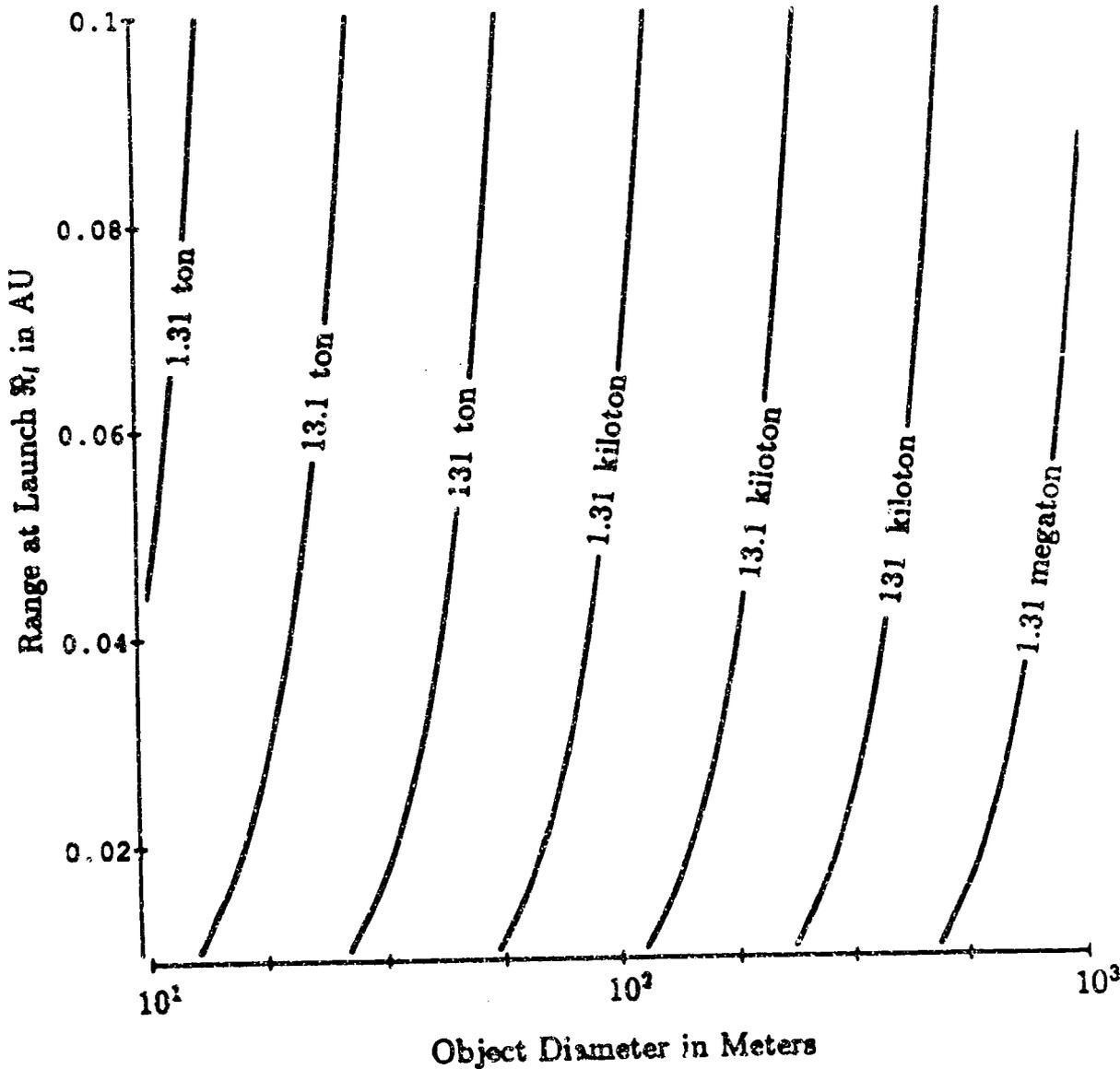


Figure 2.



$\alpha = 2 \times 10^{-4}$

$\delta = 0.775$ (30% energy to blow-off)

Figure 3.

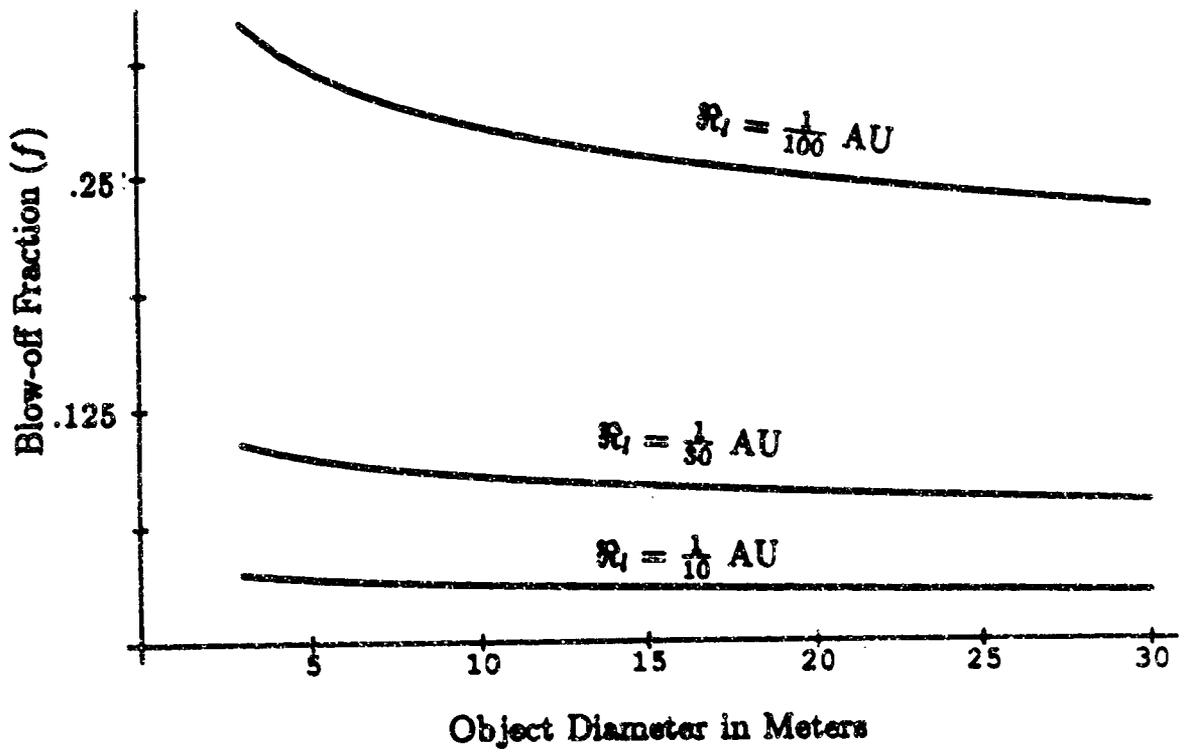


Figure 4.

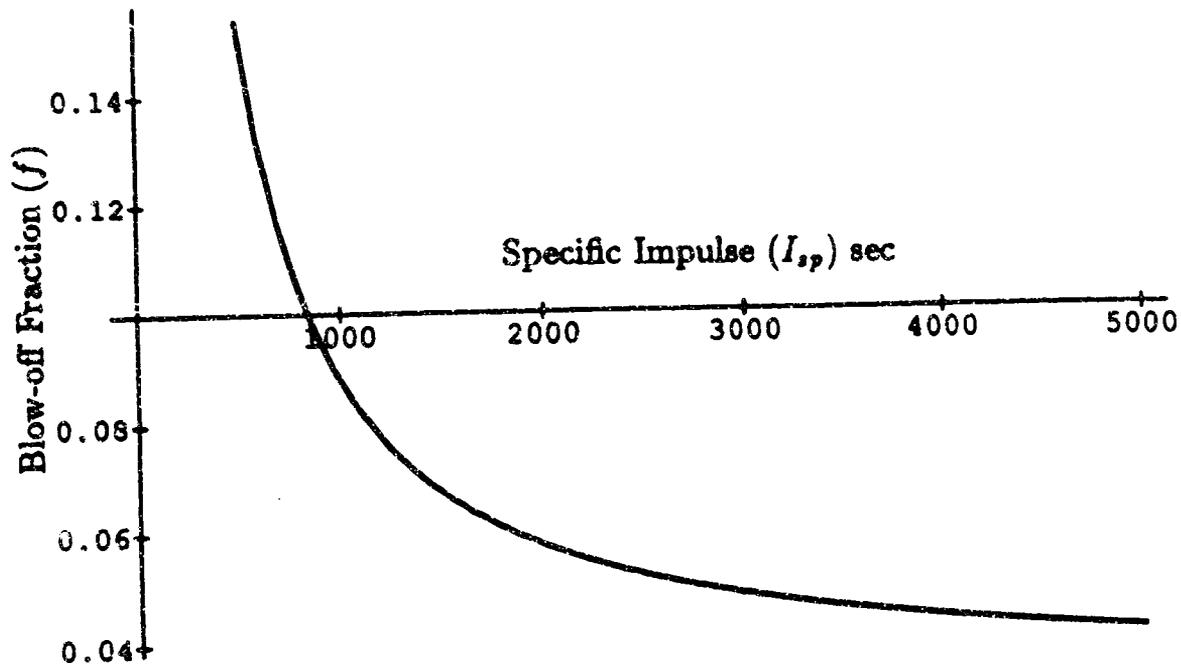


Figure 8.

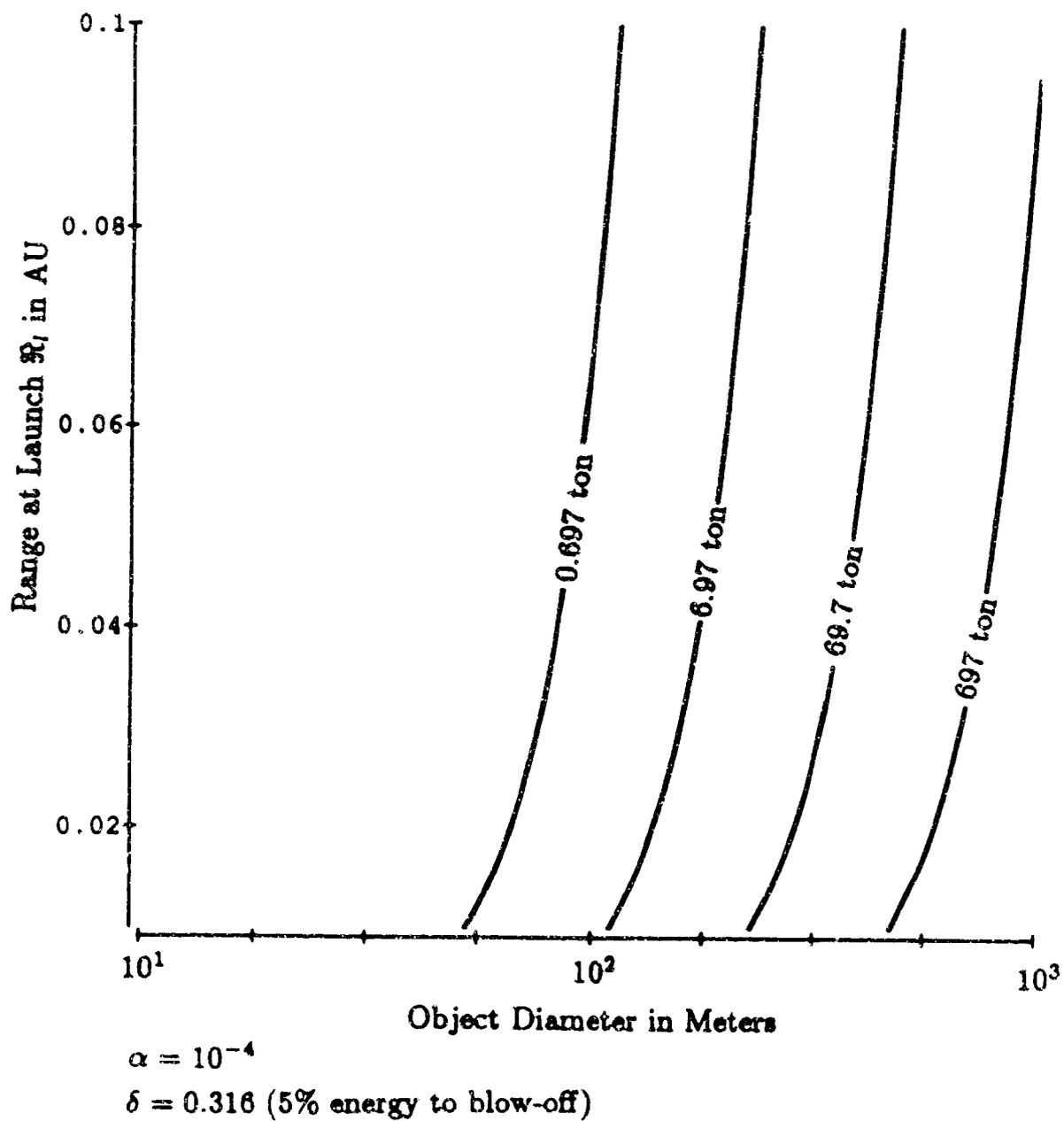


Figure 6.

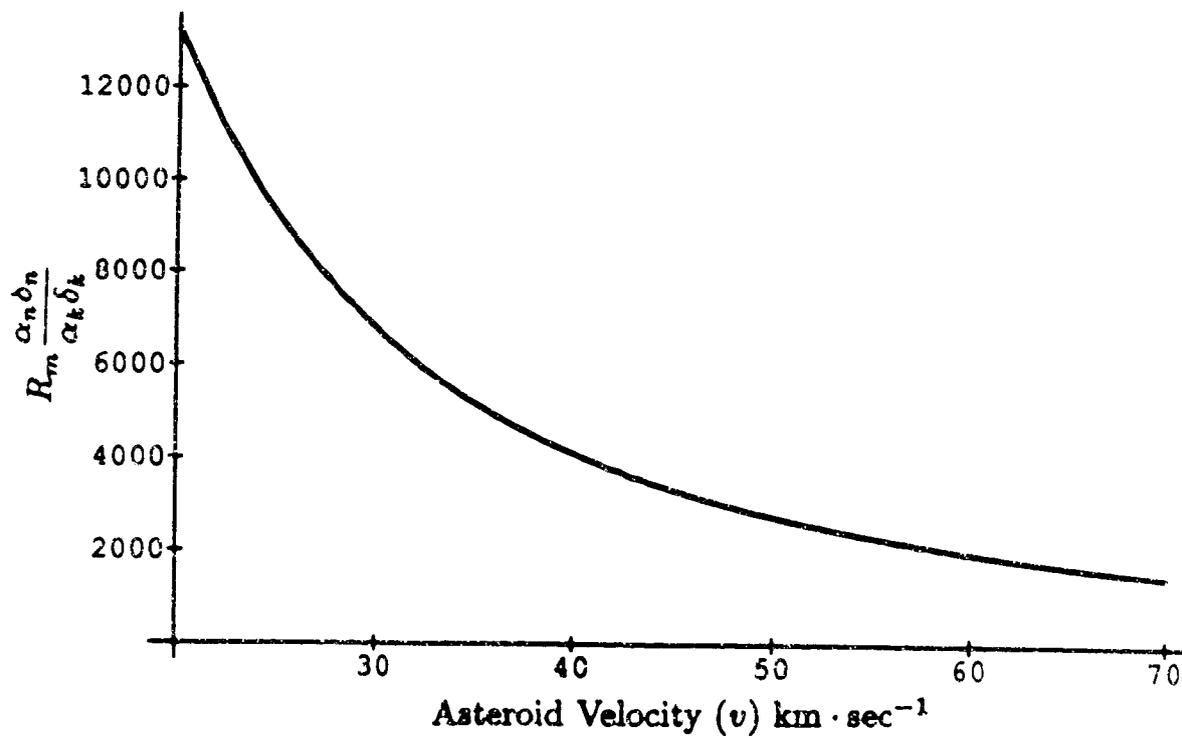


Figure 7a.

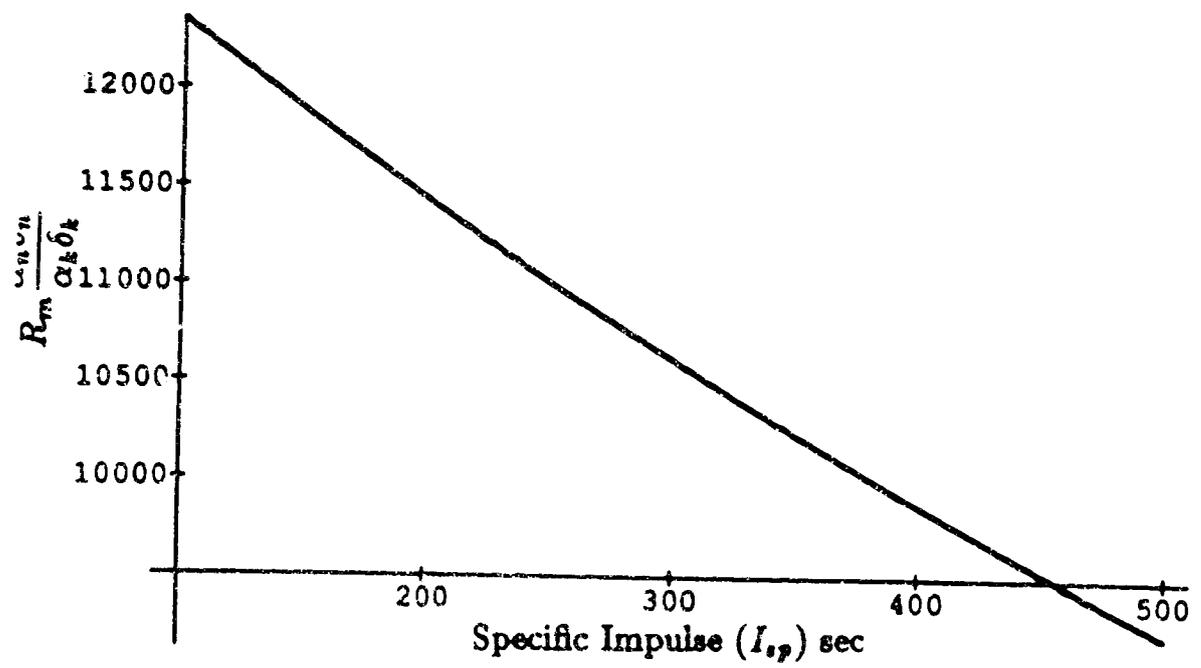


Figure 7b.

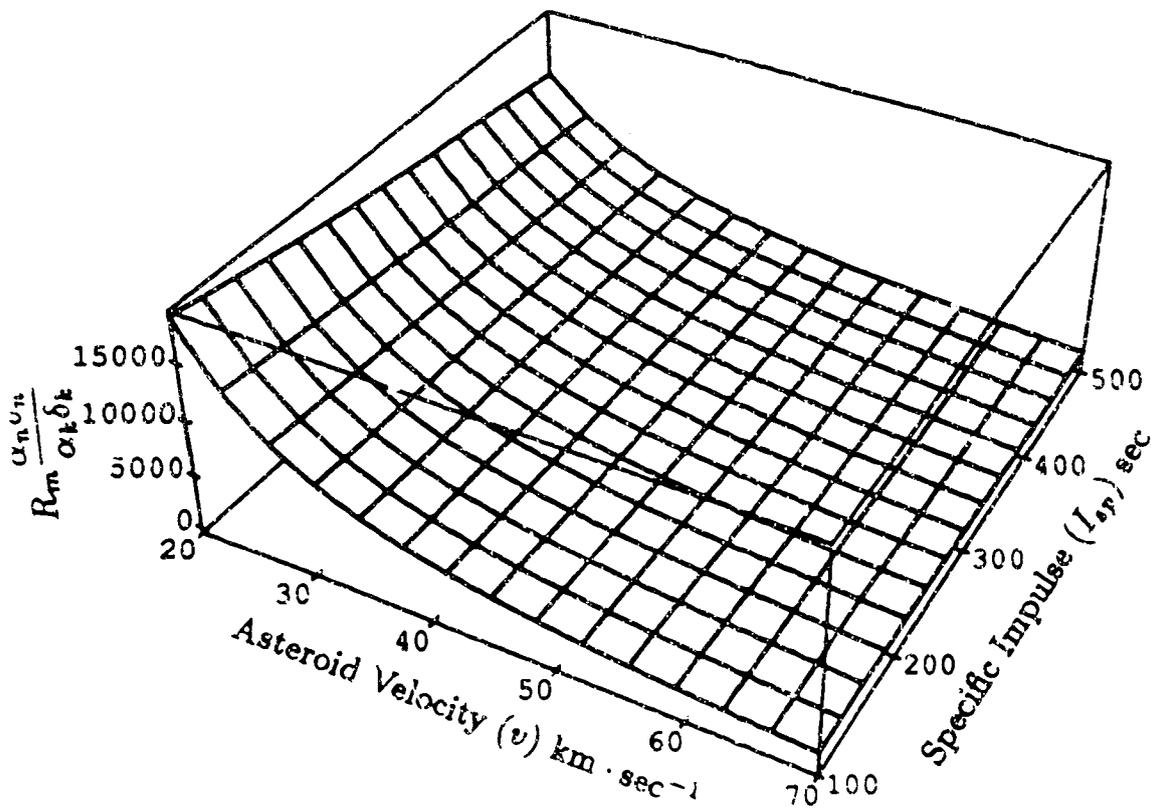


Figure 7c.

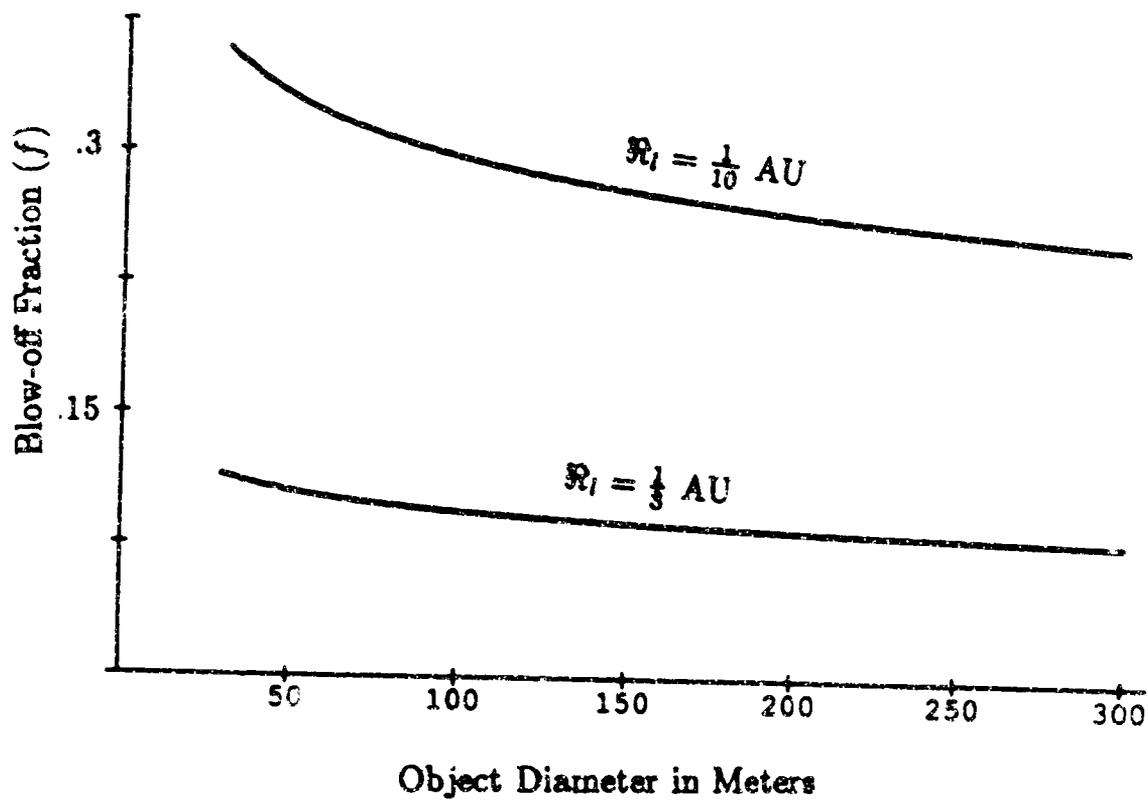


Figure 8.

COSMIC BOMBARDMENT III: Ways-And-Means Of Effectively Intercepting The Comets

A Presentation Prepared For

The NASA Near-Earth Object Interception Workshop

14 January 1992, at the
Los Alamos National Laboratory



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Is Cosmic Bombardment a Serious Threat?



- impacts come in many sizes
 - There is a continuous range of impact sizes and likelihoods
 - But the consequences fall into two basic classes
 - Local: Those that kill individuals, but do not threaten civilizations
 - Global: Those that destroy human societies, and possibly our species
- Local events
 - These are produced by impacts of varying types
 - Small ones, ~30 m, that will likely occur within anyone's lifetime
 - But that generally do no great harm
 - Large ones, ~300 m, that are improbable (~0.1–1% per lifetime)
 - But will cause damage, killing thousands to millions of people
 - Functionally, however, these do not endanger our civilization
 - They represent a statistical loss rate
 - its size is uncertain, but is ~100 people/year, time-averaged at present
- Global events
 - These are due to collisions with large, ≥ 1 km diameter bodies
 - They are extremely unlikely to occur within our lifetimes: $< 0.01\%$
 - But are known to have occurred repeatedly over the life of our planet
 - When such an impact occurs, damage is extensive and global
 - Functionally, these events can endanger our civilization and our species
 - The ascension of mammals and Man is probably due to a large impact

Should We Respond to the Local Threat?



- The argument against responding
 - We've tolerated this (without notice) in the past
 - The loss rate is very small
 - There are much larger ones to worry about
- The argument for acting
 - Now the danger is avoidable; in the past it wasn't
 - It is the duty of a government to protect its citizens
 - People cannot protect themselves from this threat, by choosing how or where they live
- Proposition: Treat this decision as an economic one
 - Determine the statistical damage rate (\$/yr)
 - Multiply by some appropriate safety/benevolence factor
 - This determines the yearly investment which should be committed
 - Typical calculation of the damage rate
 - Start with a cumulative collision rate: $N \sim 1.6 D^{-2.5} \text{ Myr}^{-1}$
 - Relate size of object to the energy release: $Y \sim 100 D^3 \text{ Gton}$
 - Determine the area destroyed by the released energy: $A \sim 15000 Y^{2/3} \text{ km}^2$
 - Apply population density: $P \sim 10 \text{ people/km}^2$
 - Assign an economic value: $V \sim 0.2 \text{ M\$/person}$
 - Combine these and integrate over size distribution: $C \sim 5 D_{\text{min}}^{-0.5} \text{ M\$/yr}$
 - A cutoff, $D_{\text{min}} \sim 0.05 \text{ km}$, discounts objects that breakup at very high altitudes
 - This leads to a loss estimate of $20 \text{ M\$/yr}$ and 100 people/yr
 - Refinements in data and statistics should be applied
 - But they don't change the nature or the order-of-magnitude of the threat/hazard
 - Damage is dominated by rare, but deadly events: Tunguska-like strikes
 - This threat is comparable, although events are rarer, to that from large earthquakes
 - But unlike earthquakes, protection (not just warning) is possible
 - An insurance policy is worth $> 10 \text{ M\$/yr}$, $< 100 \text{ M\$/yr}$, at the present time
 - Worth ever more, as more people create more improvements all over the world

Should We Respond to the Global Threats?



- The argument against responding
 - While hits will occur sometime, odds are overwhelming that it won't be soon
 - The future will be much different than now
 - Our capacity to respond will improve as our technology does
 - The necessity will drop as human civilization moves off-planet
 - While the likely death toll becomes ever more horrendous
 - This becomes a local tragedy, rather than a species-threatening one
 - So it's not worth much effort to provide near-term (100 year-scale) protection
 - We've survived many such intervals already; one more surely won't hurt

- The argument for acting
 - While the odds of a near-term impact are very small
 - They're the same now as when the dinosaurs died
 - They did not act, and paid the ultimate price: Extinction
 - We have a duty to our fellow life on Earth
 - We might choose to take this risk, or avoid it by escaping into space
 - But our choice to not act condemns many fellow species to extinction
 - Half of all extant species died in the K-T event
 - Only ourselves and our technology can prevent their extinction

- Proposition: This is a philosophical and ethical issue, not a simple economic one
 - Detailed threat assessments are interesting, but not particularly relevant
 - Are we at risk now, as the dinosaurs were in the past?
 - Insuring against another such catastrophe is a fundamental moral imperative
 - Once we have achieved the ability to prevent it
 - Then we incur the positive moral duty to do so
 - If saving a single species (Northern Spotted Owl) is worth 10^4 (loggers) jobs and a $\$10^9$ /year industrial loss, what is saving a million species worth?
 - Half of all presently existing species - the same fraction as died in the K-T Extinction

The Challenge of Preventing Cosmic Impacts



- We must locate the threatening body
 - Preferably with enough warning (time and distance) for us to prevent the impact
 - But certainly with enough precision to allow warning (effective against local threats)

- We have only limited knowledge about the threatening body
 - We do know its speed and light-scattering size
 - We do not know its actual mass, dimensions or shape; nor its internal structure or properties
 - For catalogued NEOs we have enough time to investigate these properties
 - But for first-pass-deadly threats we must act without detailed information

- The threatening bodies are big and fast
 - The smallest, Tunguska-like local threats involve ~100,000 ton objects
 - The Great Extinction-causing global threats involve $\geq 10^{10}$ ton objects
 - First-pass-deadly threats do not allow much time to react
 - EarthGuard provides about ≤ 10 days' warning of local threat impacts
 - The global-threatening LPCs are easier to see; typically we have a few months' warning
 - It is very hard to rendezvous with first-pass-deadly objects
 - They generally approach us at 20-50 km/sec
 - We must first accelerate to comparable speeds in order to reach them quickly
 - We can't afford the rocket fuel to match velocities upon arrival
 - So our action must involve impact or flyby, not landing or hovering

- First-pass-deadly objects are the most challenging threats
 - The orbiting NEOs are readily catalogued
 - As cataloguing proceeds, the threat represented by NEOs diminishes
 - The size and flux of yet-uncatalogued NEOs falls
 - Preventing impacts from pre-catalogued NEOs is relatively easy
 - There is plenty of time to rendezvous with them using efficient low-thrust propulsion
 - Hence we can soft-land for detailed inspection and emplacement of our defensive gear
 - There is a long time available to our actions to exert their effects
 - The flux of Great Extinction-causing objects is dominated by LPCs, which are first-pass-deadly
 - First-pass-deadly objects are intrinsically harder to deal with

Preventing First-Pass-Deadly Impacts

- Operational considerations
 - Our preferred solution is a full-miss deflection
 - While leaving the body intact, so it can be re-engaged if necessary
 - An imperfect dispersal (chunks too big and/or too slow) leaves less backup options
 - After an initial failure, we are faced with many individual targets
 - Dispersal can backup deflection; but the converse is not true
 - We need a multi-layer defense
 - The initial engagement should attempt a deflection
 - As far away as practical; to reduce the required push, and to allow more time to re-engage
 - This will involve at least two missions
 - One for empirical calibration of the delivered velocity
 - Followed by one or more to deliver the desired shove
 - Terminal defense should re-engage if the first-layer fails
 - While multiple deflections can be attempted, if they fail we should have an alternate approach
 - The last-ditch effort should emphasize target rubblization and dispersal
 - For global-killers, dispersal must be > planet-wide; concentrated mass-flux still kills
 - Training and practice missions are essential
 - We need to learn how to do the job well before a real biosphere-threatening event occurs
 - Objects passing through cis-lunar space, at ~ 10⁴ higher rate, are available for such training
 - They can be engaged after passing the Earth; insuring against 'training fatalities'
 - Proposed defensive approach
 - Local threats
 - First engagement: After detection, send nuclear explosives on flyby missions to deflect the body
 - Terminal defense: Position array of penetrators in object's path to fragment it prior to aerial-entry
 - Global threats
 - First engagement: Send large nuclear explosives on long-range penetrating missions to disperse the body
 - Terminal defense: Use arrays of nuclear explosives to rubblize and disperse the body

Deflecting an Object with Nuclear Explosives



- We prefer to use 'high-altitude' bursts from fly-by explosives, not surface-contacting detonations
 - We want to gently shove the object, not shatter it
 - Surface bursts couple energy into the object by a strong shock wave
 - This excavates a crater; the ejecta acts as rocket exhaust
 - To deliver the ΔV s of interest, the crater size is not small compared to the size of the body
 - The object will disassemble; we have little recourse if the dispersal pattern is unacceptable
 - High-altitude bursts deliver energy by radiation
 - Energy deposits into the entire exposed surface
 - The depth-of-exposure depends on the coupling radiation; bomb neutrons deposit 10-100 cm deep
 - A thin, wide-area skin blows off, delivering impulse
 - This delivers a much gentler, more uniform push than does a surface burst
 - Even if the object breaks apart, the chunks are more uniformly and predictably pushed
 - We can adjust the impulse easily, by selecting the flyby distance
 - Flexibility is essential because object's characteristics are uncertain when mission is launched
 - Surface-contacting bursts do not offer this great flexibility
- Very big, global-threatening comets require more desperate measures
 - A 10 km comet involves 10^{12} tons; it must be deflected by ~ 10 m/sec, ≥ 2 weeks before Earth-strike
 - Hundreds of Gtons of energy are required to execute this by shoves from "high-altitude" bursts
 - If the object's dispersal is sufficiently uniform, then required energies are reasonable: ~ 100 MT
 - Detonate a warhead deep within the comet
 - The resulting shock wave generates a quasi-uniform radial dispersal of comet's mass
 - The warhead is emplaced within the comet by following a rectilinear train small, properly spaced of penetrators
 - This process must be tested and refined by experimenting on smaller, near-miss comets

Conclusions



- The "Cosmic Bombardment" continues
 - History of terrestrial life — and the Earth's crust itself — bear its major scars
 - Major events/episodes every $60 \pm M$ years seen as "Great Extinctions" in the fossil record
 - Last one terminated the Cretaceous Period, exterminated the Great Reptiles, and opened up the terrestrial ecosystem to Class Mammalia
 - Next one is due anytime — no known "leading indicator"
 - Once-per-human lifetime 10-100 MT events (e.g., Tunguska) constitute Nature's "drum-roll" leading up to the next "Great Smash"
- During the past four decades, Earth has seen the rise of its first space-faring, thermonuclear explosive-wielding species
 - Terrestrial life just now has a representative capable of actively defending it from the Bombardment
 - After 4.0 Aeons of simply enduring it

Asteroid/Meteorite Analogs and Material Properties

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Abstract: Analogs between meteorites and asteroids are organized to permit a classification scheme for Near Earth Objects (NEO's) in terms of their mechanical strength and thermal properties. An abridged database on meteorite mechanical and thermal properties is presented with a brief discussion. Some materials science approaches to meteorite analysis are discussed. There is a need to carry out systematic experiments on meteorite properties. Recommendations for NEO material classification scheme (NEOM) is suggested and a NEOM interception-interactions matrix is outlined.

1. Introduction

This paper has three objectives. The first is to utilize associations between meteorite mineral structures and observational spectra of asteroids in order to establish a classification of NEO's based on meteorite mechanical and thermal properties anticipated dynamic response to kinetic and radiation energy interactions. Second, a preliminary database is initiated based on currently available laboratory measurements which may not be representative of the NEO properties in their environment. Third, a material science approach to the analysis of meteorite properties is discussed. Because of these objectives, the contents of this paper are preliminary, limited in detail, and in some cases incomplete. Also, recent significant experimental results are not included; we hope to present them elsewhere. Nonetheless, it is anticipated that some of the suggestions contained herein will spark interest or even controversy that will provide support and motivation for continued research, which is the main objective.

In the past, the major objective of modeling asteroid types according to meteorite analogs has been to associate the origin and evolution of asteroids and meteorites in terms of the origin and evolution of the solar system. This objective has met with some success in enhancing our understanding of the solar system. Additional understanding of the solar system may also be derived from a study of Near-Earth-Objects (NEO's) in general and Near-Earth-Asteroids (NEA's) in particular, which are regarded to come primarily from mainbelt asteroids^(1,2). These objects are expected to further increase our scientific knowledge because:

1. Many NEA's are believed to be remnants of the original planetary building blocks as well as being meteorite parent bodies.
2. Some NEA's may be related to extinct comet nuclei and thereby provide insight into the origin and evolution of comets.
3. Terrestrial impacts of NEA's are generally regarded to have significantly influenced geological and biological evolution on the earth, ie K/T extinction hypothesis⁽³⁾.
4. NEA's may provide a basis for space resource exploration.
5. Some NEO's may be related to unknown mineral assemblages.

Our approach is to characterize NEO's as asteroid-like objects that have mineralogical analogs with meteorites and analyze how such classes of materials will respond to technological processing during NEO orbital adjustment. This approach does not minimize the importance of this material serving as a link to the origin of the solar system. Understanding the mechanical and thermal properties of meteorites will aid in anticipating likely NEO characteristics. This will assist the technology of NEO orbit management while conserving as much as possible the integrity of the asteroid, comet nucleus, or whatever the NEO turns out to be, for the natural history record.

2. Asteroid Composition Types

Both mainbelt asteroids (MBA's) as well as NEA's have been classified photometrically using reflectance spectra in the visible through infra-red (VIS-IR) and in a more limited manner by radar reflectivity measurements, thereby establishing some important mineralogical characteristics that set limits for plausible meteorite/asteroid materials analogs for the most populous classes^(4,5,6,7). Additional detailed (astrodynamic) data on asteroid size, spin rate, orientation, and surface properties is provided by radar reflection⁽⁸⁾. A brief example of some of the results comparing asteroid composition types with meteorite mineralogy and relating them to mechanical properties is given in table one. From the population of dozens of classified NEA's, the (major types) S:C:M ratio is approximately 7:3:1; while among the hundreds of classified Mainbelt-Asteroids (MBA's) the ratio is approximately 7:5:1⁽⁹⁾.

Asteroids as the source of meteorites is based on the following generally accepted judgments:

1. Petrographic, physical, chemical, and isotopic differences among various meteorite groups imply that at least 80 separate parent bodies are needed to account for the origin and evolution of known meteorites. Characteristics of chondrites, irons, and eucrites imply formation in parent bodies with radii of 100 to 600 km.
2. Orbital and petrographic data of recovered meteorites and high density meteoroids generally rule out the moon, active comets, and extra-solar objects as the source for a significant number of the recovered meteorites. However, there is the possibility Mars may be the source for SNCs; highly shocked shergottites, mildly shocked chassignites, and slightly shocked nakhlites.
3. Only a few of the thousands of recovered Antarctic meteorites are clearly recognizable as lunar in origin.
4. Analogs between asteroid and meteorite reflectance spectra suggest the Earth receives a nonrepresentative sample of meteorites. Complete resolution of the asteroid/meteorite analogs will not be realized until the asteroids are sampled.

In terms of relative abundance among fallen meteorites, the chondrites make up the overwhelming majority of the meteorites with roughly 84% of the total. The achondrites represent about 8%; the iron meteorites represent about 7% with the remaining 1% consisting

**Table 1: Most Abundant Near-Earth Asteroid Composition Types,
Possible Meteorite Analogs, and Mechanical Strength**

I. B, C, F, and G (Primitive and Metamorphic)

Inferred Mineralogical Surface Composition (IMSC): Hydrated silicates and carbon/ organics/ opaques. Low albedo, ~ 2 - 7 %.
Spectral Reflectivity: Neutral, slight blue absorption, and strong UV absorption.

Possible Meteorite Analogs (PMA): Carbonaceous chondrites. CI1-CM2 as well as assemblages produced by aqueous alteration and/or metamorphism of CI/CM precursor materials. Low crushing strength.

II. D and P (Primitive)

IMSC: Carbon/organic rich silicates. Low albedo, ~ 2 - 7 %.
Spectral Reflectivity: Red

PMA: Carbonaceous chondrites. Organic rich, primitive, cosmic dust grains; CI1 - CM2 plus organics; low crushing strength.

III. S (Igneous)

IMSC: Enstatite and/or other iron free silicates.
Spectral Reflectivity: E; High albedo >23 % and appears slightly red but otherwise featureless (no diagnostic spectra). R; Moderate albedo, is very red with a strong infra-red absorption due to pyroxene.

PMA: Enstatite chondrite and enstatite achondrite (E); pyroxene-olivine achondrite (R); moderate structural strength.

IV. M (Igneous)

IMSC: Metal (Fe-Ni) with possible traces of silicates.
Spectral Reflectivity: Neutral, moderate albedo, High radar reflectivity.

PMA: NiFe metal with possible silicate inclusions. Enstatite, NiFe metal, or a combination of both and enstatite chondrites derived from differentiated parent bodies; very strong structurally if metallic.

V. S (Igneous and/or Metamorphic)

IMSC: Olivine, pyroxene, and FeNi metal combined.
Spectral Reflectivity: Moderately high albedo, ~ 7 - 23 %;
Red; absorption band at 0.9 to 1.0 and near 2 microns; Broad absorption band in the blue and UV.

PMA: Ordinary chondrites and/or stony irons; possible parent body of chondrites. Only the extreme metal poor and olivine poor members of the S group have spectra that approach the ordinary chondrites; moderate structural strength if chondritic; strong if stony-iron.

of stony iron meteorites. The proportional representation among the meteorite classes is very different for finds which are heavily weighted toward irons and stony irons because their distinctive metallic characteristics are so different from terrestrial rocks. The observed fall statistics are generally regarded to represent the proportions of meteoroids orbiting in the vicinity of the earth, and this statistic heavily favors the likelihood that most asteroids are stony. However, there are other factors to consider with regard to the probability of an encounter with a large NEO.

In Table 1 the most abundant (not all) asteroid composition types are categorized with meteorite analogs that will have generally the same mechanical and thermal properties. This allows the classification of a meteorite-like NEO to be divided into three structural classes. Based on the inferred mineralogical surface composition (IMSC) and the possible meteorite analogs (PMA) the composition types B, C, D, F, and G as well as D and F are likely to be mechanically (structurally) weak and can be placed in the same category. Similarly, from the IMSC and the PMA we may assume that the E and S have compositions similar to chondrites and achondrites and are somewhat stronger mechanically than the B, C, D, F, G, D, and P types. Continuing this argument, we consider the M type asteroids to be predominantly metallic and structurally resemble metallic meteorites which are mechanically the strongest class, which is apparent from the data in Table 2 and other experimental work^(17,18,19).

Although meteorite-like asteroids may be divided into three structural classes and present a relatively limited range of materials, there is still an extensive range of mechanical and thermal properties on the micro and macroscopic scales caused by inhomogeneities originating from the circumstances of origin and evolution. Most of the data from which the mineralogical properties of asteroids is inferred comes from telescope observations of NEA's which are generally faint and must be observed within a narrow spectral window (figure 1 on the last page) which compares reflectance spectra of minerals, asteroids and meteorites.

Data presented in tables 2, 3, 4, and 5 which describe the mechanical and thermal properties of meteorites is taken from individual samples with relatively homogeneous microstructure, but this is only sometimes the case^(10,11,12,13). However, there are complications and factors to consider in understanding asteroid properties based on meteorite analogs:

1. First is the effect of large scale (more than a cm) inhomogeneities within given microstructural phases.
2. Second is the possibility that totally different phase are in physical and structural contact or fusion, possibly as a result evolution within the same parent body or from collision. One phase masks the other, giving a deceptive spectral analysis, which may yield an incorrect asteroid composition, creating uncertainty in anticipated mechanical and thermal properties.
3. Even if there is an ideal homogeneous microstructural composition, there may have been thermal, radiation, or impact

interactions throughout the history of the asteroid which altered its integrity from an ideal structure.

4. There is the effect of small scale inhomogeneities (less than 1 cm) in the microstructure such as inclusions or grain and phase boundaries. Collectively, these can present either large or small scale discontinuities to a propagating shock wave.
5. The NEO object may not be a contiguous object. It may be composed of meteorite space debris nucleated around a solid object or a swarm of rocks or small silicate and metal grains. The received spectral signal would correspond to integration of the individual spectral components.
6. The NEO object may be a two (contact binary)⁽¹⁴⁾, three, or many-body system composed of relatively large components (on the order of hundreds of m).
7. The NEO may resemble an extinct comet (nucleus), implying a density of around 1 gm/cm³ or even less.
8. ?

Other factors to consider when applying the values in Tables 2,3,4, and 5 to a model is that these measurements of the meteorite properties were most likely performed in terrestrial laboratories, at room temperature and atmospheric pressure. Therefore, it would be desirable to carry out a more extensive and systematic set of measurements of meteorite samples at conditions similar to those found in the region of space between Earth and the asteroid belt. We have already started such an undertaking.

3. Iron (NiFe) Meteorite Analogs

Predominantly iron meteorites (M type analogs) are sometimes relatively easy to detect by radar (reflectivity is enhanced by the metal or stony metal surface). Because of their structure they are probably the most lethal per unit mass to the earth of all the NEA's. Observations indicate that there are currently at least two M type NEA's (1986 DA and 1986 EB)^(15,16) which have a mineralogy identifiable with iron meteorites. Additional M type asteroids are thought to exist in the main belt. These asteroids, which are either partially or completely composed of iron-nickel, are generally thought to be fragments of large cores and/or localized metal reservoirs of differentiated parent asteroids. Their survival, after the outer layers were (presumably) stripped away by collision, demonstrates an ability to withstand a high velocity impact with other asteroid bodies. This is not surprising from detailed studies of their mechanical properties and microstructure. Their survivability is based upon two physical properties; first, the relatively high mechanical strength, especially when Ni enriched (taenite phase) and second, their density (7.8) and hardness which is an impediment to external penetration and the ensuing pulverization mechanisms. For parent asteroids tens of kilometers in size, an additional structural factor is internal (hydrostatic) pressure on the core which can lower the ductile-brittle transition temperature thereby strengthening the core against catastrophic failure. However, the asteroid must be well over 100 km for this effect to be significant.

4. Mechanical Properties of Nickel-Iron MRA's

The great mechanical strength of M type asteroids can either be an important asset or pose a formidable problem to NEO interaction missions whose aim is to modify the orbit. One of the assets of such robust materials is their presumed ability to absorb the large amount of energy (impulsive forces) necessary to undergo the required change in momentum to satisfactorily adjust their orbit. Another advantage is the relatively simple modeling afforded by an ideal iron-nickel surface which is not complicated by several variables associated with a variety of mineralogical components as well as the presence of extensive regolith and/or breccia. Disadvantages in dealing with M type asteroids include resistance to penetrator devices, the presence of a network of inclusions which may introduce faults which can weaken structural properties, and large scale discontinuities (eg. stony-iron mixture). Materials properties and design methods to optimize penetrator device effectiveness for M type asteroids or planetary surfaces will be discussed elsewhere. Also, the high density of M type asteroids indicates a large inertial mass to size ratio which will require a precisely targeted payload delivery system.

Some mechanical properties of iron-nickel meteorites are listed in table 2. These results are based on a limited number of select samples which do not take into account inhomogeneities and other variations in the material properties. In addition, the actual asteroid analog to these meteorite properties may be composed of internal layers or regions of silicate material mixed with the iron nickel phases. Such a structure will present gross mechanical discontinuities to a penetrating projectile or HE. Other surface complications external radiation photo-ablation HE impulsive force are structural discontinuities such as a substantial regolith layer. Ideally, the velocity vector of the asteroid should be changed with a minimum amount of work done on the structure of the asteroid, preserving its structural integrity. An example of the gross mechanical property dependence on microstructure, or in particular the weight % Ni, is the ductile-brittle transition temperature as shown in figure 2. The yield strength for an impact depends on the Ni content. In figure 3, the impact yield energy for the three iron meteorite classes, octahedrite, hexahedrite, and ataxite are plotted as a function of temperature. Other factors, such as the effects of micro-inclusions as a function of temperature are also important and are currently being studied^(16,17,18,19).

Yield Energy for Ataxite, Octahedrite, and Hexahedrite Meteorite Iron as a Function of Temperature

Figure 3

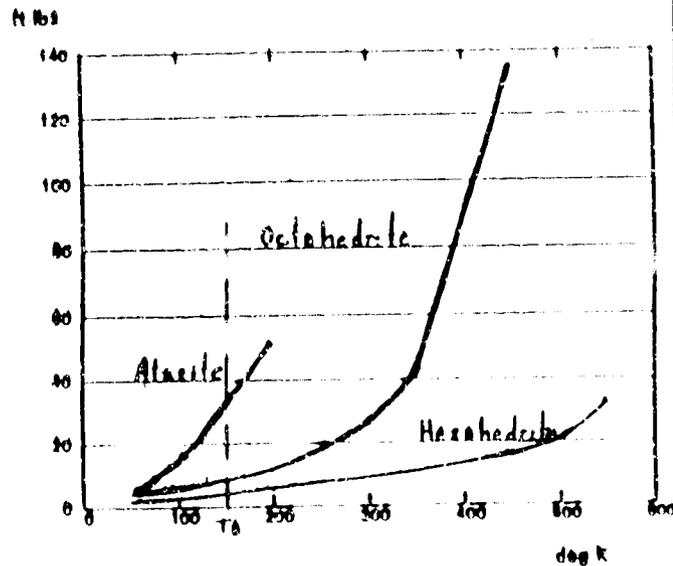


Figure 2

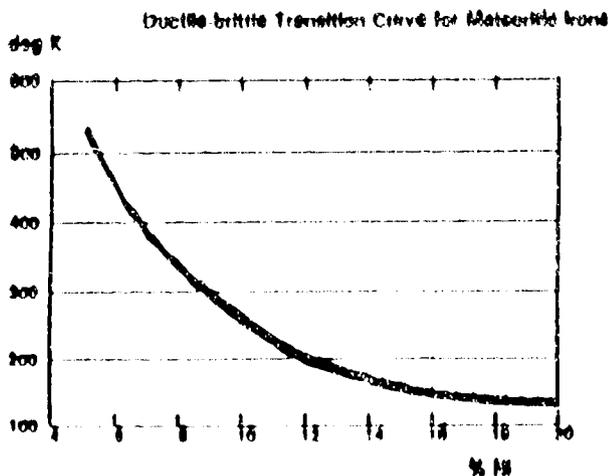


Table 2. Mechanical Properties of Iron Nickel Meteorites

1. Density; Iron Nickel	7.29 - 7.88
Mesosiderites	5.20 - 6.20
Pallasites	4.74
2. Hardness; Brinell, correlated with Ni content-Taenite	90 - 660
	Kamacite 90 - 320
Brinell, hard inclusions (cohenite, troilite, schreibersite, and chromite)	950
Vickers	200-350
3. Tensile strength;	$0.58 - 1.8 \times 10^{10} \text{ d/cm}^2$
4. Young's modulus (tensile)	$2.0 \times 10^{12} \text{ d/cm}^2$
5. Compressive strength;	$1.1 - 3.4 \times 10^{10} \text{ d/cm}^2$
Compressibility; Bulk modulus (all sides compression)	$1.67 \times 10^{12} \text{ d/cm}^2$
6. Surface tension;	1200 d/cm
7. Coefficient of viscosity; 0.026 to 0.019 poises (d s/cm^2)	
molten meteoritic iron;	0.02
at effective temperature of vaporization;	0.01

5. Thermal Properties of Iron-Nickel Meteorites

Modification of the NEO orbit should couple as little energy as possible into thermal modes of melting and vaporization. However, an instantaneous alteration of the asteroid trajectory is likely to require a large amount of energy to be imparted in a very short time. Examples of such heat generating methods include high speed impact by penetrators with or without HE or nuclear devices, external nuclear explosives and the associated X-ray photo-ablation and vaporization, or excavation and vaporization effects associated with surface nuclear detonations. Thermodynamic properties of iron-nickel meteorites are presented in Table three.

Little effort has been directed toward understanding meteorite properties in terms of the technology of materials science, or mining engineering. Characterization of impulsive loading from hypervelocity impact and associated shock, radiative scattering, and thermal cycling effects over a broad temperature range simulating NEO space interception should be carried out and added to the database. Such data can assist in validating computer codes that may be used to simulate complex materials response to arbitrary stress loading and to determine strain levels required for a material to fail either locally or catastrophically.

Table 3: Thermal Properties of Iron - Nickel Meteorites

1. Melting point (with 10% Ni):	1770 K
2. Boiling point:	3580 K
3. Average specific heat:	
a) Solid (0 - 1500 C)	6.91×10^6 erg/g-deg
b) Liquid	6.66×10^6 erg/g-deg
c) Gaseous	$C_p = 3.72 \times 10^6$ erg/g-deg
	$C_v = 2.23 \times 10^6$ erg/g-deg
4. Latent heat of vaporization: 3.72 ev/atom =	6.40×10^{10} erg/g
5. Latent heat of fusion:	2.69×10^9 erg/g
6. Thermal conductivity (deg/cm):	4×10^6 erg/cm ² -s
7. Vapor pressure:	
a) Iron	$\log p = 10.607 - 16120/T$
b) Nickel	$\log p = 10.725 - 16120/T$

6. Suggested Metallic (M) Asteroid Material Properties Research

It is suggested that to address the issues associated with the benign modification of NEO, a systematic and detailed study should be carried out on the iron-nickel and related stony iron meteorite analogs of M type asteroids. From this study, one may be able to determine what is known, what can be extrapolated from similar terrestrial materials, and what research must be carried out to generate critical new data. To generate predictive models on the results of explosive and impulsive interactions with any type of asteroid or comet, we must attempt to understand such mechanical properties;

1. Low strain rate impact properties.
2. High strain rate impact properties.
3. Shock wave propagation and microstructural effects.
4. Effects of inclusions and dislocations on plastic structure and fracture characteristics.
5. Radiation effects in meteoritic and comet-like materials.

Measurements must be carried out on synthetic samples of (extinct?) comet nuclei to determine the distribution of CO₂ and H₂O ice, dust, carbonaceous and other meteorite related minerals. Generally required are accurate values of those thermodynamic properties that will be of assistance in modeling interactions with high energy generated X-rays if nuclear explosives are used.

In addition to the above proposed new work, many of the iron meteorite properties listed in Tables 2 and 3 should be re-calibrated and extended with special emphasis on the effects stony-iron mixtures, inclusions, and other imperfections in the FeNi phases. There are critical gaps in the data base, especially those involving high strain rates, effects of inclusions, shock

wave effects, and high energy x-ray and neutron flux interactions. Some additional experimental work may have to be carried out on the mechanical and thermodynamic properties of iron meteorites if one wishes to accurately model and predict the effects of orbital modifications by the methods discussed in this communications.

7. Stony Asteroids

The physical properties of metallic meteorites are more homogeneous than those of the stony meteorites. The origin of iron-nickel meteorites is generally regarded to have occurred when the liquid metal solidified yielding the important steel alloys kamacite and taenite which have been extensively studied by metallurgists. While meteorite structures of kamacite and taenite differ from steel, they still retain many of the same properties and resemble a manufactured material in uniformity. Stony asteroids on the other hand can be divided into three groups with significantly different physical and chemical properties:

1. Primitive (C, D, and P types): Dominate the outer part of the asteroid belt.
2. Metamorphic (F, G, B, and T) Peak in the central region of the asteroid belt.
3. Igneous (S and E): Common in the inner part of the belt. The metallic (M) asteroids may also be considered in this group, although its materials properties are very different from those of the S and E.

Table 1 categorizes asteroid types based on their VIS-IR spectra and relationship to known meteorite types (analogs). From the point of view of interacting with the asteroid by means of HE and/or penetrator systems, we will regard the asteroids to be further classified into the above three material groups.

Additional complications for the interaction with stony asteroids:

1. They may not be composed of one type of (meteorite analog) material.
2. They may have cracks and fractures or be otherwise degraded which will considerably reduce their structural integrity. This is less likely for the stronger metallic meteorites.
3. They may have extensive regolith or regolith breccia on their surface.

Tables 4 and 5 outline some of the mechanical and thermal properties of stony meteorites. As in the case of the iron meteorites, the values presented are representative of a very limited sampling of ideal specimens and do not take into account inhomogeneities, structural, or chemical variations within a given meteorite class. Also, the conditions under which these measurements were obtained did not properly take into account space conditions associated with asteroid orbits. We are currently designing a series of experiments to more accurately determine these chemical and physical properties.

Table 4: Mechanical Properties of Stony Meteorites

1. Density: Range 2.38 - 3.84
2. Mean atomic weight: 23
3. Porosity: a) micro 2.7 - 3.59 %
b) macro 3.0 - 12.4 %
4. Surface tension: at fusion 400 d/cm
at volatilization 360 d/cm
5. Compressive strength: 0.062 - 3.7 kb.
6. Viscosity: 1.3×10^4 poises at 1400 C.
7. Seismic velocity: chondrites
 - a) Longitudinal 2050 - 4200 km/s
 - b) Transverse 600 - 1220 km/s

Table 5: Thermal Properties of Stony Meteorites

1. Average melting point: 1350 - 1800 K
 - a) Magnesia olivine 1890 C
 - b) Iron olivine 1100
 - c) Magnesia pyroxene 1554
 - d) Ferrosilicate 1100
2. Boiling or dissociation point: 2960 K
3. Average specific heat: solid, 0 - 1200 C ; 8.95×10^6 deg/g-deg
liquid, 1.1×10^7 deg/g-deg
4. Latent heat of fusion (fayalite): 2.65×10^{11} erg/g
5. Latent heat of vaporization (average for meteoritic stone)-from
mean lattice energy: 6.05×10^{10} erg/g
6. Thermal conductivity (at 50 C) : $3.6 - 5.8 \times 10^{-3}$ cal-cm/deg-sec

8. Recommendations

In terms of the mechanical and thermal properties NEO-materials (NEOM) are divided into three meteorite related groups and one comet related group:

NEOM 0: NEO's identified as being similar to what is regarded to resemble extinct comet nuclei are expected to have a very low density $\sim 1.5 \text{ gm/cm}^3$, poor mechanical strength, variable compositions, and variable thermal properties.

NEOM 1: NEO identified as being composed of materials similar to the structurally weakest (friable) meteorites, and resembling the (primitive) asteroid classes; C, D, P, B, F, G, and T. These materials will also have similar thermal characteristics.

NEOM 2: NEO identified as being composed of metamorphic and igneous materials and corresponding to asteroid classes E, R, and S, and have similar thermal properties. This group is stronger than the NEOM 1 group.

NEOM 3: NEO identified as resembling metallic meteorites and corresponding to the M type asteroids. This is the group with the strongest mechanical structure and similar thermal characteristics.

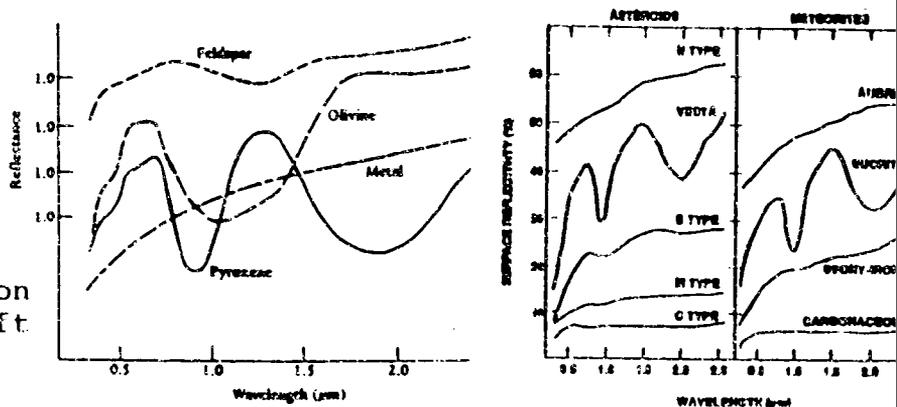
This classification is not ideal and may need revision or expansion. However, this appears to be the simplest starting point. Note that if a NEO object is classified into one of the above categories, it does not necessarily mean that it is homogeneous. Indeed, a NEO might represent fused collision fragments from two or more different type of asteroid-like bodies, thereby leaving a macro-heterogeneous object which falls into two or more of the above groups.

The NEO asteroid mitigation methods mission will take into account interactions with objects from each of the four materials groups which gives the following interactions matrix:

	<u>NEOM0</u>	<u>NEOM1</u>	<u>NEOM2</u>	<u>NEOM3</u>
<u>Surf HE/NE</u>				
<u>Subsurf HE/NE</u>				
<u>Stand-off NE</u>				
<u>Laser</u>				
<u>Kinetic E</u>				
<u>Thruster</u>				
<u>Other</u>				

The interactions matrix elements is meant to describe the interaction of a given material type (NEOM) with an interactive device, and does not take into account such parameters as the size of the object or other gross material characteristics. Therefore, each matrix element in the materials interaction group may have an additional parameter associated with NEO size, thereby giving a three dimensional matrix.

Figure 1: Reflectance spectra for olivine, pyroxene, and iron-nickel metal. Meteoritic material consisting of a mixture of these minerals would have a composite spectrum formed by the weighted integration of these curves. To the left is a comparison of the reflectance spectrum of asteroids and meteorites.



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Report of NEO Interception Workshop: Appendix to Workshop 4

NEO Material Properties

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Detailed information on the possible range of NEO material properties is critical to the successful application of NEO Defense Options, the Systems Analysis evaluation, and the establishment Program/Policy Options. Therefore, a strategy to mitigate the NEO threat must be based on a comprehensive analysis of the NEO material properties and their response to:

- * Buried, surface burst, and stand-off nuclear explosives
- * Kinetic-energy deflection and pulverization
- * Laser deflection
- * Attached thrust deflection methods

The working group report of NEO Interception Workshop 4, "Energy Delivery/Materials Interaction" evaluated the above options. The Materials Properties appendix briefly outlines additional scientific and technical efforts on the likely NEO materials that should be carried out in order to provide the best data possible, given the current uncertainties in knowing the NEO composition. Efforts should be directed towards:

1. The establishment of a high probability property database (HPPD) for the range of NEO compositions and structures based on asteroid/meteorite analogs. The HPPD should provide information on the mechanical and thermal properties as well as atomic compositions. Input to the HPPD will be obtained by means of a series of experiments on a set of meteorites which will serve as analogs to the observed asteroid types from which a portion of the NEO population is likely to have originated. Other laboratory work is necessary to measure basic physical properties of meteorites.
2. Development of detailed modeling of both the macro and micro-structure response to thermal, mechanical, and nuclear radiation alteration as encountered in a NEO response strategy. This modeling should be based on experimentation and simulate the NEO orbital (encounter) environment. The HPPD will be enhanced by such experiments and integrated into the modeling.
3. The HPPD and modeling may be extended to (extinct) comet nuclei.
4. A satellite reconnaissance mission to remotely sample one or more NEO objects should be carried out to test the model analogs.

We have already started to conduct research in the first two categories.

Some Notes on Terrestrial Blasting Design and NEO Interception

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These notes result from experience in terrestrial blasting practice. They are very qualitative, like terrestrial practice which is dominated by trial and error.

The design of rock fragmentation with conventional explosives as terrestrially practiced is controlled by two broad considerations: powder factor and blast geometry.

Powder factor is the amount of energy (commonly measured as mass) of explosive required to fragment a unit mass of rock. Geometry determines how the energy is delivered in space and time. Geometry has a profound influence on powder factor.

These considerations have implications for deflecting and fragmenting asteroids. While unconventional point sources are obviously orders of magnitude higher in energy than conventional chemical explosives, there will be similarities in application.

Previous workshops have already incorporated the concept of powder factor into the problem definition, although defined in different terms.

POWDER FACTOR

The basic measure of explosive application is powder factor: the amount of blasting agent required to fragment a unit mass of rock. It is, more properly, the amount of energy delivered to a unit mass of rock (Morehard, 1987).

A common conventional powder factor measure is kg/t. To fragment hard crystalline rock (e.g. basalt) into pieces smaller than several meters requires a factor of about 0.05 to 0.5 kg/t. Making several gross assumptions, a million t asteroid would need 50 to 500 t of conventional chemical agent or equivalent unconventional agent.

Even if this overly simplified analysis would work, it says nothing about the geometry of application. Powder factor tells how much explosive energy should be delivered, geometry tells how that energy should be delivered.

It is interesting to note that powder factor as used in mining is largely an economic measure. Since explosives cost money, a great effort is made to reduce it and still maintain the required degree of fragmentation.

BLAST GEOMETRY

In terrestrial blasting, poorly applied explosive energy can result in uncontrolled fragmentation, which is particularly undesirable in NEO interception. At least as bad is using more sources than necessary because of poor application geometry.

Efficient blasting results from well designed blast geometry. There are two related geometries to be discussed: space and time. Both are the result of the concept of free face.

FREE FACE

The most important design factor in terrestrial explosives is the free face, which is a rock face at some distance from the explosive source (Figure 1). In reflection theory, the explosive charge initiates a compression wave. The wave hits and is reflected from the face, in tension. The wave action causes fragmentation at the free face. Other theories such as gas expansion, flexural rupture, nuclei, etc., still require a free face (Morehard, 1987; Langefors and Kihlstrom, 1978).

Consider two conditions without free face: If the source is too deep, the shock wave is dissipated before it can transfer energy to fragmentation at the free face. If the source is outside the rock mass, little energy is transferred to the rock.

Fragmentation, conventional or otherwise, requires a free face. This necessity controls the geometry of the sources both in space and time.

OPTIMAL ENERGY PLACEMENT: DELIVERY in SPACE and TIME

The ubiquitous terrestrial method used to place explosives in rock is to drill holes in the rock and load the holes with the blasting agent (Figure 2). Each hole with its explosive is designed to break a cylindrical column of rock. While a drill emplacement for NEO is very unlikely, a look at mining practice should be illustrative.

A single point source is almost always not a desirable fragmentation geometry. In general, fragmentation is improved by diffusing the explosive throughout the rock mass as much as practical. However, diffusion is probably more of a consideration for low energy conventional chemical agents compared to high energy unconventional ones.

Terrestrial drill hole placement is defined by burden, spacing, hole depth, explosive energy, and rock strength (Figure 2). The holes are placed so that over time each hole fragments rock using the same locally optimum powder factor. Rock strength combined with hole spacing, burden, and depth define the volume of breakable rock. Explosive energy and the rate of application of that energy are controlled by the type of explosive.

In Figure 2, the drill holes are designed to be fired sequentially in order to have each one break to a free face. The exact pattern may vary, e.g. one hole at a time or each row at once. The timing may also be varied in order to cause interaction of the explosive columns; one fast firing method detonates a hole when the shock wave from its predecessor arrives. Within the free face principle, there are many variations on firing methods.

Rock strength is an extremely difficult variable to quantify, yet it has the most influence on charge placement. The stronger the rock, the higher the powder factor. But cracks or faults profoundly change the fabric of the rock strength and can direct the energy in unwanted ways, causing uncontrolled fragmentation and energy waste.

As a minimum, the effect of very powerful point sources within large rock masses is unknown. The geometry of explosive application is an important question. To fragment a body, it may be far more effective to apply 100 hits of 100 kt than to apply one hit of 10 Mt.

Deflections using mass ejected from the object raise the same questions. A series of smaller ejections could possibly outperform one large one, while maintaining better control over the object.

Deflection with stand-off shots may also be improved with point source arrays. To ensure no rogue fragments hit the earth, a stand-off plane of point sources may give better odds against uncontrolled break-up than a large single source.

SHAPED CHARGES and ARRAYS

The concept of shaped charges is not new, but the concept of shaped arrays is. A shaped charge directs energy through the geometry of the blast. An early application was the anti-tank rocket (bazooka) that employed a forward focused parabolic shape to direct energy toward the tank armor.

It should be possible to direct the energy with an array of unconventional sources to enhance both deflection and fragmentation. In deflection for example, a shaped array could ensure that a rogue fragment, in the case of an uncontrolled break-up, will still be deflected away. Similarly, several fragmentation scenarios may be more tractable with shaped arrays.

SOME IMPLICATIONS for NEOs and UNCONVENTIONAL SOURCES

Object Rotation: The whole notion of delivery in space and time is contradicted by rotating objects. Almost all NEOs rotate. How are point source arrays delivered to a rotating object?

Flying Gravel Pits and Other Nasty Surprises: It was established at workshop 4 that some NEOs are completely unconsolidated. What else is out there? How to deliver energy to such a body has not been considered. In the terrestrial excavation business, the one major unknown, the source of all problems, is the rock itself. Given a six month warning scenario, a quickly delivered and gross over-kill is the only solution.

The need for over-kill increases as the size of the body increases. Large bodies are far more destructive, mechanically less predictable, need far more energy application, and need, consequently, far more overkill.

Timing and Fratricide: Point sources delivered in time need to be far enough apart to prevent fratricide of the sources. In the scale of space, the equivalent of a five second terrestrial blasting round may last days.

Available Point Source Inventory: The available size distribution inventory may dictate the point source array delivery design. Are there other implications of the available inventory?

Critical Size: There is an asteroid size threshold where a single point source will sufficiently fragment the NEO. For NEOs larger than this critical size, the blast design is critical.

CONCLUSIONS

Terrestrial experience tells us that, geometrically, large single point explosions will probably be less useful than smaller multiple patterned blasts. Our thinking should include arrays of point sources.

Similarly, the number of devices and their total effective energy transfer will depend heavily on delivery geometry. Good point source delivery geometry will lower the number necessary. The time to begin the design of the delivery geometry is now.

Uncontrolled fragmentation, either during a deflection or a fragmentation attempt, is the least desirable result of the attempt. Blast design for either case must have the ability to counteract it.

Probably, the best defense is highly reasoned and well designed overkill.

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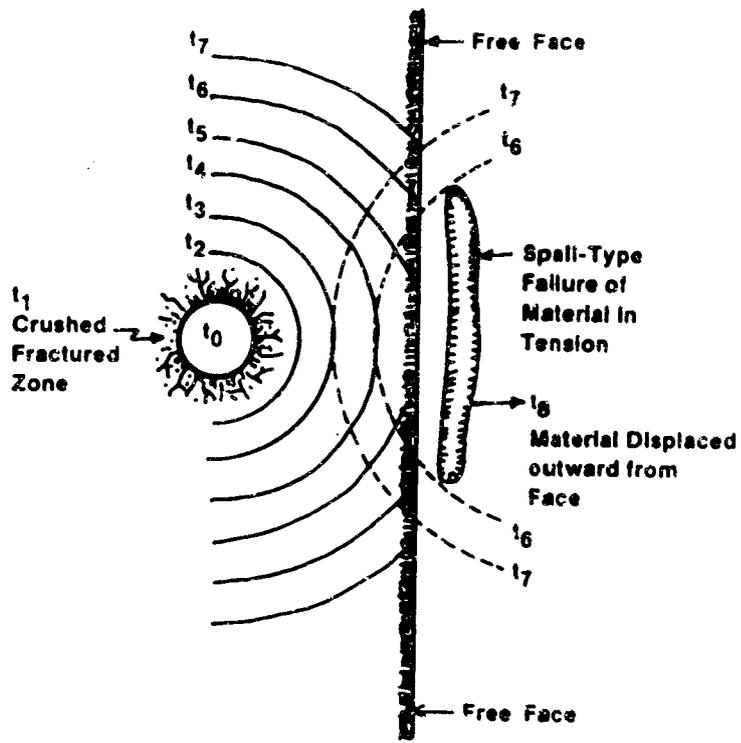
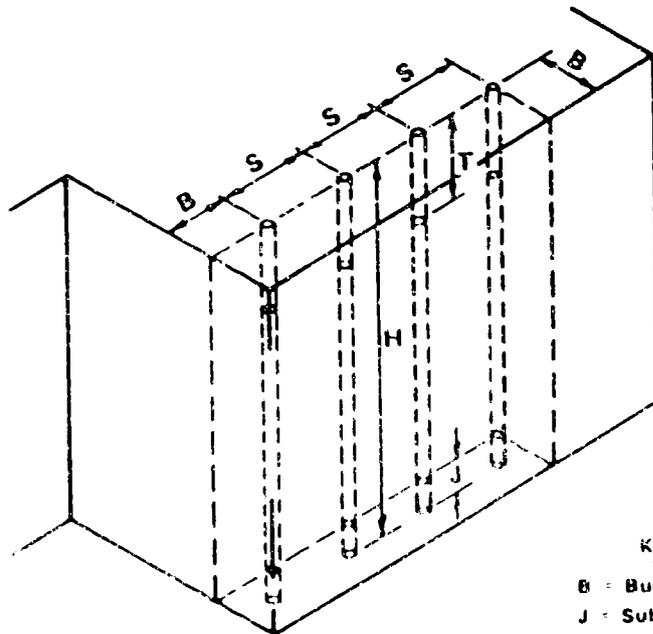


FIGURE 1.



- KEY
- B = Burden
 - J = Subdrilling
 - T = Stemming
 - S = Spacing
 - H = Hole Depth

FIGURE 2.

Penetrator Device Applications and NEO Materials Properties

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Abstract: Penetrator devices (PD) represent a robust technology that may play a key role in NEO (or planetary probe) diagnostics missions, initial NEO orbital adjustments, and dispersing secondary threats originating from NEO fragments. The advantage of PDs is location of the payload within the NEO body and thereby optimizing coupling for analysis, momentum transfer, or pulverization. The major disadvantage of some PDs is large mass, especially uranium alloy penetrator cores, which can reduce the NE or HE payload. Metallurgical properties of uranium alloy penetrator are discussed and some design requirements to facilitate the NEO interception mission are addressed.

1. Introduction

Penetrator devices (PD) may play a key role in modifying the NEO-orbit by directly imparting momentum with or without a high energy (HE) or nuclear energy (NE) explosive payload, depending on the size, density, mechanical structure, and the amount of orbital change or pulverization desired. The PD can also be used as a NEO or planetary and satellite probe in general. HE and NE payloads are generally available and lend themselves to integration with the penetrator system. The mission criteria for the penetrator will likely require a design configuration based on a high strength alloy and/or a depleted uranium alloy core or component with a hard tip or insert to maintain structural integrity to facilitate the optimum depth penetration by the (payload) inertial mass into the NEO target. Designs not requiring a large inertial mass and the associated weight penalty are more desirable. Whatever the eventual design configuration, the ultimate goal is to achieve the optimal depth penetration into the target in order to maximize the momentum coupling and explosive yield directly to the NEO the NEO.

Advantages and factors to take into consideration with respect to the use of a PD include:

1. If there is a thick regolith and/or breccia like surface layer which must be penetrated to deliver the HE or NE payload to the main NEO body. The PD must be protected as much as possible against deformation and fragmentation during the initial impact, even at high velocity (order of 1 or 2 km/s) by recessing the tip and sheathing the (payload) core. The specific design options should be influenced by the range of NEO target materials and structure.
2. The amount of momentum transferred to the NEO target will depend on the depth at which the HE or NE payload is detonated and the structural integrity. Again, this will be a function of the NEO material density, mechanical structure, and HE or NE yield.

3. If the purpose of the mission is to pulverize the NEO, the PD should embed itself to optimize fragmentation and crater size. This implies that the burial should be as near to the center of mass as possible and still allow the shock wave to be reflected from the free face in tension. The pulverization interaction can take place during the primary NEO interaction with the use of HE or can be used to neutralize secondary fragments from the original NEO mass. The secondary interaction may rely only on kinetic energy to neutralize the fragments.
4. The PD may be able to overcome the barriers presented to HE or NE emplacement by penetrating through regolith and outer strata to achieve optimal emplacement for momentum transfer and/or pulverization. Optimal application requires a knowledge of the mechanical, geological, and dynamic properties of the NEO.

2. Depleted Uranium Alloy Systems

There has been an extensive amount of full scale testing and engineering design to penetrate metal targets (armor) and a range of penetration depths as a function of velocity, mass, aspect ratio, and tip configuration. Much data is available and can be applied to the NEO problem. For instance, depleted uranium alloy penetrator cores (PC's) have been extensively tested and used for numerous missions. Several robust configurations of penetrator cores are available with excellent aspect ratios for deep penetration while delivering a high energy HE or NE payload at a rapid spin rate and under extreme g (acceleration) levels.

- a. PC technology can be adapted to be used with a high speed rocket payload for use in either an (instrumented) diagnostic or payload supporting interactions mission.
- b. HE or NE payloads for PC's are standardized and readily available for NEO missions with a variety of equivalent TNT yields.
- c. Currently available combined penetrator core and HE configurations can penetrate 50 meters into tuff and several meters into hard rock.
- d. With modification PC technology can be adapted for use with a variety NEO class objects.

However, depleted uranium alloy may not be the best choice for all three of the possible PD missions.

3. Some Metallurgical Issues

A review of the literature indicates there are some metallurgical issues that must be addressed if the PC technology is to be applied in the space environment and perform at temperatures as low as 150 to 200 K. A primary concern regarding the utilization of penetrator cores with or without HE or NE payloads for the asteroid intercept mission is the ductile-brittle transition temperature of depleted uranium alloy, such as U-0.8 wt% Ti, which exhibits a ductile to brittle transition at about 243 K^(1,2,3). It has been demonstrated that tensile ductility of polycrystalline uranium decreases rapidly with decreasing temperatures < .25 T_m (306 K). The ultimate tensile strength also decreases with decrease in temperature in this range.

the impact energy vs temperature for U-0.8 wt% Ti is shown in figure 1. The anticipated asteroid temperature range at impact is (shaded) is below 50 C. The fracture of uranium alloys versus that of iron-nickel meteorites shown in figure 2 where the Charpy impact energy as a function of temperature is plotted on the same graph as the Charpy impact energies for three crystalline classes (function of wt% Ni) of iron nickel meteorite. The PD yield strength does not compare favorably to the iron at these low temperatures. This indicates that unless precautions are taken, the PD will fracture in a brittle manner upon impact with the NEO.

Other metallurgical factors that are of concern which will enter into the model (depending on the mission) include the plastic flow and strength of the uranium alloy, and fracture characteristics. Since the strength of uranium and its alloys as well as other candidates for the penetrator device are influenced by the crystal structure as well as the point, planar, and volume defects, the temperature and strain rate influence the various strengthening mechanisms in different ways. Some strengthening mechanisms to consider for PD's in general include:

1. Textural, strain, and solid solution hardening
2. Intermediate and high temperature hardening $> .35 T_m$, where $T_m = 1225$ K is the absolute melting temperature of alpha uranium.
3. Grain and subgrain boundary hardening.
4. Precipitation and dispersion hardening.
5. Superplasticity of uranium and its alloys.
6. Utilization of composite materials.
7. Low temperature ductility.

4. Recommendations for Penetrator Technology

Table 1 shows the ductile-brittle transition characteristics of U-0.75 wt% Ti penetrator cores. This data indicates that the impact energy required to cause fracture is a function of temperature, being extremely brittle at -54 C. To effectively carry out the NEO-Asteroid mission, this brittle behavior must be suppressed before impact. The impact energy required to cause fracture appeared to be insensitive to microstructural and hardness variations. Therefore, modifications to the penetrator core design should be analysed principally to overcome the effects of the high ductile-to-brittle transition temperature. A possible solution is the complete heating of the PC to at least 300 C prior to NEO impact.

<u>T °K</u>	<u>Average Impact Energy (J)</u>
219	3.3
296	5.0
347	6.4
373	6.5
473	12.7
500	18.3

Table 1: Ductile to brittle transition of U-0.75 wt% Ti
2 Penetrator Cores

5. Summary

An optimally buried NE will eject a considerably larger amount of mass from a crater and thereby provide the opportunity to optimize the momentum coupling effect necessary to adjust the NEO orbit which cannot be achieved with either a surface or stand-off NE. Also, the penetrator device may overcome boundary discontinuities of the NEO such as regolith layering or other inhomogeneous effects. Information regarding these inhomogeneities and other physical characteristics may be obtained from a precursor penetrator mission which can provide diagnostic information on NEO geology, macrostructure, and other dynamic characteristics. Another advantage of the penetrator with a NE payload is the ability to provide a highly efficient destruction of the original NEO or one of the larger fragments by pulverization, if that is deemed necessary. The penetrator may be able to place the NE close to the center of mass and interact with as much material as possible.

A drawback of the PD is the large increase in mass to the interceptor payload that might otherwise be used to transport NE. This is especially serious in the case of the U alloy PC which also have the added problem of brittleness at temperatures typical of NEO orbits. On the other hand, if a lightweight terrain penetrator can be developed that is ductile in the NEO orbital interaction environment, the NEO penetrator device may provide an optimal solution for orbital adjustment, pulverization, or a diagnostic interception.

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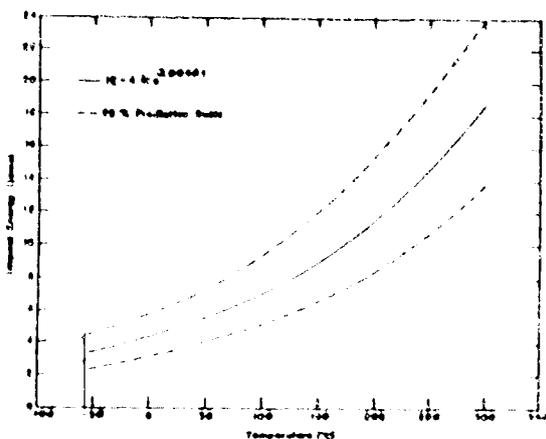


Fig 1
Impact energy vs temperature for U-0.75 wt% Ti penetrators.

From "Fracture of Uranium Alloys," Harry J. Saxton, Sandia Laboratories, Livermore, California, and John L. Remo, unpublished and published data.

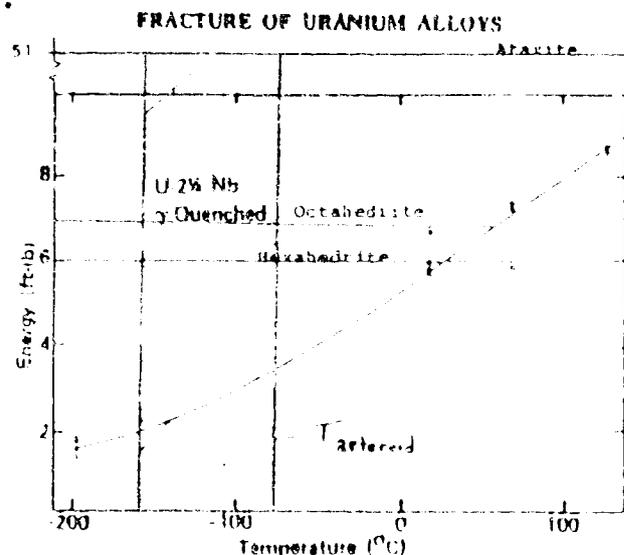


Figure 2. Charpy Impact energy as a function of temperature for quenched U-2 1/4 Nb alloy. Initial impact velocity is 170 in/s. Based upon the author's unpublished results. Hexahedrite data is for Charpy impacts at 200°K.

NEO Interaction with X-Ray and Neutron Radiation

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INTRODUCTION

One potential approach to dealing with a large near-Earth-object (NEO'S) on a collision course with the Earth¹ is to attempt to alter their orbits by means of radiation induced momentum transfer produced by the surface blow-off from stand-off nuclear bursts. This effect will depend primarily on the NEO composition via the atomic cross-sections and is therefore particularly advantageous in mitigating uncertainties associated with the observational characterization of NEO'S. Reflection spectra and radar reflectivity data at best provide limited information on material composition, and current information on material compositions makes it difficult to establish meteorite/asteroid analogs. Another advantage of using nuclear irradiation to deliver the specific impulse is that it could first be used to provide a diagnostic of the NEO size and composition and then subsequently be used via a sequence of repetitive interactions to impart precision orbital adjustments to the NEO. At each step in the nuclear burst sequence the NEO surface will be "fire-polished" thereby setting the stage for a penetrator device or surface detonation if it should appear desirable. The blow-off and "fire-polish" can also mitigate other physical characteristics such as regolith layers, past fragmentation history, shape, center of mass, and structural integrity, which present various levels of uncertainty to a surface nuclear explosion or penetration device.

It is therefore reasonable to suggest that nuclear irradiation in the form of X-rays and neutrons will provide, via ablation induced momentum transfer, a means to adjust the NEO orbit sequentially. The interaction cross-sections will vary between those appropriate to silicate and metallic (FeNi) values with a density range from 2 to 7.8 gm/cm³. However, if the NEO resembles an extinct comet head the density may be 1 gm/cm³ or less and the use of stand-off nuclear irradiation may be problematical. The NEO is expected to range in size up to several kilometers.

We present below some order of magnitude estimates to help evaluate this concept. The estimates are intended to provide a guide to the problem and are not to be considered a substitute for more elaborate computer simulations.

ANALYSIS

The specific impulse (momentum per unit area), I , imparted by ablation due to x-ray or neutron absorption is found by integrating the differential relationship:

$$(1) \quad dI = \rho v dx$$

where

$$(2) \quad v^2 / 2 = \epsilon - \epsilon_v$$

ρ is the density, ϵ and ϵ_v are the incident energy per unit mass and vaporization energy per unit mass respectively, and dx is the radial differential to the NEO surface. ϵ is related to the fluence F , and the opacity, μ , by

$$(3) \quad \epsilon = \mu F$$

Therefore:

$$(4) \quad I = \sqrt{2} \int_0^{x_v} (\mu F - \epsilon_v)^{1/2} \rho dx$$

Additionally, it is assumed that the fluence varies with the penetration depth according to

$$(5) \quad F = F_0 \exp(-\rho \mu x / \cos \theta)$$

where $\theta = 0$ is normal to the surface

For simplicity we take the obliquity factor to be unity and ignore the temperature variation of the opacity.

Using the scaled variables

$$(6) \quad \begin{aligned} I &= (\sqrt{\epsilon_v} / \mu) I^* \\ F_0 &= F_0 / F_{min} \\ F_{min} &= \epsilon_v / \mu \end{aligned}$$

The evaporation depth, X_v in the integral is given by:

$$(7) \quad X_v = (1/\rho\mu) \ln F_0'$$

With this form, the integral can be readily evaluated:

$$(8) \quad I' = 2\sqrt{2} \{ \sqrt{F_0' - 1} - \tan^{-1}[\sqrt{F_0' - 1}] \}$$

which should be compared to the result quoted in the APS study², re-expressed in the same non-dimensional quantities as above

$$(9) \quad I'_{APS} = \sqrt{2(F_0' - 1) \ln F_0'}$$

If, instead of an exponentially decreasing absorption, one used a constant absorption model up to X_v and zero thereafter, the above calculation gives

$$(10) \quad I' = \sqrt{2(F_0' - 1)}$$

These and other similar models also have been discussed by Lawrence³. In the asymptotic regime, $F_0' \gg 1$, and, using Equation 6

$$(11) \quad \begin{array}{ll} I = 2\sqrt{2F_0' / \mu} & \text{exponential absorption} \\ = \sqrt{2F_0' / \mu} & \text{constant absorption} \\ = \sqrt{2(F_0' / \mu) \ln F_0'} & \text{APS form} \end{array}$$

It is seen that the results are relatively insensitive to the model used, and even to approximations.

I is usually measured in taps (gm/cm-sec).

Assuming a nuclear device with its entire yield in x-rays or neutrons explodes at a distance L from the NEO's surface, the resulting fluence is

$$(12) \quad F_0' = Y/L^2 = 4.2 \times 10^5 (Y/L^2) \quad \text{J/cm}^2$$

where the yield, Y , is expressed in MT and L in km. If τ denotes the "burn-time" of the explosion then the intensity, I , is, with τ in units of 10ns ,
 $I = 4.2 \times 10^{13} (Y / L^2 \tau) W / \text{cm}^2$.

X-RAY FLUX

We first will apply the above to ablation by x-rays. Typically for 1 keV x-rays the opacities lie in the range

$$(13) \quad 10^3 \leq \mu \leq 10^4 \quad \text{cm}^2 / \text{gm}$$

and the vaporization energy:

$$(14) \quad 10^3 \leq \epsilon_v \leq 10^4 \quad \text{J/gm}$$

so that

$$10^{-1} \leq F_{\text{min}} \leq 10 \quad \text{J} / \text{cm}^2$$

For example with a 1 MT yield exploded at a distance of 1 km and taking $\mu = 10^4 \text{ cm}^2 / \text{gm}$ and $\epsilon_v = 10^4 \text{ J/gm}$, $F_0 = 4.2 \times 10^6$, and $I = 5.8 \times 10^4 \text{ taps}$, assuming exponential absorption of the x-rays.

Let us compare this baseline result to some specific materials. For silica, using mass averages of the tabulated data, $I = 1.3 \times 10^6 \text{ taps}$ at 1 keV and an order of magnitude higher at 10 keV. For iron, $I = 6.5 \times 10^4 \text{ taps}$ at 1 keV and $I = 4.7 \times 10^5 \text{ taps}$ for 10 keV x-rays. We see the sensitivity to the spectrum of x-rays irradiating the NEO.

We can also make contact with studies of x-ray driven ablation in the context of the inertial confinement fusion (ICF) program. This can be done by using the results of Murakami and Meyer-ter-Vehn⁴ for the mass ablation due to soft x-ray absorption:

$$(15) \quad m_a \propto I^{0.86} \text{ mgm} / \text{cm}^2$$

and the ablation pressure

$$(16) \quad P_a \text{ (Mbar)} = 40 I^{0.82} / t^{0.10}$$

In the above, time is measured in units of 10ns and the intensity in units of 10^{14} W / cm^2 . The specific impulse is related to the ablation velocity, v_a , and the ablated mass by:

$$(17) \quad I = m_a v_a$$

The ablation velocity is related in turn to the ablation pressure and mass ablation rate by:

$$(18) \quad v_a = P_a / (dm_a / dt)$$

Combining Eqns. (15)-(18) results in an expression for the specific impulse:

$$(19) \quad I = [m_a / (dm_a / dt)] P_a$$

$$(20) \quad I \cong 4.7 \times 10^5 I^{0.82} t^{0.9} \text{ taps} \\ \approx 2.3 \times 10^5 \text{ taps for a 1 MT burst at 1 km.}$$

The simulations on which the above results are based used a 20 frequency group Planckian spectrum, tabulated equations of state (SESAME) and tabulated opacities assuming LTE (local thermodynamic equilibrium). The radiation temperature corresponded to the absorbed flux.

It should be noted that if the x-ray intensity is too high, a supersonic heating wave rather than an ablative heating wave may result. The breakpoint is in the region of $10^{13} - 10^{14} \text{ W / cm}^2$.

Estimates based on these order of magnitude calculations or numerical simulations require more detailed knowledge of the composition, opacities, and equations of state for typical NEOS as well as the correct spectral profile of the x-radiation.

NEUTRON IRRADIATION

We now consider the effect of an intense flux of ~14Mev neutrons. The neutron cross section, σ , is about a barn for all elements of interest hence the mean free path, $l = (1/N\sigma)$, is, assuming an average solid density, $N = 5 \times 10^{22} \text{ cm}^{-3}$, $l = 20 \text{ cm}$, or

an opacity, $\mu = 0.01 \text{ cm}^2 / \text{ gm}$, on using an average density of $5 \text{ gm} / \text{ cm}^3$. Again using a vaporization energy of $10,000 \text{ J/gm}$, we see that $F^* < 1$ for $Y=1 \text{ MT}$ and $L=1 \text{ km}$. Putting in the exact numbers for iron, which is worst case from this point of view, $F^* = 0.7$, hence for neutrons, due to their deeper penetration depth, the fluence must be increased, for example, using $Y=10 \text{ MT}$, $L=0.5 \text{ km}$, we have for iron using the above expressions, $I = 2.6 \times 10^8$ taps (exponential deposition) and $I = 1.8 \times 10^8$ taps (uniform deposition).

DISCUSSION

What specific impulse is required to deflect the NEO? This depends on its size and orbital parameters. The required velocity change, Δv , has been calculated for a variety of Earth-crossing asteroids in the Snowmass report⁵ and range from centimeters to hundreds of centimeters per second. The specific impulse can be estimated from the expression:

$$(21) \quad I = m \Delta v$$

where m is the areal mass density of the asteroid, $m \sim \rho (R/3)$ where R is the asteroid radius. For $\rho = 5 \text{ gm} / \text{ cm}^3$,

$$(22) \quad 2 \times 10^4 \leq m \leq 2 \times 10^5 \text{ gm} / \text{ cm}^2$$

where the lower and upper bounds correspond to $R=100 \text{ m}$ and $R=1 \text{ km}$ respectively. For velocity increments in the range

$$1 < \Delta v < 200 \text{ cm/sec}$$

the necessary specific impulse to produce such deflection velocities lies within the range:

$$2 \times 10^4 \leq I \leq 4 \times 10^9 \text{ taps (R=100 m)}$$

$$2 \times 10^5 \leq I \leq 4 \times 10^7 \text{ taps (R=1 km)}$$

We see that by a judicious combination of x-rays and neutrons from a thermonuclear device one should be able to achieve the desired Δv 's. The time delay between the time of arrival of the x-rays and the neutrons is around $15-16 \mu \text{ sec/km}$ yielding a 2-stage specific impulse. Since even with a neutron enhanced device there

will be copious x-rays the effect of the transient x-ray precursor needs more study. With lower yields than those required to deflect, one could "fire polish" and prepare the surface, by removing surface regolith, for subsequent penetration devices. The blow-off vapor also could be analyzed to help deduce the composition of an asteroid. In any event the above simple considerations indicate that more complete simulations are worth making in order to better quantify the conclusions.

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Near Earth Object (NEO) Orbit Management by
Explosive Impulse Thrusters

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Abstract The non-catastrophic NEO-Asteroid orbital management by explosive impulse thrusters such as a penetrator device with a HE or NE payload is considered. Computations estimating the amount of energy required to achieve desired orbital adjustment (velocity change) for asteroid radii from 10 m to 10 km and densities from 2200 to 8000 kg/m³ are carried out for the case where the asteroid orbital velocity is 30 km/s. Computational results are presented from three independent analytic methods; Crater Ejection Characteristics (CEC), 2) Kinetic Energy Transfer (KET), and 3) Impulsive Momentum Transfer (IMT). Range of validity and limitations of each method are discussed with special emphasis on how the inferred material properties data from meteorite/asteroid analogs of the NEO affect the mechanical properties. Within the defined ranges of validity, the three independent computational methods are found to yield consistent results. These computations can serve as a basis for more detailed analysis utilizing the equations of state for the three phases associated either HE or NE explosions; the coupling, hydrodynamic, and non-hydrodynamic regimes.

1. Introduction

To safely deal with a massive (10^6 kg or more) near-earth object (NEO) whose orbit brings it on a probable collision courses with Earth, it is necessary to either pulverize it into harmless fragments of much smaller size, which upon entry into the Earth's atmosphere are likely to be consumed by ablation, or adjust its orbit sufficiently that there is no longer a threat to the Earth. It is the purpose of this communication to describe a means of achieving the latter through the use of an impulsive force generated by explosive charges detonated below the surface of the NEO within a borehole or crater formed by a penetrator vehicle. The total thrust levels required to successfully alter the NEO (asteroid) orbit may be achieved by carrying out one or more high energy explosive (HE) or nuclear explosive (NE) events. Since the encounter velocity could range from one to several km/s, a wide range of penetration phenomena will be confronted. At very high velocity encounters it may also be necessary to consider, depending on the mass of the NEO, the initial transfer of kinetic

energy in addition to the explosive thrust of the HE or NE payload yield. However, it our purpose to concentrate on the dynamics of a penetrator device (PD) delivering a HE or NE payload to a depth within the NEO body and estimating the momentum transfer to the NEO from the buried HE or NE. From the beginning, we realize that these results will strongly depend on both the mass and material properties of the NEO, the penetration depth and the yield of the explosive device. Our approach is analytical, using methods similar to those of Sedov⁽¹⁾ and Zeldovich and Raizer⁽²⁾. Crater scales have been adopted from Teller et al.⁽³⁾

2. The Dynamics of the Problem

There are several possible approaches to NEO asteroid orbital management which will leave the main asteroid mass intact and non-threatening to the Earth. Examples of such methods include

- * X-ray (nuclear) generated surface material blow-off.
- * Very high energy laser radiation pressure or photo-ablation.
- * Stand-off or high energy surface explosions with HE or NE.
- * Very high velocity PD's.
- * Thruster devices.
- * PD's with HE or NE sub-surface detonation.

While the above approaches to NEO (asteroid) orbital management have both advantages and disadvantages, any approach will strongly depend on the range of material and physical properties of the NEO including densities, structures, chemical composition, mixtures, as well as regolith associations which will allow little "a priori" certainty. Given the uncertainties we choose the last method, PDs with a HE or NE payload and compute momentum coupling within the constraints of current technology and the level of uncertainty that is likely to be encountered by the internal and external structure of the NEO⁽⁴⁾. This approach which enhances momentum coupling allows a latitude of response and may mitigate risks associated with asteroid identification and surface characterizations that can complicate the application of other methods. Furthermore, this approach has the desirable feature, through repetitive application of highly reliable and robust modular units (see Penetrator Materials Properties), of providing a means to control the asteroid orbit in a predictable way that may present the optional capability of capturing NEO's into an Earth or Moon orbit for utilization as a resource. We present an initial set of computational results based on the application of HE or NE with PDs.

The dynamic problem involves a PD vehicle which can penetrate a predetermined distance into the body of a NEO (asteroid), at which point a HE or NE is detonated. The high pressures and temperatures at the burst depth are communicated to the solid material around the crater. Some high velocity gas will vent back through the penetrator bore hole, followed by a massive ejection of molten and fragmented target material. The ejecta momentum from the accelerated escaping gas will provide an impulse to the NEO to perturb its motion into the desired orbit. The absence of an

atmosphere makes it preferable that the explosive release of energy be carried out below the surface while the reduced gravity relegates the lithostatic pressure field to a diminished level of importance. The two factors of atmospheric and gravity effects are generally of importance for planetary scale impact or explosion events which are the source of most present data.

3. Composition of the NEO (Asteroid) Material

The nature of the NEO-asteroid material, its strength and thermodynamic characteristics⁽⁴⁾, are, as in planetary studies, of considerable significance in determining the performance of the penetrator/thruster HE/NE system. An additional factor is the relatively small mass of the asteroids which will limit the amount of impact energy and HE that can be used to adjust its orbit. This is especially true for NEO objects that do not fit our idealized preconceptions, i.e. burnt out comet heads, rock collections, etc. Composition of the NEO-Asteroids, based on laboratory analysis of meteorites, may range from relatively soft and friable carbonaceous objects (density 2200 kg/m^3), to stronger stony objects (density 3500 kg/m^3), and to very hard and structurally strong iron-nickel bodies (density 8000 kg/m^3). Comet material is thought to have a density of about 1000 kg/m^3 but may be 50% more or less. Such an object presents problems particular to the application of PD technology. There is less dispersion in the heat of vaporization for the different types of asteroid which, based on meteorite analogs, will vary from 6×10^{10} ergs/gm for stony meteorites to 6.4×10^{10} erg/gm for the iron meteorites⁽⁵⁾.

It is possible that the NEO asteroid encountered may be composed of two or more meteorite types (eg. stony-iron) or may be coated with massive regolith. Such large scale inhomogeneities or surface irregularities are likely to cause coupling problems to the bulk of the NEO mass from stand-off HE or NE. However, a thrust penetrator, if embedded deeply enough, may overcome this problem.

While only the larger NEO-Asteroid bodies, (radius = 1 km with mass 12.6 to 33.5×10^{12} kg) pose a serious global threat to the earth, smaller iron-nickel meteorites can pose a serious local threat. A 1 km crater, Meteor Crater, Arizona, is considered to have been caused by an iron-nickel object (meteorite) about 50 m in size⁽⁶⁾.

4. Energy Requirements for Orbital Management

The mechanical and thermodynamic properties of the asteroid will affect the penetrator design characteristics if we wish to ensure appropriate crater depth and shape without producing undesired large scale fragmentation of NEO asteroid fragments. The mass of the asteroid will determine the amount of energy required to adjust the orbit. However, the amount of energy carried by each payload in the delivery sequence will depend on the inferred structural characteristics so that a catastrophic failure of the entire mass can be avoided while still achieving the orbital adjustment goals.

The targeting of a penetrator with a HE payload must be accurately achieved in order to minimize spinning and/or chipping which will not only affect the orbital adjustment but also create difficulties for additional targeting. Perhaps a precursor interaction (X-ray or neutron radiation⁽⁷⁾, remote laser sensing or modified PD with a NE) can guide the final targeting parameters. All of the above factors will be influential in determining the type and yield of the explosive device used to produce the desired impulse by the ejection of bore hole material from the cratering event.

In order to achieve the required orbital adjustments the necessary energy yield and placement required to produce the velocity change must be determined. Three methods are outlined and used to provide computational results to estimate the energy requirements.

A. Crater Ejecta Characteristics (CEC): This approach treats the penetrator and HE or NE as thrust device. A mass of material is ejected and its momentum is related to the energy yield and charge placement. If one can estimate the effective exit velocity of the target material generated from the crater cavity originating from the explosive device, the effective velocity change of an asteroid of a given mass can be determined. This method will give reliable results when the ejecta mass is much less than the asteroid mass. Figure 1 shows the relationship between the energy yield, as a function of explosive yields in equivalent KT of TNT and the effective velocity (m/s) for a variety of NEO (asteroid) sizes and for densities of 1000, 3500, and 7500 kg/m³. Ejecta velocities are strongly dependent on the target density and scale depth⁽²⁾.

B. Kinetic Energy Transfer (KET): This method utilizes the change in kinetic energy in conjunction with estimates of energy partition resulting from the HE or nuclear charge. This method is highly dependent on the amount of heat, compression work, and shock wave effects within the asteroid body and will therefore be highly dependent on the asteroid material properties. Computational results of the energy requirements for a range of asteroid sizes and compositions will depend on the equation of state (EOS), density, mechanical structure, defects and inhomogeneities. Obtaining values for the KET model to agree with the CEC & IMT (below) models depends on the material parameters chosen.

C. Impulsive Momentum Transfer (IMT): From the explosion of a charge at a given depth an impulsive force is generated instantaneously, giving rise to the subsequent shock and ejecta processes. The total impulse is then determined from the pressure profile of the shock wave. This approach exploits the conditions behind the shock wave, expanding through the material as a result of a surface or buried explosion⁽³⁾. Advantages of this technique is that the computational method is inherently accurate and there is a sufficient amount of shock data available to provide reliable computational results. The results obtained from this method are analytically equivalent to those obtained from the CEC model.

Figures 2, 3, and 4 show NEO velocity increments for effective ejecta velocities of 30, 100, and 300 m/s plotted as a function of radius for explosive yields of .01, 1, 10, 100, 1,000, and 10,000 KT of TNT. The target density is 3500 kg/m³ and the scale depth is 10m/KT^{1/3.4}. In figure 2 the 100 m/s ejecta exhaust velocity is plotted as a dotted line to indicate the greater effectiveness of higher ejecta velocity (100 m/s vs. 30 m/s) in transferring momentum. Similarly, in figure 3 the 300 m/s is plotted as a dotted line and the original ejecta velocity of 30 km/s is referenced by notches at the top of the abscissa. Figure 4 shows the NEO asteroid velocity increment for an effective ejecta exhaust velocity of 300 m/s. Figure 5 is similar to figure 3 except that the scaled depth is now 20 m/KT^(1/3.4). The 10 m/KT^(1/3.4) for ejecta velocity 100 m/s is plotted as a dotted line. These figures show the strong effect of NEO material properties and scale depth on the ejecta exhaust velocity which directly affects the momentum transfer to the NEO the velocity change. All of three of the above methods estimate the amount of energy necessary to modify the asteroid orbit. Depending on the asteroid size, density, orbital velocity, and desired velocity change, the requisite energy can range from 10¹⁰ to 10¹⁶ joules. This is a large range of energy demands for this mission, even if the most likely scenarios are confined to an energy range from 10¹² to 10¹⁵ joules. Such large amounts of energy should probably not be contained within a single device. To effectively take into account this energy range it would be prudent to give the mission greater versatility, reliability, and minimizing of risk if a standard module or unit can be used repetitively.

One must realize that these numbers are only based on idealizations which are not the result of detailed modeling taking material properties into account. Such modeling will be carried out in the future only after a better understanding of the physical properties of the asteroid/ comet/ meteorite analogs is achieved. Nonetheless, it is significant that two independent theoretical approaches to the same problem yield the same analytical expressions and are consistent with the third approach over the same parametric range.

5. Summary

These results indicate that the penetrator/thruster mechanism can effectively introduce minor velocity adjustments to the orbital trajectory of a NEO such that it will avoid a collision with the Earth and overcome many many of the difficulties associated with modeling momentum transfer to NEO asteroids (summarized in the Appendix. Therefore, penetrator devices with HE or NE payloads can carry out this mission with a minimum of risk by:

1. Providing several smaller unit modules that can effect a continual orbital adjustment.
2. By carefully locating the PD impact point and calibrating the depth and HE or NE payload, the probability of catastrophic damage to the NEO will be limited. This will also serve to maximize the momentum imparted to the NEO without causing a catastrophic disruption.

3. The PD can avoid uselessly dissipating its energy on (surface) regolith and breccia by boring into the NEO main mass (if it exists), and thereby minimize the effects of the NEO surface material discontinuities near the surface.
4. From an analysis of the asteroid's inferred composition and dynamic characteristics, scaled depth, the critical amount of energy to modify the orbit can be computed.

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Appendix: Difficulties in Modeling NEO Orbital Adjustments

1. Inhomogeneity in both the large scale structure (crystalline reservoirs) and the small scale structure (inclusions in otherwise homogeneous phases).
2. A very wide range of possible densities (0.5 to 7.8 gm/cm³)
3. A very wide range of structural strength;
 - a) single crystal of FeNi
 - b) silicate inclusions in FeNi
 - c) igneous stone
 - d) metamorphic stone
 - e) carbonaceous stone
 - f) a collection of regolith without structural integrity
 - g) large stony or metallic boulders loosely bound or orbiting one another.
 - h) a collection of sandy grains and dusty material loosely bound.
 - i) a burnt out comet nucleus
 - j) an ice or methane ball with a stone or iron core
 - k) a mixture of any of the above
 - l) something different
4. A layered material that may not reveal NEO major composition
5. A mass with discontinuities that will spall off large fragments
6. Obtaining the correct scale depth.

Effective Exhaust Velocity as a Function of kT Explosive Yields for Different Target Densities

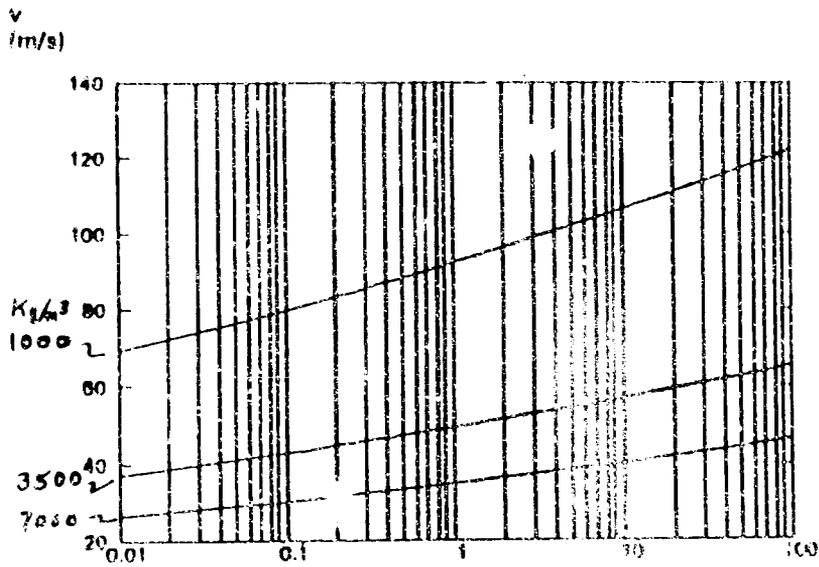


Figure 1 Eo (kT)

Typical Results for Asteroid Velocity Increment as a Function of Radius for Various Explosive Yields Assuming $\rho = 3500 \text{ kg/m}^3$ and Scaled Depth of $10 \text{ m/kt}^{(1/3.4)}$; Eff. Exhaust Vel = 100 m/s

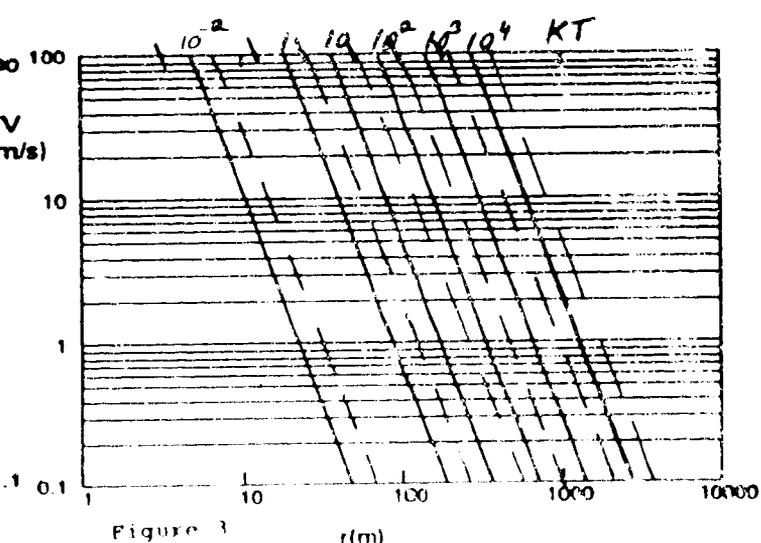


Figure 3 r(m)

Typical Results for Asteroid Velocity Increment as a Function of Radius for Various Explosive Yields Assuming $\rho = 3500 \text{ kg/m}^3$ and Scaled Depth of $10 \text{ m/kt}^{(1/3.4)}$; Eff. Exhaust Vel = 30 m/s

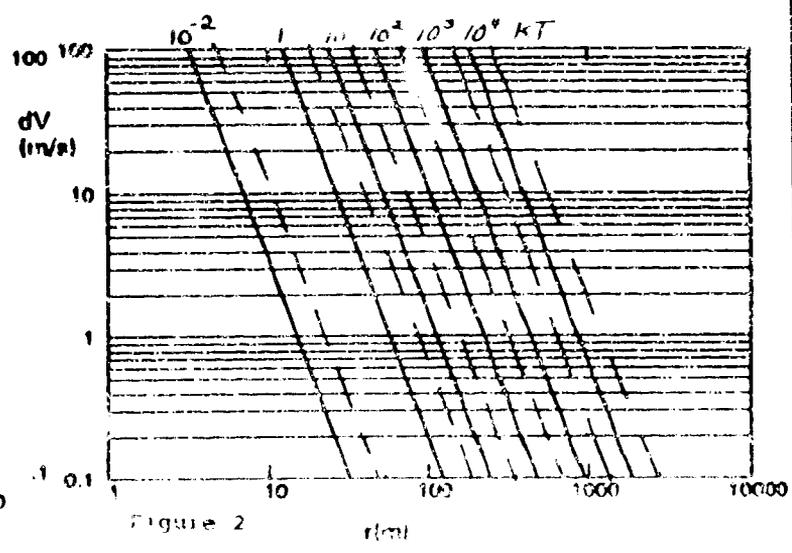
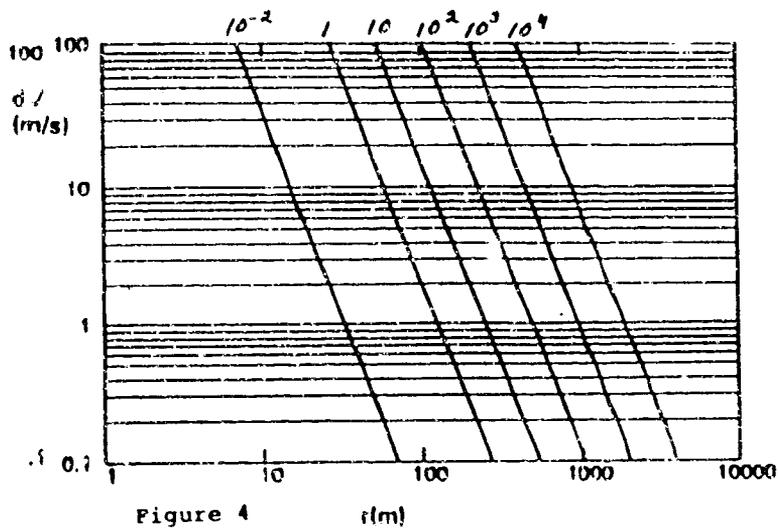
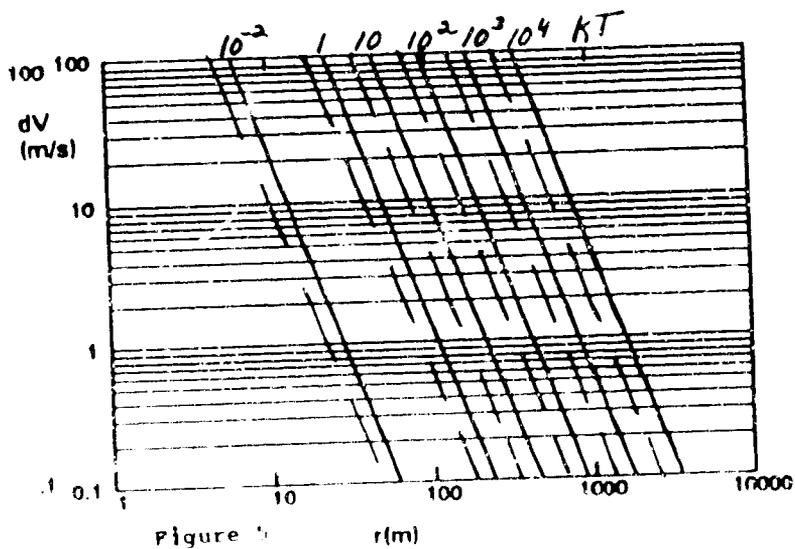


Figure 2 r(m)

Typical Results for Asteroid Velocity Increment as a Function of Radius for Various Explosive Yields Assuming $\rho = 3500\text{kg/m}^3$ and Scaled Depth of $10\text{m/kt}^{1/3.4}$: Eff. Exhaust Vel = 300m/s



Typical Results for Asteroid Velocity Increment as a Function of Radius for Various Explosive Yields Assuming $\rho = 3500\text{kg/m}^3$ and Scaled Depth of $20\text{m/kt}^{1/3.4}$: Eff. Exhaust Vel = 100m/s



4. AVAILABLE VEHICLES AND PAYLOADS

Workshop Summary

The vehicles and payloads working group identified three types of missions which could be designed to deal with potentially threatening NEOs or to perform survey missions to better characterize the NEO population. The first type of mission is a reconnaissance precursor using lightweight interceptor components and launch vehicles. The second type of mission would be designed to divert or fragment an asteroid of any size at ample distances from the Earth. A subset of this type of mission would seek to destroy large objects when the warning time is short.

4.1 Mission Type I: Precursor Missions

Early reconnaissance probes to a variety of near-Earth objects to characterize their diversity are readily feasible and highly desirable. Because of the wide variety of such objects, it is reasonable that at least 10 to 20 missions would be required to begin to characterize details of NEO physical and chemical composition. To be affordable, such missions should be low cost, which suggests small, lightweight spacecraft and launch vehicles.

The Department of Defense has developed a number of lightweight technologies which can be used for this type of mission. The suitability of these new technology vehicles for valuable space science was confirmed by a joint NASA/DOD workshop conducted in 1991 with participation from both the NASA Office of Space Science and Applications and the Office of Aeronautics, Exploration, and Technology. Small lightweight spacecraft sensors, computers, and propulsion systems offer the possibility of capable spacecraft within a modest mass and volume envelope. If the existing technologies are not directly suitable for an asteroid mission, the components can be modified and repackaged to meet the needs of the scientific community. It has been shown by DOD and NASA that such probes can perform a flyby or rendezvous to a near-Earth asteroid at distances from the Earth less than 0.2 AU in less than three years from program initiation at a cost of less than \$70M each.

Flybys of NEOs can, in many cases, be done at relatively low specific energy ($C_3 < 5 \text{ km}^2/\text{s}^2$) and short flight times (of the order of a few months). Communication distances are also modest by planetary mission standards. Rendezvous missions are more difficult, involving C_3 ranging from 18 to $100 \text{ km}^2/\text{s}^2$ and substantial total spacecraft ΔV ranging from 4 to 7 km/s after injection into low-Earth orbit. Ranges will normally be less than 0.2 AU for routine exploration, but if a threatening asteroid is being investigated, missions might exceed 2 AU. These larger and more complex missions may or may not be a part of Type I. A possible Type I scenario might involve several flyby missions of a variety of bodies and one rendezvous with a body offering the best compromise of ease of access and scientific interest. The rendezvous mission, which conceptually might include a landing as its final phase, could provide a measure of "ground truth" for the flybys as well as detailed data on one NEO.

Use of small spacecraft, especially for low departure energy flyby missions, opens up the option of using a variety of smaller and less expensive launch vehicles (e.g., Pegasus, Scout, and derivatives of the Minuteman II and III strategic missiles). The Peacekeeper missile is also an option; but it is in a substantially higher payload category (possibly for rendezvous missions). Another option which should not be ignored is to launch probes as secondary payloads on a large launcher, e.g., Titan III/IV or Ariane launched for other purposes. By riding along with a larger payload which might pay most of the cost, a ride to a geostationary transfer orbit might be had at modest cost. The propulsion requirements to go from this highly elliptical orbit to Earth escape are modest. The disadvantage is that the spacecraft may have to wait in this orbit for weeks until the orbit precesses into the proper position relative to the departure asymptote, which may raise issues such as cryogenic fuel storage and frequent traversal of the Van Allen belts.

Another payload-enhancing option is lunar swingby. At low-departure energy, flyby of the Moon can be quite effective in increasing departure energy, thus allowing increased payload for a given launch vehicle. A spacecraft launched at $C_3 = 0$ or slightly less, could have its energy enhanced to a positive C_3 , comparable with some NEO missions, by this means, thus enabling an otherwise marginal launch or providing weight growth margin.

4.2 Mission Type II: Divert or Fragment Missions

Type II missions are assumed to be active efforts to divert or fragment potential impacting NEOs. In the case of a very large body which is detected well ahead of time, the strategy would probably be to attempt to change the orbit sufficiently to ensure a miss. A few cm/s velocity, precisely applied to the NEO, would be required. This would probably occur with a flight profile longer than a year, and could be done by using one or several nuclear explosives engaging at the appropriate point in the orbit. To ensure the required precision, the carrier spacecraft would ideally rendezvous with the asteroid. Unfavorable rendezvous opportunities, however, might require excessive ΔV , so a fast intercept might be necessary, with precise trajectory corrections in the terminal phase to assure that the detonation imparts the required momentum change. In cases requiring large nuclear yield, a large spacecraft would be required, up to an including the Titan IV or Energia class. Table 4-1 shows an approximate weight versus yield estimate that can be used to characterize the nuclear payload weight.

Additionally, the possibility of fragmenting or deflecting objects detected only weeks or months prior to impact must be considered. This might involve one or more nuclear explosives or inert kinetic disrupters impacting the body as far from Earth as possible. Hence, flyout time becomes a critical issue. For ground-launched interceptors, the payloads may be modest, but high C_3 will be necessary for short trip time. Such missions probably exceed the Scout/Pegasus/Minuteman capability, but may be compatible with Peacekeeper, Taurus, etc. The worst case of trying to divert a large object discovered late would require launchers having payload capabilities in the range from Titan III through Energia to achieve both high velocity and high nuclear yield.

Other emerging technology possibilities for Type II NEO flyby/rendezvous/intercept missions were considered, using advanced propulsion systems such as nuclear and electric (see Chapter 6). Nuclear rockets will have specific impulse (Isp) approximately twice chemical rocket capability, with a factor of 2 to 5 increase in burn life and thrust. Trip time can be decreased approximately 30 percent, together with highly desirable increase in the intercept distance from Earth. State-of-the-art nuclear propulsion devices are currently 4 to 5 years from initial operational capability.

4.3 Mission Type III: Destroy Large Incoming Object on Short Notice

Although large strategic missiles (e.g., Minuteman II/III and Peacekeeper) offer potential for conversion to space launch, there is no launch response that has a high probability of success, and evacuation from impact areas may be the only response. For purposes of discussion, however, the working group did follow a "what if" line of thought relative to converting existing strategic ballistic missiles to space launchers. There are a number of constraints. The missiles are designed for a 5,000 to 10,000-mile range over the surface of the Earth. In order to achieve low-Earth orbit (LEO), some reduction in payload would be required. The amount of reduction depends upon exact propellant and staging arrangements. Such missiles may also benefit from substitution of higher performance upper stages. Table 4-2 shows payload capability to LEO for a large number of vehicles, including Minuteman II/III and Peacekeeper. The guidance systems employed in the missiles usually have much higher

Table 4-1. Approximate nuclear device weight versus yield

Payload Weight (kg)	Nuclear Yield (KT)
50	10
100	100
1,000	1,000
20,000	100,000

accuracy than required for orbital insertion. However, new software for on-board computers might be required.

Since all NEO missions involve Earth-escape velocities, generally along departure asymptotes incompatible with direct ascent from existing launch sites, an on-orbit coast followed by an additional rocket burn would be required. It might be straightforward to use the existing missiles for ascent to the parking orbit and a new, optimized escape-stage/spacecraft combination for the rest of the mission. This escape stage may use liquid or solid propellants. Developed from first principles, such as escape stage/spacecraft, could cost from \$500 million to \$1 Billion. It seems likely, however, that it could be prepared for a fraction of this cost by making modifications of existing rocket stages, spacecraft components, and warheads. Two to three years lead time would be sufficient for expedited development, with one year being a lower limit for newly modified hardware. Much more evaluation is needed to determine what can be done with available launchers (worldwide) to identify the lowest cost approaches. *It seems quite probable that combinations of existing hardware may be adequate for most contingencies.*

Table 4-2. Launch vehicle payload weights*

Launch Vehicle	(28.5) LEO (lbm)	C3-0		C3-5		C3-0		
		Useful Payload (lb)		Useful Payload (lb)		Useful Payload (lb)		
		Solid (lbm)	Liquid (lbm)	Solid (lbm)	Liquid (lbm)	GTO (lbm)	Solid (lbm)	Liquid (lbm)
1 Scout (37.7)	532	122	106	109	94	120	85	84
2 Pegasus	868	199	172	178	152	275	194	193
3 Scout (Enh, 37.7)	968	223	193	198	170	240	169	168
4 Pegasus XL-C	1025	236		210	190	-325	-230	-228
5 MM/III STAR 37	1180	271		244	209			
6 Conestoga	2200	506	439	451	387	1000	708	700
7 Taurus	3000	690	597	615	528	830	566	581
8 Pegasus/AMM						-900	-635	-630
9 Pegasus (Enh)	6400	1288	1114	1148	986	-950	-671	-655
10 Titan II/SLV	5600	1268	1114	1148	986	850	671	655
11 H-1 (31)	7300	1578	1453	1487	1285	2400	1594	1580
12 Ariane 40 (5.2)	10600	2484	2149	2214	1901	4180	2958	2933
13 Long March	11000	2530	2189	2255	1938	3300	2330	2310
14 Delta II	11000	2530	2189	2255	1938	4010	2831	2807
15 Atlas II	14000	3220	2786	2870	2484	5900	4185	4130
16 Zenit 2	30300	6969	6030	6212	5303			
17 Titan III	32000	7360	6368	6580	5832	11000	7768	7700
18 Shuttle	53700	12351	10688	11009	9451	13000	9178	9100
19 Energia	194000	44620	38606	39770	34144	40000	28240	28000

* Launch Vehicle Payload Weights
 Vehicles & Payloads Session
 NEO Workshop, 14-16 January

**THE STRATEGIC DEFENSE INITIATIVE ORGANIZATION
CLEMENTINE MISSION**

**COL. SIMON P. WORDEN
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I'd like to discuss the application of missile defense technologies that we have developed to a variety of additional problems. Last year at this meeting we discussed the potential use of missile defense technologies for global ecological monitoring. Several weeks ago in Dubna, in Russia, considerable progress was made in that area. As this chart illustrates, the applicability of a distributed set of small satellites to global ecological monitoring has considerable potential for this purpose and I am confident that we will be able to proceed in this area in the next few years. But what I would like to discuss today is the application of the same light satellite sensor technologies to the problems of space exploration and, indeed, another potential planetary emergency that Professor Zichichi mentioned yesterday. That's the potential strike of near-Earth asteroids on the planet. I'd like to discuss a research program that the SDI organization is undertaking. I think it has a lot of applicability to the problem.

Just to review briefly, near-Earth asteroids are objects left over from the formation of the solar system. This is an area of increasing concern in the United States. At the insistence of Congress, the National Aeronautics and Space Administration held two workshops in 1991 and 1992. The first one discussed the detection of these objects and the second one discussed if we find that one is going to strike the planet how does one protect against that.

Roughly speaking, there are probably 200,000 objects larger than 100 meters in diameter that could, potentially strike the Earth. One of these strikes roughly once a century with megaton effects. The last known large strike was in Siberia in 1908. It probably had the effective impact of between 5 and 10 megatons. There are some two thousand objects that we believe larger than one kilometer in diameter. One of these strikes roughly every ten million years or so. That would be a global catastrophe. Indeed, it's generally accepted that the destruction of the dinosaurs was due to one such strike 60 million years ago. There is some controversy over small objects in the ten-to-hundred meter size range. These strike once per year or more often. With these there is roughly the equivalent of a kiloton of TNT released.

I want to announce that the U.S. Department of Defense sensors did detect on the first of October 1990 roughly a ten kiloton impact. It was an airburst in the central Pacific. I note the significance of this date because had that strike occurred at that time not in the central Pacific, but in the Middle East, it could easily have been mistaken for a nuclear detonation and could have

triggered very serious consequences. So it is important that there be a survey of these objects so that we understand that they are natural events and are not mistaken for a nuclear attack.

There is controversy over how one might divert these objects if they were discovered — it appears the best approach is nuclear. I do want to point out that the same technology that we are developing for missile defense is applicable to finding these objects, investigating their character, and eventually mitigation of their effects. We have a mission which is ongoing called the Clementine program. It is designed to checkout in deep space missile defense sensors. We are anxious to find out some of the high radiation effects of our sensors. Indeed we think we can do a lot of the things we previously had to do in underground nuclear tests. We are using the moon because we think it is an ideal target. We are also going to fly by an asteroid with this mission because that will check out much of our software for autonomous navigation. The whole mission will cost 50 million dollars plus launch. We are looking at February 1994 launch for the first Clementine probe and about a year later for the second one. There is substantial scientific return on this mission. NASA has organized a team of scientists who work with us to tell us what is the best configuration of the sensors and how can we best map the targets. It is sponsored, as I said by the SDI organization. We're using sensors supplied by the Lawrence Livermore National Laboratory and I'll briefly review what those are.

The Clementine spacecraft is being built by the U.S. Naval Research Laboratory. It will be launched, as I said in early 1994. It will do a number of passes through the Earth's radiation belts to get high radiation exposure. It will then be inserted into lunar orbit where it will stay for roughly five months and perform a complete map of the moon. Then it will leave lunar orbit, do a swing-by of the Earth with an injection burn and then intercept the asteroids Geographos when it's roughly 4 million kilometers from the Earth.

Geographos is one of the better-known Earth-crossing asteroids. The probe has about a two-month flight time in interplanetary space before it intercepts Geographos. We hope to get within a few kilometers of the asteroid. This will be a very extensive checkout of our software to prove that we can navigate that accurately.

The spacecraft, as I said, is a very small spacecraft. The basic configuration consists of a simple spacecraft bus and solar panel with the sensors mounted in a payload bay and a thrust package — a rather standard thrust package that will give us several kilometers per second of delta-v.

Onboard the spacecraft, we're currently looking at a variety of sensors. Again, these are the basic sensors that will be on strategic defense systems starting with the lidar which is probably the most interesting sensor. This is a laser ranger experiment with a relatively large telescope on it. With this instrument, we ought to be able to get mapping of the moon with something like a few meters resolution. If we can get a real close flyby of the asteroid we could achieve spatial

resolution of some few number of centimeters. This will be the highest resolution photographs ever taken of an object in space. It will be the first time that we get any imagery on an Earth-crossing asteroid. We will also have an infrared camera on-board. We've asked NASA to give us the optimum set of bandpasses in this spectral range. This will begin to give us some interesting information on the composition of both the moon and the asteroid. In addition, we will have an ultraviolet and visible camera that covers a very broad set of wavelengths. This, in addition to the infrared will give us a good resource map on the moon as well as give us a preliminary idea of the asteroid's composition. Indeed, if we ever move to developing asteroid diversion systems, it is very important to know their composition because any means to move them would involve blowing-off some of the surface material either with a nuclear or conventional explosion. There's a considerable difference in the direct performance depending on the asteroid's composition.

This technology, I've discussed is applicable to the next step --- a sample return from these objects. Clementine is the lowest cost interplanetary mission the United States has ever undertaken. We think that with the same type spacecraft, which weighs about 200 kilograms, we could adapt it to bring back actually a tiny sample of these Earth-crossing asteroids. A similar system could be adapted if necessary to divert an asteroid.

My summary point is that this Clementine mission is an example where SDI and missile defense technology has much broader application. Thank you.

5. ACQUISITION, TRACKING, AND HOMING

5.1 Workshop Summary

The two principal sensors for the acquisition, tracking, and homing on near-Earth objects (NEOs) are visible cameras and radars. Both have achieved useful levels of performance today. Current sensor technology is sufficient potentially to provide the data necessary to identify and determine orbits for the majority of threatening objects capable of approaching the Earth. The orbital motions of these objects can usually be extrapolated accurately for a few decades into the future.

This chapter assumes that discovery acquisition is accomplished by visible-light sensors. We discuss the employment of post-discovery, follow-up observations to establish secure orbits (tracking) and the issues related to intercepting threatening objects (homing).

5.2 Visible Cameras

Visible cameras have been the most useful sensors for the discovery of new NEOs to date; they are also useful for re-acquisition, tracking, and homing. Most searches to date have been manual, but charge-coupled device (CCD) focal-plane detector arrays have reached the megapixel sizes needed for fast searches, and computers have reached the gigaflop computation rates needed for automatically detecting tracks on these large focal planes. The NEO Detection Workshop recommended that megapixel CCD arrays be coupled with fast computers for semi-automated NEO searches using six telescopes with apertures of 2 to 3 meters; such a program would have an initial capital cost of \$48M with NASA's contribution recommended to be two of the six telescope facilities.

Such cameras would be able to provide good short-term tracking. Radars could then quickly point at the objects and provide the data necessary for precise orbit determination. These cameras would also provide valuable whole-sky searches that would be useful for a variety of other astronomical purposes, among which is a systematic search for transient phenomena such as supernova explosions.

Radiances and detector sensitivities are an order of magnitude lower in the infrared than the visible, and detector costs may be one to two orders of magnitude higher per pixel. Overall, visible search techniques appear to be preferred, although further research is needed since the background may be more amenable to infrared search, and NEOs certainly have brighter stellar magnitudes in the thermal infrared (3 to 10 microns wavelength) than they do at visible wavelengths.

Follow-up observation programs need to be improved. Currently, about 10 percent of the objects discovered are lost due to inadequate follow-up. Only a modest number of follow-up observations are necessary to refine NEO orbits to a point where their recovery is ensured. Once implemented, the Spaceguard Survey program will produce about 1,000 discoveries per month; commensurate follow-up observations are needed. In terms of discovering the population of larger near-Earth asteroids and periodic comets that could cause catastrophic collisions with the Earth, ground-based telescopes are adequate. Space-based detectors would be necessary or desirable for the very fast reaction times required for first appearances of long-period comets (LPCs) on Earth-colliding trajectories. Space-based detectors may also be important for improving knowledge of the Aten-type NEOs, which spend much of their time within the Earth's orbit. Ground-based telescopes are not able to view large portions of the sky for months at a time because glare from the Sun in the day sky necessitates waiting for the Earth to move around its orbit; space-based telescopes would greatly reduce that restriction.

5.3 Radars

Radars are uniquely capable of measuring range out to distances of several tenths of an AU for kilometer-sized NEOs at all angles with respect to the Sun as viewed from the Earth, which is essential for precise and rapid orbit determination. Radars can also measure reflectivity and polarization to constrain surface characteristics such as roughness and composition. They can also use Doppler and time gating to image, which gives a clearer picture of the objects to be intercepted and of the orientation and rotation of asymmetric bodies prior to interception. That is particularly important for irregularly shaped or multiple objects. Radar is a mature technology, but the range of existing facilities could be increased by an order of magnitude. Radars with at least twice the range of current instruments could be built. There are options for extending the range even farther with shorter wavelength high-power radar systems. It is predicted that a 5- to 10-MW, 94-GHz free electron laser (FEL) with a 15- to 50-m antenna could track objects at about 1 AU. A single radar has been estimated to cost about \$100M, comparable in costs to conventional radar systems. The potential for increased performance must be balanced against the increased cost risk, as such a radar has not yet been built. A current NASA research program is studying FELs for other applications which may lead to further advances in the state of the art.

It is important to develop optical search and radar track capabilities together. As optical cameras are improved and proliferate, it will be necessary to increase the number of tracking radars to address the increasing throughput of discoveries. The key contribution of radar data is the ability to secure orbits quickly to the level required to identify potentially hazardous NEOs before they are lost due to inadequate tracking precision.

Handover or re-acquisition from discovery sensors to radar is not an issue; it can be done rapidly. Data volume is a concern, however. Current radars can follow-up on only about 10 percent of discoveries. Dedicated radars with the current Arecibo capabilities in the northern and southern hemispheres could handle most of the 1,000 discoveries per month anticipated from the Spaceguard Survey. *No radar optimized for NEO investigation exists; such a facility would greatly increase the confidence of NEO risk assessments.*

5.4 Homing

Homing techniques have been studied less than those of discovery and tracking. Optical or radar sensors on the payload vehicle or on companion probes could re-establish the orientation of objects prior to precise delivery. They could also provide the data necessary to refine the object's trajectory for intercepts at perihelion or elsewhere in the object's orbit. The mid-course maneuver commands for rendezvous could be based on small, on-board sensors. The technology for flyby or rendezvous exists and has been demonstrated in interplanetary space on numerous missions.

It does not appear possible to command vehicles for terminal intercepts using ground-based tracking systems. Radars have beam widths of about 100 microradians. High signal to noise could be used to divide the beam to 3 to 10 microradians. But even at a range of about 1 million kilometers the beamwidth would be 3 to 10 km, which is too wide for precise targeting. The interceptor vehicle could not guide upon the object's reflected radar beam efficiently because of the object's curved trajectory. Present optical telescopes are limited to about 1 microradian. At a range of a million kilometers the error would be 1 kilometer, which is still too large for terminal interception.

The interceptor could be guided to within range of the object, and then control could be transferred over to onboard sensors and computers. Sensors could be either radar or

infrared. The handover is complicated by the residual error in the object's trajectory as measured from Earth, which is estimated to be typically about 10 km. Searching that area from a distance of 10,000 km would require a radar with a power-aperture product of about 1 Watt-m². Such a radar could easily be incorporated into an interceptor. A telescope with a diameter of 10 to 20 cm and a modest number of detectors would also suffice. It could identify the object with respect to the stars, and then use navigation aided by external and internal sensors to home on the object. It would have the additional advantage of resolving the target for precise impact as the range closed. To assist the intercept it would be useful to incorporate a low-power, pulsed laser into the interceptor vehicle for range measurements.

The above comments are fully applicable to asteroids. For comets, there is the additional problem that the coma of the comet may obscure its nucleus, making impact prediction more difficult. While the probes to Halley's Comet in 1985 did succeed in imaging the nucleus, it is not clear that optical or radar sensors would penetrate a new comet's coma soon enough to make terminal guidance feasible. If the interceptor had to wait until it penetrated well into the coma, the resulting required terminal maneuver might be through a wide angle, which is difficult at the high velocities of the encounter. Multiple interceptors might have to be sent in series. This should be a topic for much more study.

5.5 Summary

The optical and radar sensors for acquisition, tracking, and homing could be built with existing technology. Computers and algorithms could support automatic detection and tracking, and could solve current deficiencies in follow-up observations. Radars are valuable because of their ability to quickly refine orbital parameters and measure physical characteristics, especially size, shape, spin vector, and multiplicity. There are options and technologies for increasing both the range and number of radars. A few dedicated facilities could meet the expected discovery rates. *It would be worthwhile to consider upgrades and modifications to existing defense facilities to support these objectives.*

Homing has been studied less. Optical and radar sensors could refine an object's trajectory and establish its orientation for precise delivery. Existing technology is sufficient to accomplish distant intercepts at perihelion or elsewhere. The interceptor vehicle could be guided to within range of the object, and control transferred to on-board sensors and computers. Some combination of these sensors (radar, optical, laser) may be required for effective intercept trajectories. There appears to be a credible thread through all the technologies for acquisition, tracking, and homing.

ACQUISITION AND TRACK OF NEAR-EARTH OBJECTS

Gregory H. Canavan

Simple scaling arguments can be used to characterize search and track by optical and radar sensors, which have similar scaling. They can produce trajectory information and imagery at distances out to significant distances. Optical sensors are good for long-range search; radars are better for track and characterization; thus, their operation is largely complementary.

I. INTRODUCTION

This note discusses the use of radar and optical sensors to acquire and track large near-earth objects (NEOs). The discussion of radars is based on the simple radar equation, from which optimized power-range relationships are derived for search and track. Existing defense radars have some capability for near-Earth search and track. For track, shorter wavelength radars have additional advantages. They can produce trajectory information at a fraction of an AU. Search with passive optical sensors scales similarly. Efficient visible detector arrays appear feasible and attractive. Radar and optical sensors have largely complementary characteristics. Optical sensors are good for long-range search; radars are better for track and characterization.

II. RADAR ACQUISITION

If a radar has power P and radiates into solid angle Ω , at range R the power density is $P/\Omega R^2$. A target of cross section σ there scatters power $\sigma P/\Omega R^2$. A detector of area A at range r receives a fraction $A/4\pi r^2$ of it, giving a signal of $S = (\sigma P/\Omega R^2) (A/4\pi r^2)$. This signal is compared to the noise, $N = BkT$, where B is the signal bandwidth and $T = 1000$ K is the noise temperature of the receiver. Thus, the signal-to-noise ratio (S/N) is

$$S/N = P\sigma A/4\pi\Omega R^2 r^2 BkT. \quad (1)$$

For given $S/N = 10$ for detection, the required power-aperture is

$$PA = 4\pi\Omega R^2 r^2 BkT(S/N)/\sigma \quad (2)$$

For monostatic radars, which use the same aperture to both transmit and receive, $r = R$, and¹

$$PA = 4(4\pi\Omega R^4 BkT(S/N)/\sigma) \quad (3)$$

Their fundamental scaling is that $R \propto (FA)^{1/4}$, which means that range increases only slowly with radar system parameters. Large radars are optimized to minimize total cost. The process can be illustrated by assuming that the cost of power is pP and the cost of aperture is aA , where p and a are constants, and that other contributions to cost are smaller. The total variable cost C is minimized by choosing $P = aA/p$. Then $C = 2pP$; $PA = P^2 p/a$; and

$$P = \sqrt{[4\pi\Omega R^4 BkT(S/N)a/p\sigma]}. \quad (4)$$

The dominant scaling is $P \propto R^2$, so when power and aperture are scaled properly together, range increases more rapidly with system power than is indicated by Eq. (3). Knowing P , A can be found from $A = pP/a$.

Ballistic missile early warning radars (BMEWs) have $P \approx 1$ MWatt and $A \approx (100 \text{ m})^2$ aperture, which gives $PA \approx 10^{10}$ Watt·m². Missile warning radars are designed to detect objects with very low cross sections in low-Earth orbit. Reentry vehicles (RVs) typically have cross sections of 10^{-3} - 10^{-4} m². Expected RV trajectories traverse are known regions, so the BMEWs radars only have to search a region of $\approx 10^\circ \times 40^\circ \approx 1$ sr. The RVs' trajectories can be integrated for a few seconds, which gives $B \approx 1$ Hz. The upper left curve on Fig. 1 shows the resulting power requirement from Eq. (4) for a radar searching $\Omega \approx 1$ sr for targets of cross section 10^{-3} m². The curves are for the nominal performance parameters above and cost parameters of $a \approx \$5\text{K}/\text{m}^2$ and $p \approx 150/\text{Watt}$. For BMEWs' $PA \approx 10^{10}$ Watt·m, i.e., power $P \approx 1$ MWatt and area 10^4 m², $R \approx 6,000$ km, which is about the range from the radars to the expected trajectories.

Search for small objects involves ranges too small to be of interest for NEOs, but Eq. (4) scales as $P \propto 1/\sqrt{\sigma}$, so for larger objects the ranges are greatly extended. The three middle curves on Fig. 1 are for objects with radar radii of 30, 100, and 1,000 m, for which the detection ranges are about 50,000, 100,000, and 350,000 km, respectively. For NEOs a few kilometers diameter, the search range would extend out to about the orbit of the moon, so the search capabilities of existing defense radars are not insignificant. Their radar pulse forms are, however, specialized for non-ambiguous operation at the shorter ranges of smaller objects, so some modification would be required for operation at longer ranges. Such radars are also specialized to the characteristics of RVs, so the information they could provide on NEOs would be fairly rudimentary.

III. RADAR TRACK

The power-range Eq. (4) scales as $P \propto \sqrt{\Omega}$, or $R \propto 1/\Omega^{1/4}$, so another way to extend range is to reduce the solid angle searched. The limit of the reduction is the solid angle $(w/D)^2$ subtended instantaneously by the beam, where w is the radar wavelength and $D = \sqrt{A}$ is the effective diameter of the aperture. This is the reduction in angle involved in tracking objects that have already been located. The decrease in angle is about a factor of $1/(w/D)^2 \approx 1/(1\text{m}/100\text{m})^2 \approx 10^4$, so the increase in range is about a factor of $(10^4)^{1/4} \approx 10$. Optimization of radars for track is slightly different than that for search, but if $\Omega = (w/D)^2 = w^2/A$ is substituted into Eq. (3) the result is²

$$PA^2 = 4\pi w^2 R^4 B k T (S/N) / \sigma \quad (5)$$

Cost is minimized by the choice $P = aA/2p$, for which $PA^2 = (2p/a)^2 P^3$, and

$$P = [4\pi w^2 R^4 B k T (S/N) / \sigma (2p/a)^2]^{1/3} \quad (6)$$

The dominant scaling is $P \propto R^{4/3}$, so power increases less rapidly with range for track than for search. The curve for "BMEWs track" shows that decreasing angle increases range by another

factor of about 10 out to about 3×10^6 km. This extension is useful, but still produces ranges of only ≈ 0.01 AU rather than the 0.1-1 AU desired for tracking, fixing, and intercepting NEOs.

The power required for search is independent of wavelength, so BMEW's radars operate at wavelengths of ≈ 1 m, where RF power is relatively cheap. For track, by Eq. (6) $P \propto w^{2/3}$, so it is useful to operate at shorter wavelengths. Current Goldstone and Arecibo radars operate at wavelengths of about 5 cm, which extends range by about a factor of $1/\sqrt{w} = \sqrt{20} \approx 4-5$, as shown by the right hand curve on Fig. 1. The crosses span the region covered by the upgraded Goldstone and Arecibo powers, giving a range of about 10^7 km, or ≈ 0.1 AU.

The line for the shorter wavelength radars also indicate that with a power of about 10 MW it would be possible to reach a range of ≈ 1 AU, which would be useful for quickly establishing the many trajectories that could emerge from an enhanced detection system. There are, however, other ways to take advantage of additional power. The resulting higher S/N at less than maximum range allows coherent, wide-bandwidth signals to be broken up into many Doppler and delay bins to provide imagery of the NEOs. And rather than increasing the range of a single radar, it would be useful to use multiple radars in both hemispheres and multiple time zones to decrease the access times to various parts of the sky for directly approaching NEOs. The advantages of shorter wavelengths only apply to track. If shorter wavelength radars were used for search, that advantage would be lost and the search ranges would drop to about those shown for the BMEW's radars.

IV. BISTATIC RECEIVERS

In the monostatic geometries treated above, the receivers are assumed to be colocated with the transmitters on the Earth. The power-aperture requirements are reduced in a bistatic geometry in which the receivers are put in orbit closer to the NEOs. If the receiver constellation is at range R from the Earth and the distance between receivers is r , the total number of receivers needed for $\Omega = 4\pi$, coverage is $\approx 4\pi R^2/\pi r^2$. Each receiver has area A , and is assumed to cost $C_A A$. There are $4R^2/r^2$ of them, so the total cost is $(4R^2/r^2)C_A A$. The receiver antennas could have an areal mass density of about 30 kg/m². It costs about $\$30$ K/kg to put mass into deep space, so $C_A = \$1$ M/m², which is several orders of magnitude larger than for monostatic receivers. The transmitter on Earth would still cost $C_p = \$50$ K/Watt. Thus, the total cost would be about

$$C = 4R^2/r^2 C_A A + C_p 4\pi \Omega R^2 r^2 B k T (S/N) / \sigma A \quad (7)$$

Detector costs scale as $1/r^2$, power costs scale as r^2 . Their sum is minimized by the choice

$$r_0 = [A^2 \sigma C_A / (C_p 4\pi^2 B k T (S/N))]^{1/4} \quad (8)$$

for the distance between receivers. It scales rather weakly on all parameters but A . For the optimal separation, r_0 , the optimum cost is

$$C_0 = 16(R^2/r_0) \sqrt{[\pi C_A C_p B k T (S/N)]} \quad (9)$$

where A drops out and σ is replaced by the asteroid area, πr_a^2 . C_0 scales primarily on R^2/r_a . In

comparing this result with that for the monostatic geometries discussed above, the only difference for the optimized systems is that for bistatic geometries, a is replaced by $C_A B$; cause $C_A \approx 10$ -100 times a , and $C_O \propto \sqrt{C_A}$, that means that for equivalent performance the cost of a bistatic geometry is a factor of $\approx \sqrt{(10-100)} \approx 3$ -10 higher. Thus, putting the transmitters in space can be studied, but the gain in performance is modest and the problems involved in generating the large RF powers needed in space would be formidable.

V. OPTICAL SEARCH AND TRACK

Search with optical sensors, which are passive and do not require active illumination, is superficially different than that with radars. The overall scaling of the two is, however, quite similar. This section derives the simplest form of the equations for optical search and track, and indicates their scaling and rough predictions.

A. Search

If each pixel of an optical telescope has solid angle θ^2 , to search a solid angle Ω in time T it would need a dwell time $t = T\theta^2/\Omega$. An array of N detectors would have a dwell time

$$t = \theta^2 NT/\Omega. \quad (10)$$

The power received by a telescope of diameter D from an object at range R emitting J (watt/sr) is

$$P = J(D/R)^2, \quad (11)$$

In discussing IR detectors it is conventional to express detector noise power in terms of detectivity, so the signal to noise ratio of their output is detectivity times power. It is then convenient to introduce the detectors' specific detectivity D^* , which is detectivity times $\sqrt{(A_d/t)}$, where A_d is a detector's area and $1/t$ is its passband. Thus,

$$S = [D^* \sqrt{(A_d/t)}]P = [D^* \sqrt{(1/A_d)}]J(D/R)^2 = (D^* J/\sqrt{A_d})(D/R)^2 \theta \sqrt{(NT/\Omega)}. \quad (12)$$

The detectors have diameters $d = \sqrt{A_d}$, so it is efficient to match the size of the pixels to that of the detectors. For a telescope of focal length f and f-number $f_\#$, that means

$$d = \theta f = \theta f_\# D, \quad (13)$$

$$S = [D^* J/\sqrt{A_d}] (D/R)^2 (d/f_\# D) \sqrt{(NT/\Omega)} = (D^* J D/R^2 f_\#) \sqrt{(NT/\Omega)} \quad (14)$$

Squaring this result puts it into a form useful for analysis³

$$ND^2 = (S f_\# / D^* J)^2 \Omega R^4 / T, \quad (15)$$

which scales much as the radar search equation, particularly in its scaling on $\Omega R^4/T$. For optics, N plays a role analogous to that of power in radars, but there is one difference. For optical systems the detectors and aperture must be co-located, so there is no analog to bistatic geometries.

B. Optimization

This section explores the optimization of the sensor, assuming that the processing

supporting it is so capable that only the simple signal to detector noise need be considered. Performance, NA in Eq. (15), is bilinear in detector number, N , and aperture area, $A \approx D^2$. Costs are linear in N and A , so the total cost for a single sensor is minimized by the choice $A = Nm/a$, where m is the cost per detector, for which $E = N^2m/a = A^2a/m$. Then, $C = 2mN = 2\sqrt{(maE)}$, $E = C^2/4ma$, and performance increases as the square of cost. With this scaling Eq. (15) becomes

$$N = \sqrt{[(a/m)(Sf_{\#}/D^* J)^2 \Omega R^4 / T]} = (Sf_{\#}/D^* J) \sqrt{(a\Omega/mT)} R^2, \quad (16)$$

from which D is determined by $D^2 = A = mN/a$. Detection typically requires $S \approx 100$. For NEO detection, $\Omega \approx 4\pi$. In the visible, $D^* = 10^{13}$ cm- $\sqrt{\text{Hz/watt}}$, in MWIR, $D^* = 10^{11}$ cm- $\sqrt{\text{Hz/watt}}$; in the LWIR, $D^* = 10^{10}$ cm- $\sqrt{\text{Hz/watt}}$. Visible arrays of several million detectors are now available. In the short- and mid-wavelength infrared (SW/MWIR), arrays of $\approx 500,000$ detectors are available.⁴ Mirrors of up to a few meters are readily available in volume. Visible detectors cost about \$0.01/detector; SW/MWIR detectors cost about \$0.05/detector. Long-wavelength (LWIR) detectors cost several hundred dollars per detector on the Earth, perhaps 10 times that amount in space.⁵ It is assumed below that visible detectors would cost about \$1/pixel installed.

The time allowed for search depends on the range. At most, $T = R/V$, where $V \approx 30$ km/s is the asteroid's velocity towards the Earth. For $R = 1$ AU, that gives $T \approx 1.5 \cdot 10^8$ km/30 km/s ≈ 1 month. The calculations below take $T = 1$ day for response time. The signal J depends on the wavelength. In the visible the signal is scattered sunlight. The sun shines at $J_S \approx 4 \times 10^7$ watt/m²-sr at its surface. At 1 AU, $J_A = J_S (R_{\text{Sun}}/R_{\text{AU}})^2 \approx 4 \times 10^7 (7 \times 10^5 \text{ km} / 1.5 \times 10^8 \text{ km})^2 \approx 1$ kwatt/m². An asteroid of radius r_a scatters about $J_A \pi r_a^2$. For the example calculations below, NEO reflectivities are taken to be unity. Thus, Eq. (11) can be rewritten

$$N = (Sf_{\#}/\pi D^* J_A) \sqrt{(a\Omega/mT)} (R/r_a)^2. \quad (17)$$

The asteroid should also radiate in the IR due to its own temperature, which is set by its radiation balance with the sun. For a 2000 asteroid, at 5 μm $J_A \approx 0.01$ watt/m²-sr- μm ; at 10 μm , $J_A \approx 1$ watt/m²-sr- μm . The important parameter is $D^* J_A$, which is about a factor of 100-1,000 $\approx 10^5$ higher in the visible.

C. Results

Figure 2 shows the number of detectors needed as a function of range for visible detector arrays with $D^* = 10^{13}$ cm- $\sqrt{\text{Hz/watt}}$ and 30-100 m asteroids 0.2-1.8 AU away. For the shorter ranges, the array sizes are under 10^6 . For the 100 m asteroid they only reach 10^6 for ranges of about 2 AU. For the 30 m asteroid they reach about 10^7 by that range. Since $C = 2mN$, the cost is also indicated on the right ordinate. This is just the hardware cost for ground-based sensors.

Figure 3 shows the aperture sizes required, which range from 0.1 to 10 m². Since $A \propto N$, this is just a rescaling of Fig. 1. Perhaps the most interesting thing about these curves is the

indication that the numbers, sizes, and costs are not inordinate with visible sensors. Infrared sensors would cost more because of their lower D^* 's and higher detector costs. That optical sensors scale the same way on $\Omega R^4/T$ as radars does not mean that their costs are comparable to those of radar systems.

D. Limitations

This section assumes that the computer processing available is so capable that only the simple signal to detector noise need be considered. That is not unreasonable. But if the asteroid and background have significant motion with respect to the detector array, it is necessary to sum over paths to integrate the full signal. That can be done with simple track assembly;⁶ it can be done much more efficiently with neural nets.⁷ But both require billions of floating point operations per second. Thus, it is useful to seek techniques which take out much of the motion with the optics, which is discussed elsewhere.

VI. SUMMARY AND CONCLUSIONS

This note discusses radar and optical sensors for the acquisition and track of large NEOs. The discussion of radars is based on the simple radar equation, from which optimized power increases as the square of range for search and less strongly for track. Existing defense radars could have some modest capability for near-Earth search and track. For track, shorter wavelengths are an advantage, and can produce trajectory information and imagery at a fraction of an AU. Bistatic geometries do not appear to offer advantages.

Search with passive optical sensors is superficially different than that with radars, but scales similarly. The detector number-aperture area required scales on solid angle, range, and search time as do the power-aperture product for radar acquisition. Efficient visible detector arrays appear to be feasible and attractive. Recent advantages in processing could reduce false-track problems. Radar and optical sensors have largely complementary characteristics. Optical sensors are good for search at long range; radars are better for track and characterization at shorter ranges.

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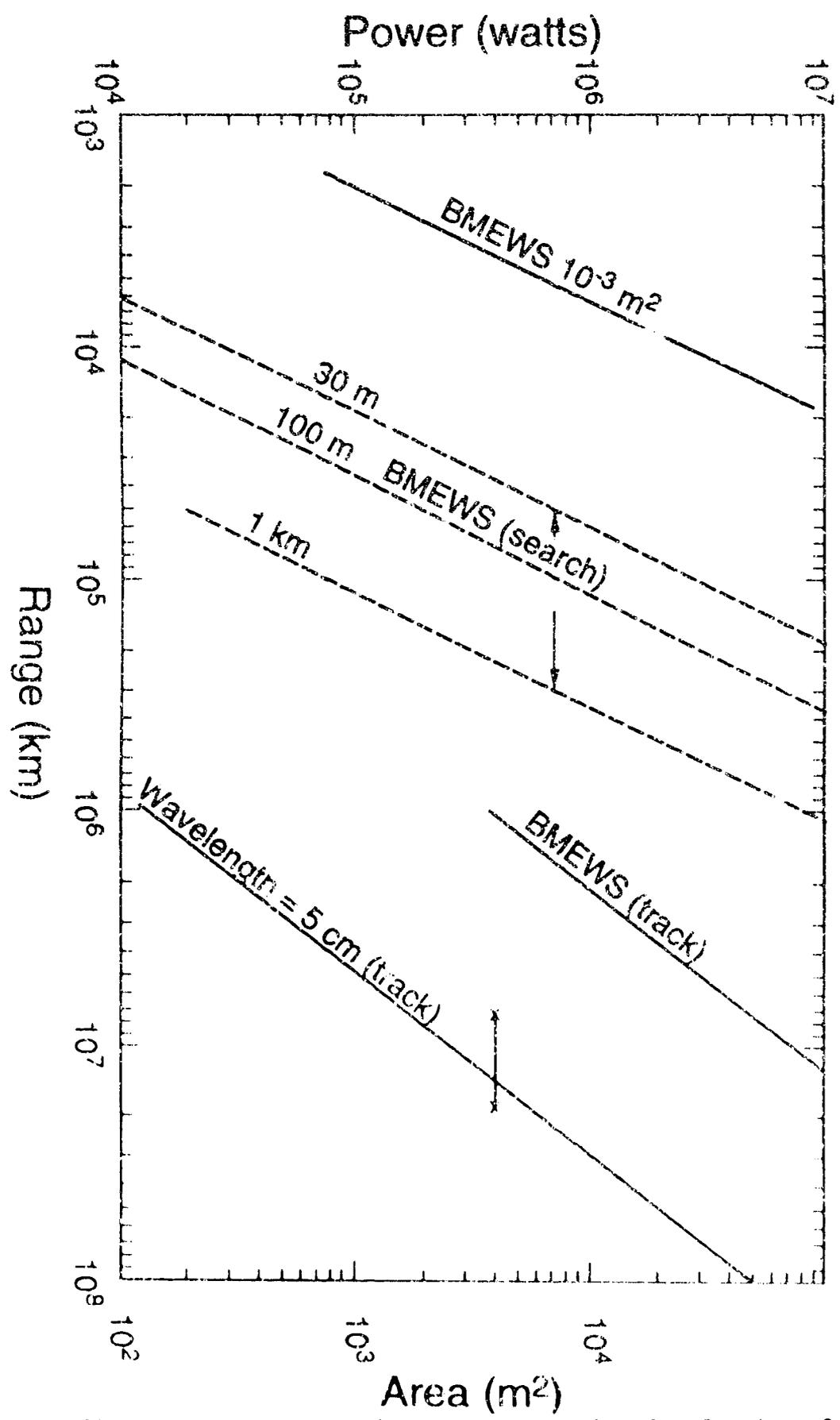


Fig. 1 Power and aperture for radar search and track as functions of range.

Fig. 2 Number of detectors vs range

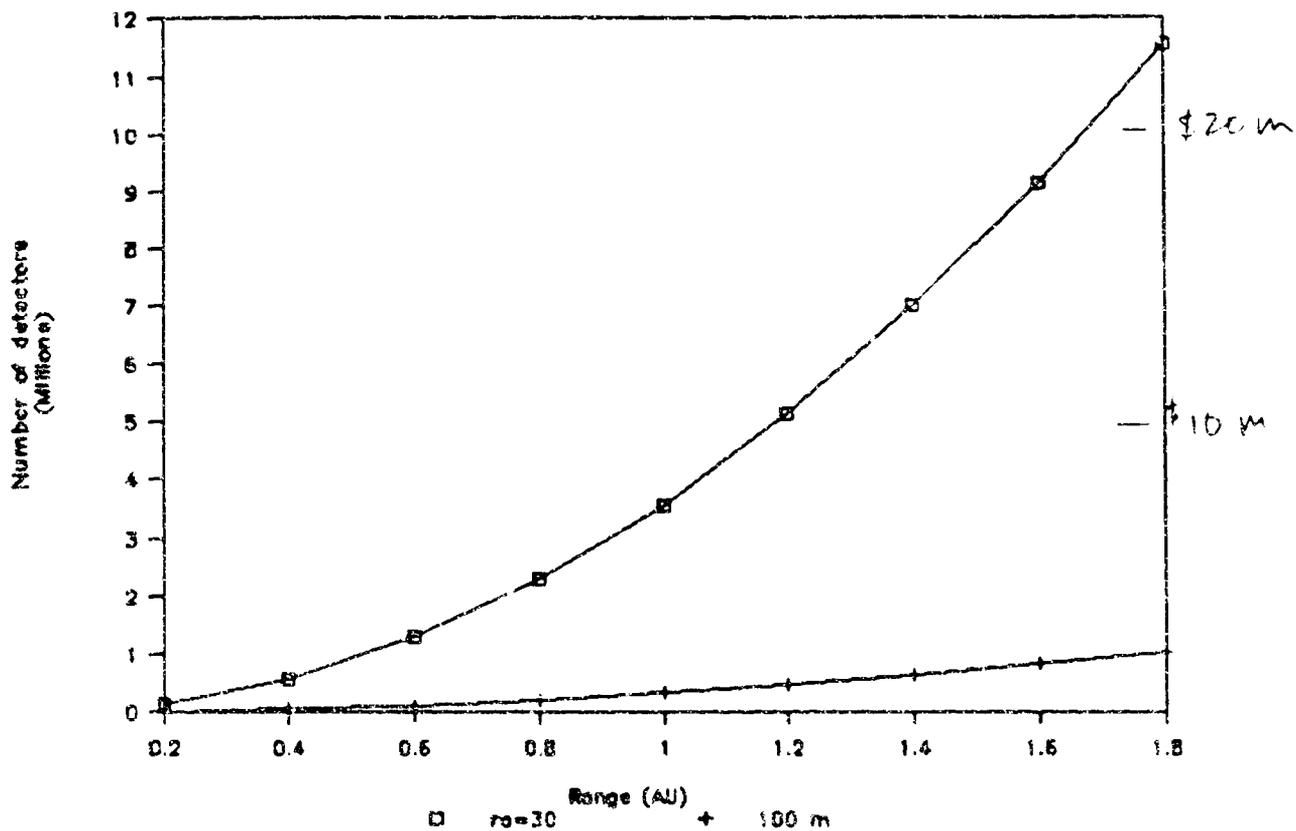
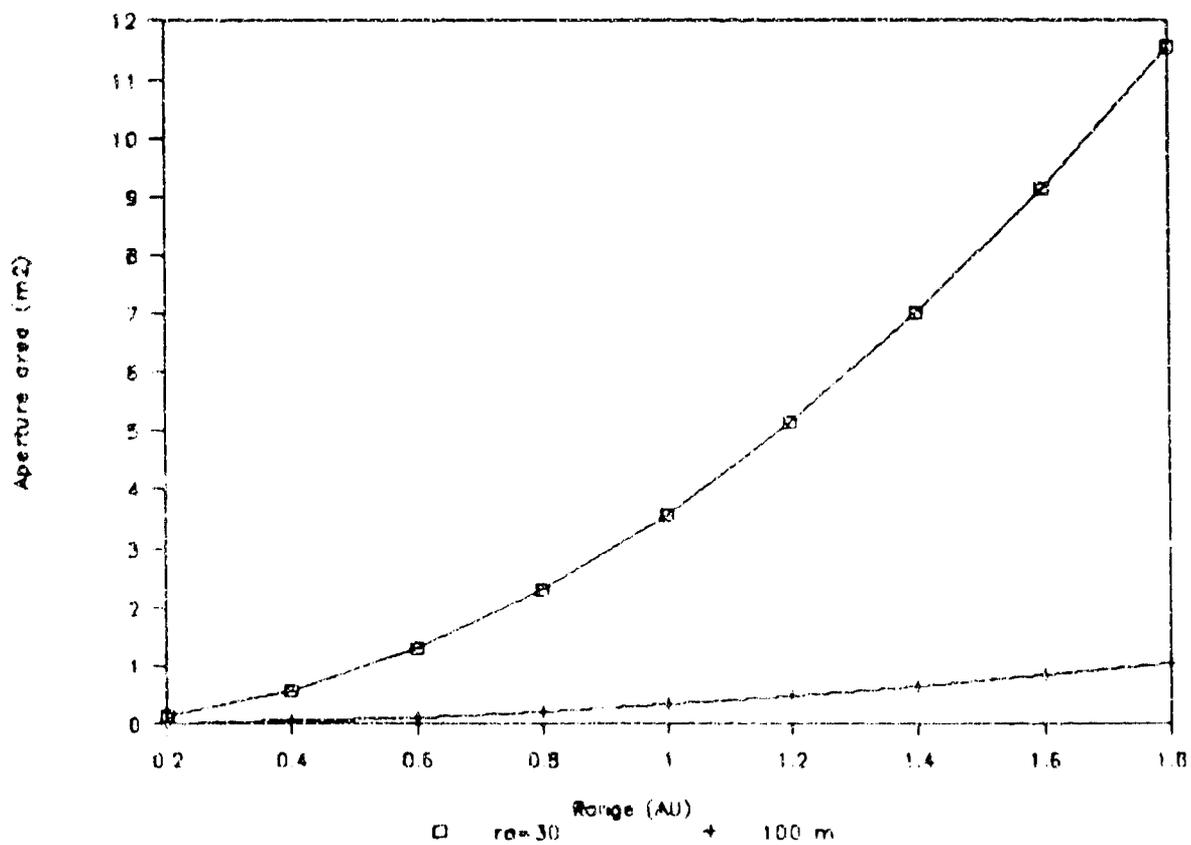


Fig. 3 Aperture area range



Fireball Observation Via Satellite

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On October 1, 1990 at 0351Z optical sensors aboard two geostationary satellites (1989-046 and 1984-037) recorded a very intense flash of light over the western Pacific Ocean. The sensors, although optimized for the detection of nuclear bursts in the atmosphere, nevertheless provided high-quality data concerning the luminous intensity/time profile of what most likely was a very large fireball of visual magnitude -23. In addition, it was bright enough to permit the companion locator to provide a fairly precise geographical position (7.6°N, 142.2E, and 30km altitude) at peak signal.

To our knowledge, this particular event has not been previously reported. Perhaps the remoteness of the region or weather conditions at the time precluded visual confirmation.

The instruments which provided the profile measurements were non-imaging transient radiometers consisting of unfiltered silicon photodiodes with bandpass of 400-1100 nanometers. The design of each radiometer is such that it views the entire earth disc plus a few degrees of surrounding space. Photocurrent in its single sensing element is proportional to the amount of earth light present, the vast majority of which is reflected or scattered sunlight. Transient signals are detected as small but rapid changes in photocurrent.

Due to satellite rotation and non-uniformity of lens/sensor off-axis response, there is appreciable cyclic modulation of this "background" signal. In addition, since the satellite is in geostationary orbit, the background waxes and wanes diurnally. Despite these variations, this particular event was distinct enough to be recorded with considerable precision.

Since background light from the earth is a factor of many thousands stronger than transient signals of interest, it is necessary to remove the DC component of the photocurrent it produces to facilitate recording of transients. Consequently, the channel from which these data were obtained contained a high-pass filter with a lower cutoff of about one Hz. To reconstruct the input waveform from recorded data it was therefore necessary to deconvolve the effects of the high-pass filter and to subtract any cyclic components due to satellite rotation. The resulting waveforms are shown in Figures 1 and 2.

As can be seen from the reconstructed waveforms, the signals at the two satellites were quite similar, implying a high degree of omni-directionality in radiated energy. The satellites were situated at approximately 165°W and 70°E so their viewing angles to the event were different by about 145°. The peak radiant intensity measured by each radiometer (assuming a source temperature of 6000°K) corresponds to a source power of approximately 3.5×10^{11} watts per steradian. Assuming this fireball event was isotropic, the thermal energy radiated was approximately 2.2×10^{12} joules which is the energy equivalent of 500 tons of high explosives (HE).

Further, an estimate of the meteor pre-entry kinetic energy by comparison of this recording with several smaller fireball events described in the literature is about 4×10^{13} joules (10 kilotons of HE). A 20,000 metric ton meteor impacting the atmosphere at 20 kilometers/second would generate the recorded waveform.

Similar optical detectors exist on currently deployed GPS satellites. However, there is no provision for downlinking background data of this type. Addition of both a background channel and a downlink capability are being proposed for inclusion on GPS Block IIR satellites. These satellites, when deployed in the 1996-1999 timeframe, could then provide truly global coverage of fireball events greater than a visual magnitude of -15.

Although the proposed Block IIR upgrade would not include an imaging-type locator, fireball event locations could still be determined with varying degrees of precision using time-difference-of-arrival (TDOA) techniques. Limitations on the accuracy of this method would largely lie in the luminous intensity waveform itself. If the waveform, over its span of duration, has a number of regions of rapid amplitude change (flares), then it may be possible with multiple-satellite observation to realize location errors as small as ten kilometers and to even estimate direction of travel. Events with slower time-intensity profiles could still be located, but with less precision.

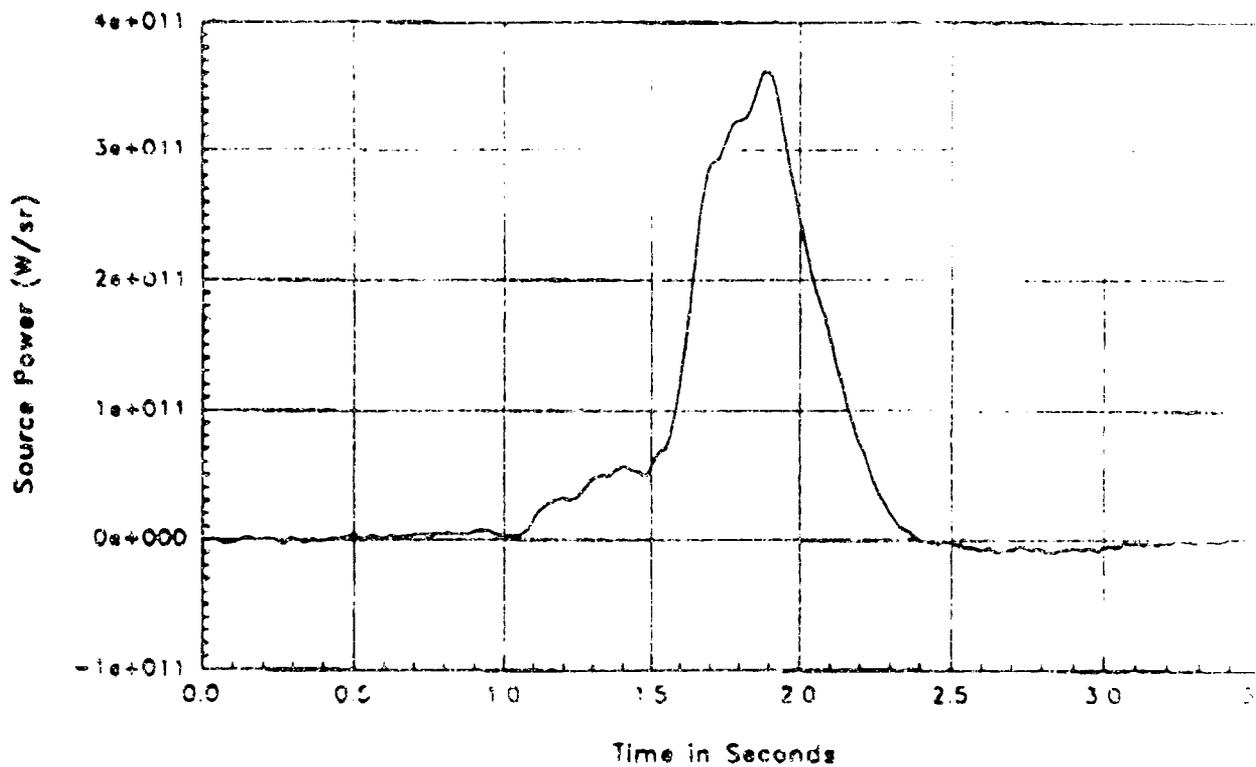


Figure 1 Sensor 1, 1984--037 Deconvolved Input Signal
(10 Hz Smoothing Filter)

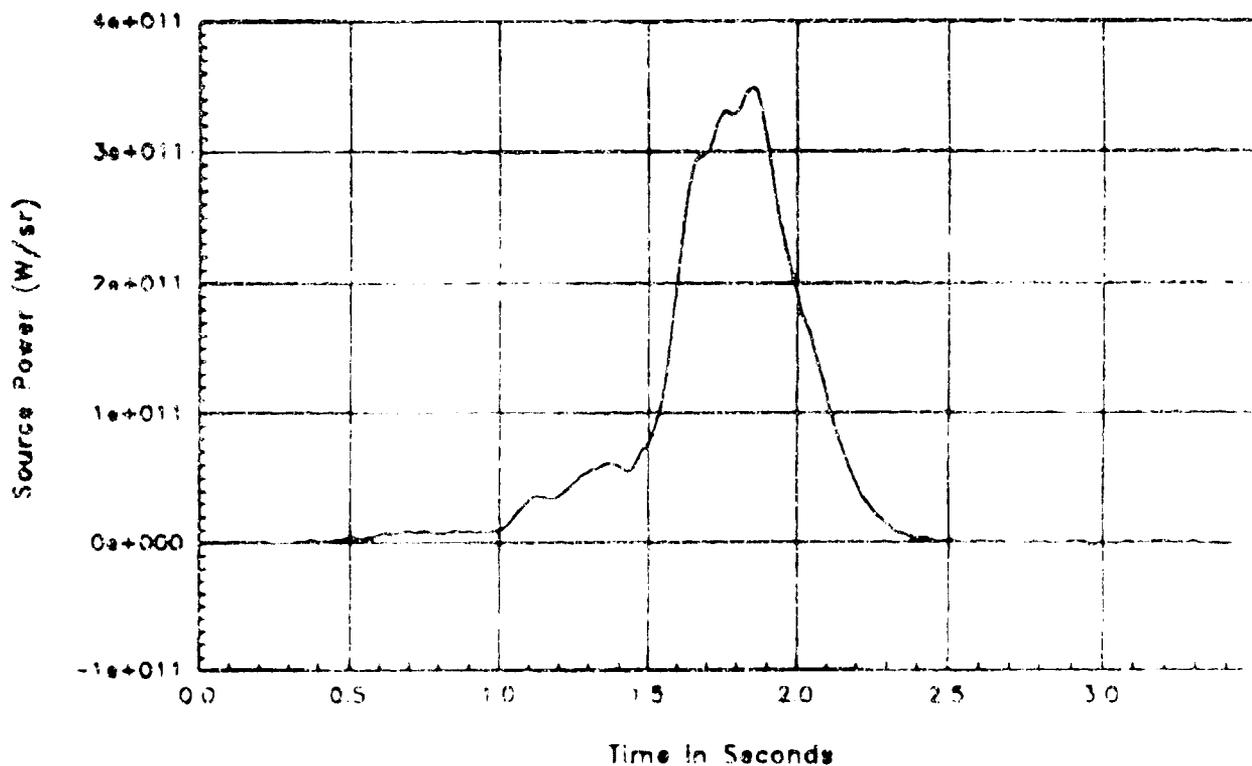
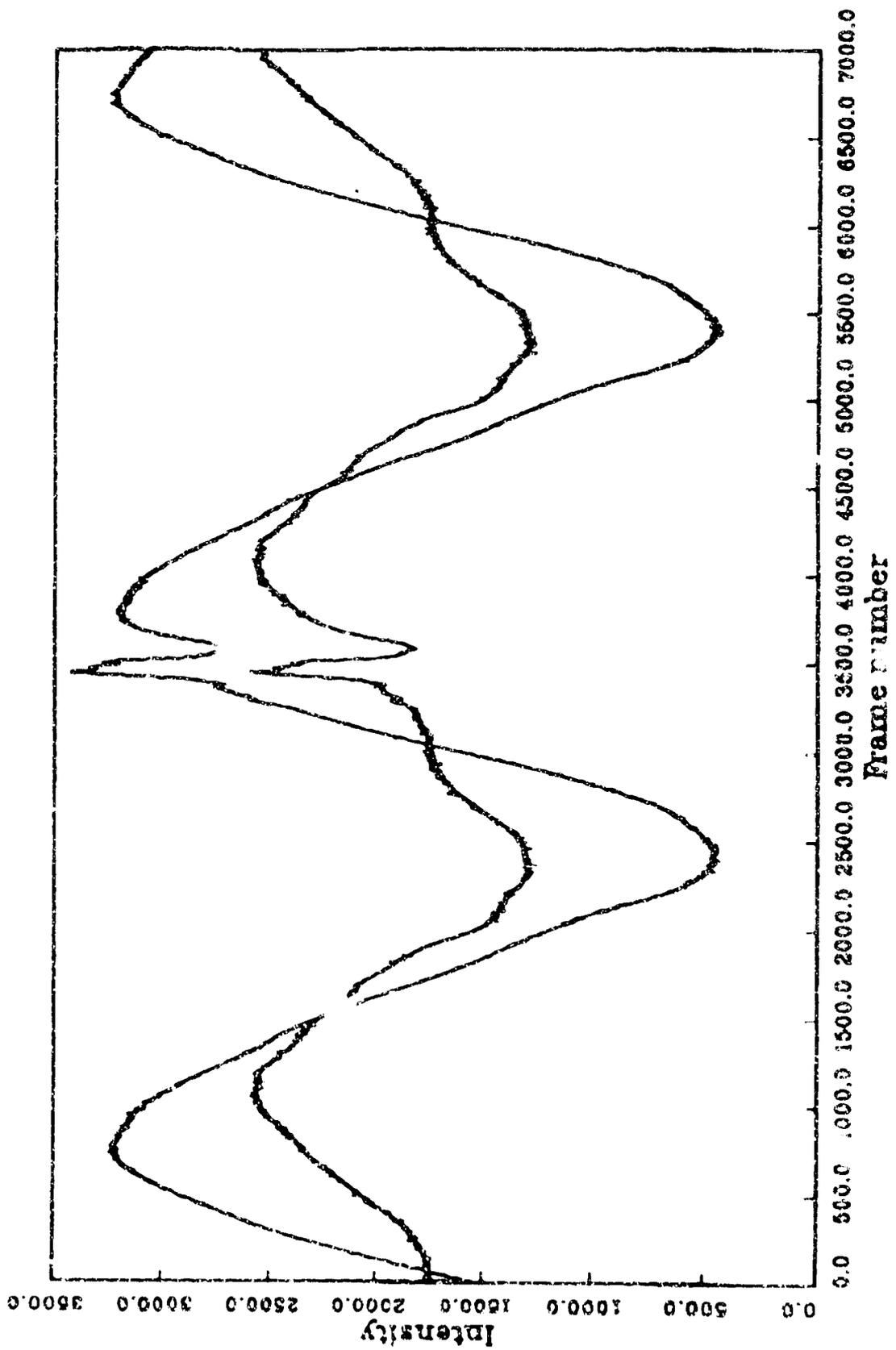


Figure 2 Sensor 1, 1989-048 Deconvolved Input Signal
(10 Hz Smoothing Filter)



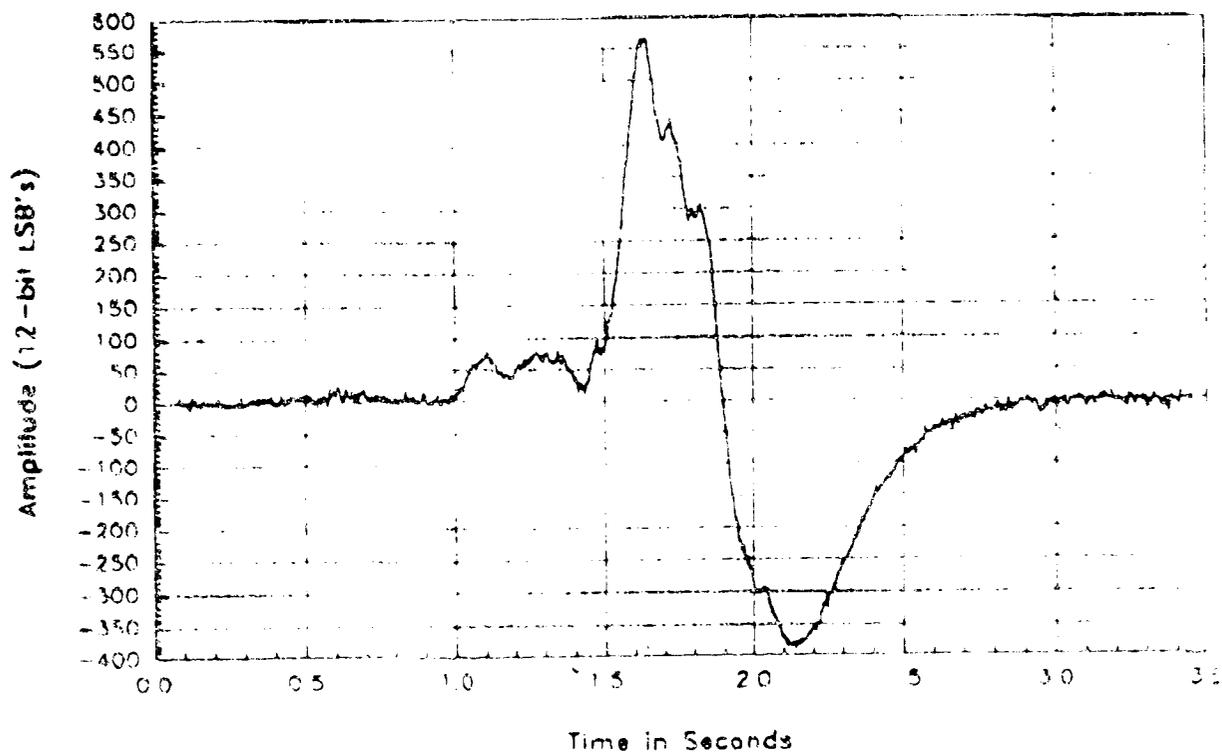


Figure 1 Sensor 1, 1989-046, Output Response

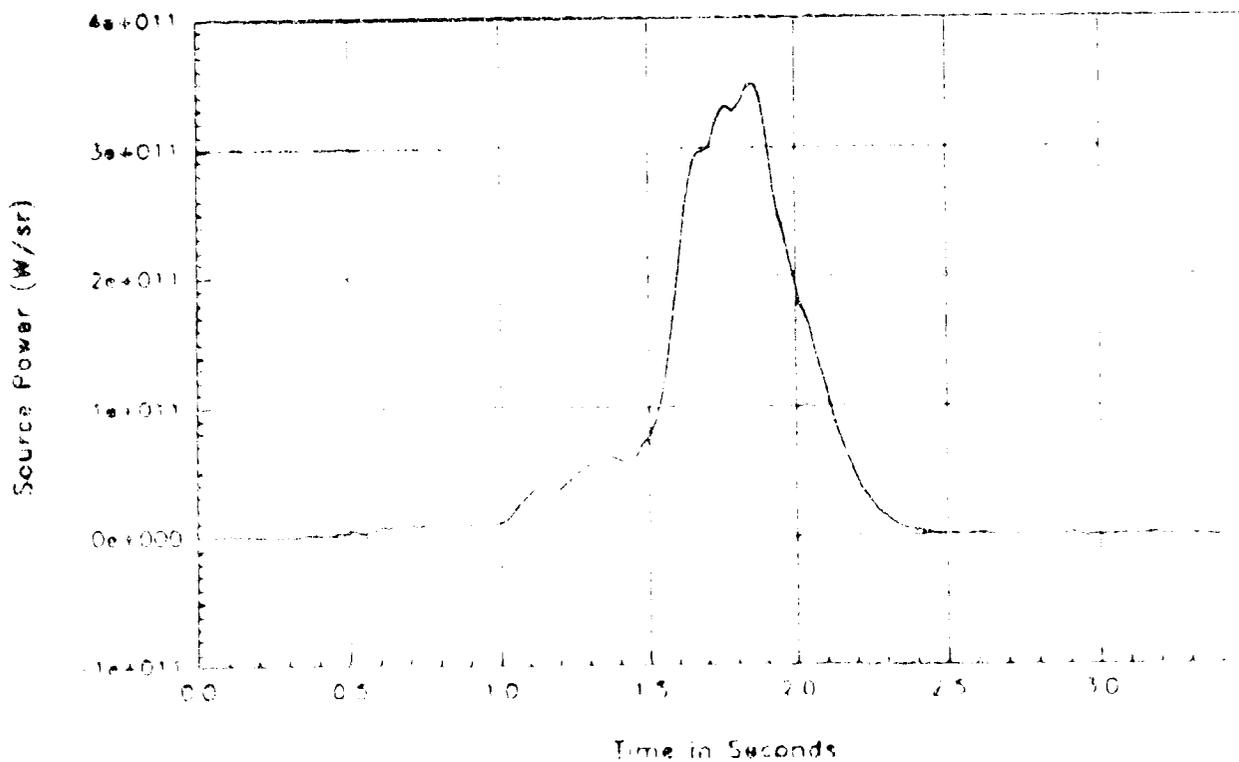


Figure 2 Sensor 1, 1989-046 Deconvolved Input Signal
(10 Hz Smoothing Filter)

6. ASSESSMENT OF CURRENT AND FUTURE TECHNOLOGIES

Workshop Summary

The technology assessment working group was tasked to explore the overall NEO interception challenge from a creative and innovative point of view. A wide range of propulsion options that would enable intercepts of potentially hazardous near-Earth objects were evaluated, together with a range of technology options for deflecting or destroying the NEOs. This assessment was not bound to presently available technologies, but sought ways that technology innovation might lead to improved capabilities. Key features of each of the evaluated propulsion and deflection/destruction options are briefly described in the following sections.

C.1 Methodology

The following criteria were adopted at the outset to provide a systematic basis for the evaluation of each candidate technology:

- Feasibility time frame for application
(now, less than 20 years, more than 20 years)
- Acceptability to the public/world governments
(on a scale of 10 [high] to 1 [low])
- Development cost (millions of dollars)
- Initial mass (tons) in low-Earth orbit (IMLEO) to accomplish task
- Target accuracy (good, questionable, or needing further investigation)
- Travel time to intercept (days)
- Risk of undesirable consequences (low or high)
- Deliverable energy capability (equivalent megatons yield)

The relevant criteria for both propulsion technologies and interception/deflection methods were observed to be essentially independent of interception range, with the exception that travel time and deliverable energy become critically important for close-in intercepts. The options considered therefore were arranged into four groups:

- Propulsion options - Distant intercepts
- Propulsion options - Close-in intercepts
- Deflection/destruction options - Distant intercepts
- Deflection/destruction options - Close-in intercepts

Table 6-1 lists all of the considered candidate technologies in expected order of development time, with near-term options at the top of each group and far-term options at the bottom. The nature of each approach is described in this chapter. Those items above the solid lines are considered essentially to be available now, while those above the dashed lines are considered to be available within the next two decades. Options below the dashed lines probably will require development times greater than 20 years. While all of the items considered are possible from the points of view of physics and engineering, practical considerations eliminate many of them from serious near-term consideration. Nevertheless, the exercise was felt to be important to point the way to future systems concept development and research guidance. The existing and near-term approaches using chemical rockets are self explanatory. Several innovative concepts are described below.

Table 6-1. Technology options considered

		Propulsion Options	Deflection/Destruction Options
Distant Intercepts	Available Now	<ul style="list-style-type: none"> • Chemical rockets 	<ul style="list-style-type: none"> • Nuclear explosives • Kinetic energy (small objects/years warning)
	Development Time Less than 2 Decades	<ul style="list-style-type: none"> • Nuclear rockets • Electric propulsion <ul style="list-style-type: none"> • Nuclear • Solar • Directed energy • Mass drivers 	<ul style="list-style-type: none"> • Nuclear rockets on surface (steam propellant) • Lasers
	Development Time More than 2 Decades		<ul style="list-style-type: none"> • Mass driver on lunar surface • Kinetic energy ("Billiards Shot") • Solar sails • Spark gun • DHe³ fusion driver • Anti-matter
Close-In Intercepts	Available Now	<ul style="list-style-type: none"> • Chemical rockets 	<ul style="list-style-type: none"> • Nuclear explosives
	Development Time Less than 2 Decades	<ul style="list-style-type: none"> • Nuclear rockets • Laser (against small objects) • Hypervelocity nuclear payload and propulsion (Super Orion) 	<ul style="list-style-type: none"> • Hypervelocity penetrators • Brilliant Darts (small objects) • Lasers (small objects) • Brilliant Mountains • Ultra kinetic energy (Super Orion)
	Development Time More than 2 Decades	<ul style="list-style-type: none"> • Hypervelocity lunar launch • NEO artillery in Earth orbit (Brilliant Mountains) 	<ul style="list-style-type: none"> • Anti-matter

6.2 Near-term Innovative Technologies (less than 10 years)

6.2.1 Nuclear Rockets. Nuclear rockets with hydrogen propellant offer significant performance benefits over chemical rockets. They have much higher specific impulse, on the order of ~1,000 seconds compared to 450 seconds for H_2/O_2 rockets. This higher specific impulse allows nuclear rockets to achieve substantially higher final velocities than chemical rockets, at least twice as great for comparable launch weight. Alternatively, for comparable final velocities and payloads, nuclear rockets can be a factor of three to four lower in launch mass.

These performance advantages are of potential benefit for NEO-interception missions. For close-in intercepts, high velocity translates into quicker intercepts, reducing the level of risk and amount of ΔV deflection required. For distant intercepts, lower launch mass translates into lower cost.

Extensive testing of nuclear engines has been carried out by the U.S. in the NERVA program, and by the former USSR. The basic feasibility of nuclear rockets has been well established. Recently, the SNTF particle bed nuclear rocket program has been disclosed by the U.S. Department of Defense. This program is developing a compact nuclear rocket with very high thrust/weight ratio. A prototype engine is scheduled for the late 1990s.

6.2.2 Brilliant Darts. A cloud of hypervelocity penetrators with "smart" terminal guidance was proposed by Hyde and Wood (LLNL) and dubbed "Brilliant Darts." The idea is suitable only for small NEOs (less than 100-meter diameter). The repeated impacts are supposed to fracture the object into small pieces that will either miss the Earth or burn up in the atmosphere at widely separated locations.

6.2.3 Lasers. The possibility of using laser energy to maneuver NEOs was proposed by Phipps (see Proceedings of the NEO Interception Workshop, available from Los Alamos National Laboratory). Current developments promise eventually to produce ultraviolet laser operation in the multi-megawatt regime with high efficiency and potentially low machine weight. Such a device would have to be put into orbit or located on the Moon because the Earth's atmosphere will not transmit ultraviolet light. Alternately, a longer wavelength laser could transmit from the Earth's surface, but would require proportionately enormous optics (here innovative large optics may be of significant help). Any such device could be used to provide ablation-driven momentum transfer to an NEO on repeated near encounters with the Earth at distances of about 10^6 kilometers, provided a relatively long time is available for deflection or if the NEO is not too massive (<100 m in diameter). Since no known objects exhibit appropriate parameters, the idea was deemed technically interesting but not applicable.

6.3 Medium-term Innovative Technologies (less than 20 years)

6.3.1 Spark Gun Propulsion. One way to move an object would be to use the object itself as a rocket propellant. Nearly any kind of object could be used this way by making bullets out of it and shooting it out of guns. The "spark gun propulsion" technique would do this by using the "slapper" technology developed by Sandia National Laboratories. The slapper uses a brief, intense, electric spark as "gun powder" to push a very small bullet. It would shoot many times per second. The projectile would develop 500 s specific impulse at about 80 percent electric efficiency. This would require landing the spark gun device on the NEO, and is thus appropriate only for situations in which years of warning are available.

6.3.3 Mass-driver or Reaction Engine. A reaction engine approach could be based upon a nuclear rocket landed on the surface of the NEO to utilize melted indigenous ice as propellant for the rocket, thus providing thrust for deflection. This concept is clearly only viable for NEOs containing ices (i.e., cometary fragments). Alternately, a mass-driver reaction engine (MDRE) could be landed on the NEO with an appropriate nuclear or solar power generator. The MDRE would use a "moving bucket" to electromagnetically accelerate the loose surface regolith material of the NEO to the desired velocity and then release the contents of the bucket, thus producing a reaction force on the NEO which would gradually deflect its orbit over a period of time. Each time, the bucket would be decelerated and returned to the starting point for refill. A system which would deliver a ΔV of 2 m/s over eight years to a 1-km object with a density of 3.5 gm/cm³ might have the following characteristics:

Material velocity:	8,000 m/s
Specific impulse:	815 s
Length:	1.1 km
Acceleration:	5,000 g's
Power requirements:	142 MW (90% efficiency)
Mass flow:	5 kg/s

This system could be manned, and a system mass including mining equipment, crew quarters, etc., would be 2,500 tons for the outbound flight to the NEO. The reaction engine could use spent tankage from launch as reaction mass. One benefit is that this system could return large quantities of asteroidal resources to cislunar space. Challenges include power switching and conditioning, and physical control of a large object, including management of angular and linear momentum. Human supervision would be required for mining and installation.

6.3.3 Super Orion. The ultra-high thrust rocket called "Orion" was extensively investigated and advocated in the 1960s by Freeman Dyson, Theodore Taylor, and others. This concept called for development of huge spacecraft with tremendous payload capability driven by a high-thrust, low-weight propulsion system using low-yield nuclear explosions with a shock absorber system interposed between the small nuclear devices and the payload vehicle. This concept has been revived by J. Solem⁸ for the NEO intercept mission, dubbed "Super Orion" because it would also deliver a very large payload. This might be the only possible approach that could produce the huge accelerations and high yields needed to intercept a large NEO or comet detected too late for more benign approaches to defense. Ironically, these technologies are quite reachable because of the very large investment that has been made in nuclear explosives over the past fifty years, and the cost of such vehicles and payloads would be low, considering the magnitude of the job to be done. There are, however, important political and cultural problems that must be carefully considered when contemplating a project of such a sensitive nature. Perhaps more acceptable would be new energy technologies farther in the future based upon antimatter nuclear devices or other concepts such as laser-initiated fission or fusion, if either concept proves feasible. Specific impulse from the Orion system was estimated to be in the 10⁴ to 10⁵ second range, which dwarfs other propulsion concepts.

6.4 Long-term Innovative Technologies (greater than 20 years)

6.4.1 Kinetic Launch from the Moon. The Moon might be used in a beneficial way to enhance late-warning time countermeasures against NEOs. For example, the lack of an atmosphere would make mass accelerators and lasers more effective, and in addition, the much lower escape velocity would enable launch of a large mass if a kinetic energy intercept is to be considered.

NASA has already studied several concepts which are lunar-based. Crucial to lunar-based operations is energy generation and storage. The generation of energy could be provided by judiciously located solar collectors. Short-term energy storage could be provided by batteries and flywheels but these may be prohibitively expensive. Long-term storage of significant quantities of energy for launching of large payloads on demand may be more difficult; it assumes that hydrogen and oxygen can be mined on the moon. Supposing that the energy problem can be solved, then a heavy-mass launch can be conceived by such means as gas guns, an electromagnetic rail gun, or a rocket. The mass so launched would then be placed in the path of the approaching asteroid. Additional leverage might be obtained by means of putting several large kinetic payloads into lunar orbit with a rocket propulsion system capable of accelerating the payloads. This approach assumes that a sufficient amount of fuel could be stored with the rocket to make a sudden diversion and approach to the target object possible.

In terms of risk, the methods described are reachable from currently available technologies. However, the mining of hydrogen and oxygen may be problematic. The cost of energy production and storage is assumed to be the major item for the rocket launch. Using a price of \$50M per ton transported to the Moon, the cost of putting a 100-ton solar power plant on the Moon would be \$5 billion. Other items can be scaled appropriately, and would clearly fall into a multi-billion-dollar category. *The NASA Space Exploration Initiative Office should consider uses of the moon for NEO detection and deflection missions.* While we fully realize that this degree of lunar development lies well into the 21st century, such capabilities will eventually emerge. The NEO interests could provide another impetus to accelerate lunar development.

6.4.2 Solar Sail Propulsion. A very large, low-weight, reflector "sail" could be anchored to the NEO, which would then have its orbit altered by solar radiation pressure, which is 9.8 N/km^2 at 1 AU. Drexler, et. al.⁹, have proposed space-based fabrication of very large, microlayer solar sails for asteroid retrieval. The material of the NEO itself might be used for this purpose. Such capabilities clearly depend upon much expanded human operations in space.

6.4.3 Kinetic Energy "Billiards Shot". This concept would employ slight deflection of a relatively small NEO by any means to cause it to impact and alter the trajectory of a considerably larger, Earth-threatening NEO. Clearly this is only practical for distant intercepts, and requires very accurate celestial mechanics capability, including the ability to predict collision consequences. It would greatly reduce energy delivery requirement, however, for dealing with the largest threatening objects (10-km class) because the kinetic energy released in the collision would do the job.

6.4.4 Brilliant Mountains. "Brilliant Mountains" refers to the concept (proposed by T. Zuppero¹⁰) of using nuclear rockets to return large quantities of cometary or asteroidal material from near-Earth objects to Earth orbit. Masses on the order of 1,000 to 10,000 metric tons could be parked in Earth orbit, using water propellant obtained directly from the object itself. The orbits of these masses could then be adjusted when necessary to provide close-in intercept of a dangerous NEO headed for an impact with the Earth. This may be one of the few possible options for dealing with very late detection of a large object. A large mass would be shifted in the way of the incoming NEO at such a position that most of the resulting fragments should miss the Earth. An interesting variation of this idea might be to use regolith material from the Moon, provided that substantial lunar operations become feasible.

6.4.5 Antimatter Energy Sources. Recent experiments have demonstrated that for each proton incident on an antimatter element, 16 neutrons are produced in addition to the

annihilation event. It is estimated that this number can be doubled with appropriate design. Protons can be stored for long times in penning traps. Production of anti-protons can occur in a modest modification of the Fermi Lab's accelerator. If anti-protons can be produced with sufficiently high yields, this might be useful for a small Orion-type device or for initiating a low-weight, high-yield nuclear device for deflecting or destroying an NEO object. The possibility of storing anti-protons in condensed matter for such an application is also being considered.

6.4.6 DHe₂ Fusion Driver. Another high specific impulse system that was proposed is the DHe₂ fusion concept. A large current is induced in a levitated copper ring with external winding to energize a poloidal magnetic field which provides a favorable configuration for a DHe₂ plasma. The fusion reaction produces predominantly protons instead of neutrons, which would then be exhausted through a magnetic nozzle thruster, providing an Isp of 10⁵ seconds with low neutron emission. This would be a low-thrust system attached to the NEO and would have to operate for years.

6.5 Summary

For distant intercepts, Table 6-2 summarizes the Technology working group's assessments for the propulsion options and Table 6-3 the assessments for the deflection/destruction options. For close-in intercepts, Table 6-4 summarizes the assessments for the propulsion options and Table 6-5 the assessments for the deflection/destruction options. The panel used generally similar criteria to evaluate the various propulsion and deflection/destruction options for both distant and close-in intercepts, with the addition of travel time as a propulsion criterion and energy delivery capability as a deflection/destruction criterion for the case of close-in intercepts.

Clearly, distant intercepts would be less difficult than close-in intercepts, and thus appear practical using a wide range of propulsion and deflection/destruction options. Distant intercepts afford greater response times and require smaller deflections. These factors also provide the opportunity to "shoot, look, shoot." Existing options include the launch of chemical rockets carrying nuclear explosive payloads. In the near-term—within two decades—lasers, mass drivers, or "steam propellant" technology may be available. Beyond that, the use of solar sail propulsion or deflection of smaller objects in the path of larger objects may be feasible. In summary, a major development program does not appear required for distant intercepts, although an option beyond nuclear explosives probably should be developed to minimize risk of breakup of the NEO.

As extensively discussed in this report, close-in intercepts would be much more challenging than distant intercepts, as they would require large deflections (and therefore substantial launch velocities), afford shorter travel times (and thus short response times), and limit "shots" to one or two. Fewer technology options exist given these constraints, and all have degrees of risk much higher than the technologies assessed above for distant intercepts. The nature of the risks varies with the option, such as whether or not the NEO may be shattered and still remain dangerous, as with nuclear explosives, or whether the option is technically or politically feasible, as with Super Orion.

For close-in intercepts, which always appear to be a possibility due to long-period comets or previously undiscovered NEOs, the development of advanced propulsion and deflection/destruction options appears desirable. The development of nuclear rockets could greatly cut travel time. If Super Orion were to prove feasible, it would provide by far the shortest intercept time, and thus maximize the chance for a successful intercept. Close-in intercepts require much more detailed study to determine best choices and probable

development times and costs. Such studies should be carried out in advance of any effort to develop a close-in intercept capability.

The bottom line is that chemical or nuclear rockets with nuclear explosives are the only present or near-term technology options available that have significant probability of success without significant research and development activities.

Table 6-2. Propulsion options for distant intercepts

Option	Time Frame for Application	Acceptability	Development Cost (\$)	Initial Mass to Low-Earth Orbit
Chemical	Now	10	Medium	Very high
Nuclear thermal rocket	+8 years	7	Medium	Low
Nuclear electric propulsion	+12 to 20 years	6	High	Very low
Lasers	+10 to 30 years	4	Extremely high	Zero if on Earth
Mass drivers	+10 to 30 years	5	Extremely high	Very high

Table 6-3. Deflection/destruction technology options for distant intercepts of NEOs

Option	Time Frame for Application	Acceptability	Risk Level	Problems	Development Cost (\$)	Initial Mass to Low-Earth Orbit
Mass-driver electromagnetic reaction engines	Medium-term	High	Low	Manned system	+5B	2500 tons
Nuclear explosives	Existing	High	Low	Break-up of NEO	0	<50 tons
Nuclear rockets landed on NEO	Long-term	Low	Low	Auto or manned extraction of propellant	+5B	<150 tons
Solar sails	Long-term	Low	Low	Sail fabrication Handling of large sails	1B	?
Super Orion propulsion	Long-term	Low	High	Radiation damage	5B	?
Anti-matter	Long-term	Low	High	Efficiency Storage	+10B	High
"Spark-gun" propulsion	Near-term	High	Low	Substantial electric source required	+3B	?
Directed energy	Near-term	Low (politics)	Low	Very large optics	+10B	0
Tethers	Long-term	High	High	Control	High	?
Kinetic energy (momentum transfer)	Long-term	High	High	Long-lead Fracture	Requires development of capability	?

Table 8-4. Propulsion options for close-in intercepts

	Time Frame for Application	Acceptability	Development Cost*	Initial Mass to Low-Earth Orbit (Metric Tons)	Inherent Probability (w/Course Corrections)	Time to Travel 1 AU (days)
Chemical	Now	10	Low	~100	>90%	~150
Nuclear rockets	+8 Years	7	Medium	~100	>90%	~75
Super Orion	+20 Years	5	High	~50	>50%	~3
Brilliant Mountains	+30 Years	8	High	NA	>90%	NA
Hypervelocity	+30 Years	8	Medium	~300	>80%	~75
Lasers (small object)	+20 Years	7	Medium	~300	>90%	~50

Options Descriptions:

1. **Chemical:** Chemical rocket launch from LEO or moon to interception point, followed by explosion of nuclear payload (stand-off).
2. **Nuclear rockets:** Nuclear rocket launch from LEO, low-lunar orbit (LLO), or (Lagrangian point 5) (L5) to interception point, followed by explosion of nuclear payload.
3. **Super Orion:** Series of nuclear explosions for sprinting from LLO or L5 to interception point, followed by kinetic energy impact, or explosion of nuclear payload.
4. **Loitering systems (Brilliant Mountains):** Large (~10⁶ T) masses in Earth orbit, directed into the path of the approaching object.
5. **Hypervelocity:** Moon-based gas-gun or electromagnetic launcher for smart masses to impact with approaching object.
6. **Lasers (small object):** Laser propelled launch from LEO or the Moon to intercept an approaching object.

* Development costs: Low < \$10B
 Medium ~ \$10B
 High > \$10B

Table 6-5. Technology options for close-in deflections or destruction of NEOs

Option	Time Frame for Application	Acceptability	Risk Level in Performing Mission	Potential Problems	Development Cost	Weight	Deliverable Energy Capability
Nuclear energy	Available now	Medium	Medium	Well-understood technology	Medium	Moderate	High
Ultra-KE (Super Orion)	Long-term	Low	Medium	Political environment	High	Moderate	High
Brilliant Mountains	Long-term	Medium	Medium	Predictability: Collision of two irregular bodies	High	High	Very high
Anti-matter	Long-term	Medium	High	Containment and delivery	Very high	Low	Very high
Lasers	Near-term	High	Low	Much R&D needed	High	—	Low
Brilliant Darts	Near-term	High	Low	Penetration of irregular bodies	Medium	Moderate	Low

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**“SPACE OPTICAL AND LOW-FREQUENCY RADIO
SEARCHES FOR EARTH-CROSSING ASTEROIDS AND COMETS”**

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ABSTRACT

Earth-crossing asteroids (ECAs) are small and exhibit strong backscattering, so they are usually discovered near opposition during close approaches to Earth. This opposition effect produces large biases in Earth-based searches for ECAs, particularly for Atens. A space platform closer to the sun than the orbit of the Earth, such as a satellite orbiting Venus, would be less biased. All Atens that cross the orbit of the Earth would be observable near opposition from Venus, so a survey from a satellite around Venus would not systematically miss any large ECAs. A satellite in a halo orbit around the Lagrangian point between the Earth and the sun would be particularly effective in detecting objects that are about to hit the Earth including asteroids and long-period comets that are approaching Earth from the sunward side. Spacecraft have observed low-frequency radio emission produced by the wiggling of the magnetic field in the solar wind as it sweeps past a comet. Comets present huge cross sections to the solar wind because of their outgassing. Radio emission at lower power levels is expected from asteroids. This radiation may be observable by a radio array in space or on the moon.

I. INTRODUCTION

The Earth-crossing asteroids (ECAs) found to date have diameters ranging from less than 100 meters to a maximum of about 10 kilometers. Such small objects are difficult to detect except near close approaches to the Earth. They also show a strong opposition effect: at a given distance from the Earth, they are much brighter when observed opposite to the sun in the sky. At opposition their disks are fully illuminated by the sun; they are full in the sense of the full moon. They also have strong back scattering that is similar to that of the moon. Backscattering causes the full moon to be about 10 times more luminous than the quarter moon even though it has only twice its illuminated area.

The opposition effect produces a bias towards discovering asteroids that spend most of their time beyond Earth's orbit. It is much more difficult to discover the Aten asteroids, ECAs with semimajor axes less than that of the Earth that have orbital eccentricities large enough to make them Earth-crossing. Spaceguard, the major asteroid survey proposed by the San Juan Capistrano workshop summary group, would only detect about 90% of the Earth-crossing asteroids one kilometer or larger in diameter after 25 years of observing including only 60 % of the Atens (Morrison, 1992). Aten asteroids are especially treacherous since they are likely to hit the Earth from the day side with no warning. Long-period comets approaching from the dayside also may hit with no warning.

I propose two solutions to these selection effects using space-based observations: An optical search for ECAs from inside the orbit of the Earth and a low-frequency space array to observe radio emission produced when the solar wind hits comets and asteroids.

II. NEW SEARCH TECHNIQUES

A. Satellites and Space Probes inside the Orbit of the Earth

The optimum place to optically search for Earth-crossing asteroids is from a spacecraft orbiting the sun in the ecliptic plane well inside the orbit of the earth. During the course of a few orbital periods, this space platform would see all Earth-crossing asteroids near opposition including those that have aphelia on the order of 1 A.U. Such objects are hard to observe from Earth because they are not seen at opposition except during a near miss encounter with Earth. A good position for such a platform would be a satellite orbiting Venus because it is in darkness when it is observing near its opposition point. Another good position for a space platform is in a halo orbit around the Lagrangian equilibrium point lying between the Earth and the sun.

The Spaceguard survey would use a battery of telescopes about 2.5 meters in diameter to detect asteroids down to magnitude 22. The number of new asteroids discovered per year with the Spaceguard search program is predicted to decrease greatly after the first 5 years (Morrison, et. al. 1992), which greatly increases the marginal cost of discovering each new asteroid. It suggests that the Venus orbiter or other space platform should be in place about 5-10 years after the start of the Earth-based Spaceguard survey.

At some point, all ECAs will approach opposition when observed by the Venus satellite. When observed at opposition from Venus, an asteroid 50×10^6 km away with an albedo of 0.20 is at magnitude 13 if it is 1 km in diameter and at magnitude 18 if it is 100 meters in diameter. This distance is greater than the minimum separation of Earth and Venus. A telescope 40 centimeters in diameter would reach magnitude 18 with the detectors proposed for the Spaceguard telescope. The Venus satellite survey with a telescope of this size would not only fill in the gaps in the large ECAs (diameters greater than 1 km) left by the Spaceguard survey, but it would detect most ECAs with diameters down to 100 meters.

While a satellite around Venus may be ideal for finding and cataloging the larger Earth-crossing asteroids without systematic biases, it may not be the best platform for detecting those long-period comets that hit the Earth from the direction of the sun. A satellite at the sun-Earth Lagrangian halo point would be particularly effective at detecting objects shortly before they strike the Earth. It could be the outer "eye" of a terminal defense system against impacting asteroids while radar would be the inner "eye" (Hills, 1992). A satellite at this Lagrangian point would see all intruders at opposition (full phase) as they approach Earth. It could easily detect objects 10 m across as they cross the orbit of the Earth.

B. Low-Frequency Radio Emission

When the solar wind impacts an asteroid or a comet, it drapes its magnetic field around it. Wiggles in this magnetic field produce Alfvén waves that propagate through the plasma as radio emission (David Westpfahl, New Mexico Tech, in a LANL Seminar). This low-frequency emission has been observed by spacecraft passing near comets. Unfortunately, it cannot be observed from Earth because it cannot penetrate the ionosphere.

Galen Gisler (SST-3, LANL) estimates that the radio emission is in the range of a few hundred to a few thousand Hertz for asteroids. The Galileo spacecraft passed near the asteroid 951 Gaspra in October 1991. The spacecraft has a plasma probe with a frequency response up to a few megahertz. This probe presumably saw any electromagnetic radiation coming from the asteroid. This data is not yet available, but it would provide a good test of the possibility of using low-frequency radio emission to detect asteroids.

To detect asteroids and comets by their low-frequency radio emission would require a large radio array in Earth orbit or on the moon. Such an array could be built very cheaply on the moon (excluding launch costs). Unfortunately, it would have to many hundreds or thousands of miles across to produce an image in the low-frequency radio with any appreciable resolution.

There remain large uncertainties in using low-frequency radio emission to detect comets and asteroids. We need a clearer theoretical understanding of the observed phenomenon, more measurements of the radio emission from comets and asteroids by spacecraft passing near them, and a better understanding of the expected background emission from other sources at the search frequencies.

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**“CAPTURING ASTEROIDS INTO BOUND ORBITS AROUND THE EARTH:
MASSIVE EARLY RETURN ON AN ASTEROID TERMINAL DEFENSE
SYSTEM”**

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held at Los Alamos National Laboratory, January 14-16, 1992

ABSTRACT

Nuclear explosives may be used to capture small asteroids (e.g., 20-50 meters in diameter) into bound orbits around the earth. The captured objects could be used for construction material for manned and unmanned activity in Earth orbit. Asteroids with small approach velocities, which are the ones most likely to have close approaches to the Earth, require the least energy for capture. They are particularly easy to capture if they pass within one Earth radius of the surface of the Earth. They could be intercepted with intercontinental missiles if the latter were retrofit with a more flexible guiding and homing capability. This asteroid capture-defense system could be implemented in a few years at low cost by using decommissioned ICMs. The economic value of even one captured asteroid is many times the initial investment. The asteroid capture system would be an essential part of the learning curve for dealing with larger asteroids that can hit the earth.

I. FLUX AND CHARACTERISTICS OF SMALL ASTEROID INTRUDERS

An asteroid 100 meters or larger in diameter (such as the Tunguska impactor of 1908 or the nickel-iron one that produced Meteor Crater in Arizona) hits the earth about every 200 years (Shoemaker, et. al. 1991). If we can ignore gravitational focusing, this requires that such an asteroid pass within 10 earth radii ($10 R_{\oplus}$) = 64,000 km about every other year and within the orbit of the moon every month. An asteroid 30 meters in diameter hits the earth every 5 years, passes with $10 R_{\oplus}$ about 20 times a year, and passes within the orbit of the moon every day. Since about 5% of the asteroids are nickel-iron, we expect a nickel-iron meteoroid 30 meters or more in diameter to pass within $10 R_{\oplus}$ every year. Such an object hits the earth about every 100 years and passes within 1 earth-radius of the surface of the earth about every 25 years. The capture of such a nickel-iron meteorite into orbit about the earth would be a major asset for future manned activity in space.

If the approach velocity, V_{∞} , of an asteroid when it is far from the earth is smaller than the escape velocity, V_{esc} , from the earth, the asteroid is particularly easily captured

in close approaches to the earth. The velocity of the object at its closest approach distance, d , to the center of the earth is, from energy conservation,

$$V_d = \left[V_\infty^2 + V_{esc}^2 \left(\frac{R_E}{d} \right) \right]^{1/2} \quad (1)$$

Here $V_{esc} = 11.2$ km/s. About 15 % of known NEAs have V_∞ less than V_{esc} and some have V_∞ less than 6 km/s (derived from table provided by Shoemaker, et. al. 1991). If $V_\infty = 6$ km/s and $d = R_\oplus$, then $V_p = 12.7$ km/s. This object would only have to be slowed by 1.5 km/s at distance d to bring it into a bound orbit around the earth (to get V_d below V_{esc}). (If a meteoroid is found with an approach velocity of 1 km/s, the required reduction in velocity for capture drops to only 0.04 km/s).

II. CAPTURING THEM WITH NUCLEAR EXPLOSIVES

The only feasible way of capturing such an asteroid into a bound orbit around the earth is with nuclear explosives. Fortunately, such explosives and the means to deliver them to an asteroid passing near the earth are readily available at small marginal cost due to the continued decommissioning of many American and Russian ICMs. Even asteroids passing within the orbit of the moon can be reached by adding a single extra stage to an ICM. This would be particularly easy for missiles with MIRVS such as the MX that could be reduced to one explosive charge.

Properties of nuclear explosions and their capabilities for changing the velocities of asteroids have been outlined in this conference by J. Solem and C. Phipps. We found earlier that to capture an asteroid with a velocity at infinity of 6 km/s requires that we decrease its velocity by only 1.5 km/s if it makes a close encounter to the earth. We consider capturing an iron meteoroid with a diameter of 35 meters, a density of 7.5 grams/cm³, and a mass of 1.7×10^5 metric tons. The energy needed to capture this object into a bound orbit is 150 kt if 20 % of the asteroid mass is blown off in the forward direction and all the energy of the bomb goes into ejecting this mass (at 6.2 km/s) (The energy requirement drops to

30 kt for a 20- meter asteroid. It would drop to less than 1 kt for the larger asteroid if one could be found with an approach velocity of 1 km/s or less.) The bomb has to be several times this minimum value because of various inefficiencies, but this illustration shows that the capture of a nickel-iron asteroid is possible with readily available technology.

The material blown off the front (in the direction of motion) of the asteroid by the explosion has a hyperbolic velocity and escapes the gravitational field of the earth. Because of its high tensile strength, it will not be difficult to hold the captured nickel-iron asteroid in one piece. Stony asteroids are more fragile. We may wish to capture only those with very low approach velocities with respect to the earth to minimize the required explosion energy. Some development work is needed to better understand how nuclear explosives couple to asteroids of various compositions. We also need to develop blankets for nuclear explosives to "cool" them: minimize the gamma rays, x- rays, and neutrons they emit, so they do not harm satellites and the magnetosphere of the earth. We may wish to practice intercepting the asteroids at lunar distances before attempting to intercept one in a close approach to the earth. The ability to capture objects with nuclear explosives is clearly achievable and could be implemented in a relatively short time at a relatively low cost using decommissioned ICMs and nuclear explosives.

A captured asteroid would be a major asset. It costs about $\$10^6$ /metric ton to launch to low-earth orbit (LOA) and much more to higher orbit. To launch the mass of a 35-meter nickel-iron meteorite into LOA would cost about $\$ 2 \times 10^{11}$ or 10% of the GNP of the U.S.A. Alternatively, to capture it into earth orbit may take only one surplus ICM and warhead if the closest approach of the object to the surface of the earth is one earth radius or less. If these missiles and warheads are scheduled to be decommissioned by treaty, the marginal cost of fitting each for this mission may be less than $\$10^7$, which potentially gives a return on the initial investment as high as 10,000 to 1. Development costs and the need for redundant missiles will reduce this return, but it is still substantial.

The captured NI asteroid would be a source of material for future activity in space. It could be hallowed out to produce a large space station. Objects fired off the captured

asteroid at its closest approach to earth would be given a boost by being within the potential well of the earth. A rail gun could be used to eject the objects. This physical process is the reverse of the one that allowed the capture of the asteroid into earth orbit. If the object is ejected at 1.5 km/s in the direction of motion of the captured asteroid at its closest approach to the earth, its escape velocity from the earth is 6 km/s. The rail gun could be used to launch cheap probes to the larger earth-crossing asteroids (NCAs). A number of these probes are needed to characterize the various types of NCAs and short-period comets.

The metal in a captured nickel-iron asteroid could be melted using a solar furnace. A good candidate may be the gas lens (a large plastic balloon shaped like a lens and filled with gas) mentioned in this conference by Claude Phipps. A lens several hundred feet across would be lightweight and cheap.

III. DETECTING INTRUDING SMALL ASTEROIDS

An object 35 meters across could be detected with current military radar within 10^5 km of the earth (Greg Canavan, this conference). The U.S. and Soviet strategic radars cover a large fraction of the sky above the earth. Currently, the radars only see objects near the earth to reduce computer processing. The computer software clips off (ignores) signals with long delay times that correspond to objects far from the earth. Because the maximum possible number of Soviet missiles that can be directed to the U.S. is decreasing as the result of arms control agreements, the U.S. Air Force radar has decreasing processing needs. The increasingly available processing capability makes it possible to search a larger volume around the earth. I propose using existing radars with their delays extended so they can observe objects out to at least 10^5 km. This would allow us to detect asteroids several hours before they hit the earth. It would also provide a scientific return by accurately determining the orbital elements of meteoroids that pass near the earth, their sizes and impact velocities. Because of its all-weather capability, radar is likely to be part of the

terminal defense system for asteroids. Ultimately, it would be desirable to build radars in the southern hemisphere to provide all-sky coverage of asteroids approaching the earth.

A satellite with even a small aperture camera equipped with a large CCD placed in a distant orbit around the earth (at the moon's distance or greater) could detect small asteroids approaching the earth. A satellite at the Lagrangian L_2 point, which lies inside the earth's orbit around the sun, would be particularly effective. It would always see the asteroids approaching the earth as full (in the sense of the full moon), so they would appear at their brightest (the opposition effect). It would see much smaller objects at large distances from the earth than is possible with radar, which suffers from the r^{-4} dilution effect. It would not suffer from weather or the inability of detecting asteroids that are approaching from the direction of the sun, which are the primary limitations of earth-based camera systems.

IV. HOW SHOULD THIS BE IMPLEMENTED ?

The asteroid-capture program could be operational in less than five years. It also would be the first terminal defense system for asteroids that approach the earth undetected until they pass within the range of the defense radars. This would provide valuable experience for building a more robust system to protect us against all asteroids.

In the first phase of the program, some ICMs that otherwise would be decommissioned under the arms control agreements would become asteroid interceptors. These recommissioned rockets would be used both to capture small asteroids into bound earth orbit and to provide a rudimentary defense against incoming small asteroids. The first such missiles would be ICMs with upgraded guidance and homing capabilities. Their nuclear explosive would not be put in a re-entry vehicle to assure that they cannot be exploded within the atmosphere of the earth. Instead, they would be encased in a blanket provided by the National Laboratories to cool them sufficiently that x-rays, gamma rays, and neutrons from them are not a hazard to spacecraft in earth orbit. These missiles would likely be subject

to continuous international inspection to assure that they are not converted to weapons use. We would invite the Russian state to institute a similar program with some of their decommissioned missiles and nuclear explosives. Their program would be coordinated with ours.

The second phase would be to add another stage to the larger decommissioned ICMs such as the MX. This would extend the range of the missile to escape velocity from the earth. This would allow asteroids to be intercepted much farther from the earth, i.e., at the distance of the moon or greater. This may provide a large enough lever arm to allow many asteroids in collision orbits with the earth to be deflected away from the earth before they strike it. Otherwise, we could only blow them into small pieces and let the atmosphere provide the final defense. This second phase would have the goal of defending against asteroids up to 1 km in diameter that are only detected in their final approach to the earth. It also would allow small asteroids to be captured into large semimajor axis orbits around the earth, which would allow them to be used as way stations for manned intrusions into the solar system.

The phase 2 work would dovetail into the proposed earth-based survey to find nearly all earth-crossing asteroids with diameters greater than 1 km over a 20-year period. These large asteroids can only be deflected away from earth, if they are hit with nuclear explosives several orbital periods before they would otherwise hit the earth.

A Phase 3 or Phase 2b program may be the development of tailored made rockets and nuclear explosives to deal with the asteroid threat. This program can be implemented faster if Russia joins the program. The Russian Zenit 2 rocket would be particularly effective for close-in intercept because it is designed to be fired off on short notice. It is said to have a built-in flexible guidance system that allows the operator to dial in any position and velocity within the energy capabilities of the rocket.

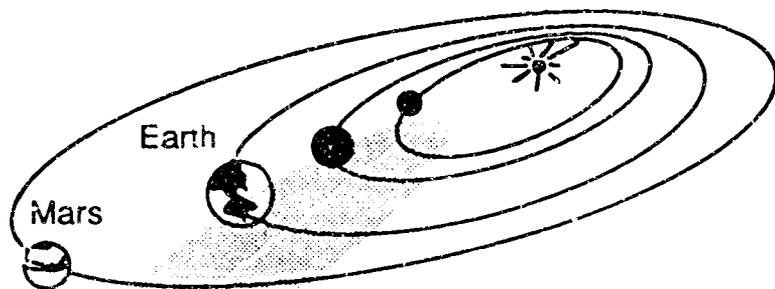
Later, it would be desirable to extend the catalog of asteroids with known orbits down to those with diameters well below 1 km, so dangerous ones can be deflected at greater

distances from the earth. New surveys based on observations from satellites orbiting Venus and at the L_2 point of the earth (discussed by the author in another report in the Conference Proceedings) would be used to fill in the systematic gaps left by the earth-based survey and to extend the survey to much fainter asteroids. These satellites would also warn of the approach of long-period comets that currently could hit the earth without warning from the direction of the sun.

III. REFERENCES

- Shoemaker, E.M., Wolfe, R.F., and Shoemaker, C.S. (1990), *Geological Society of America Special Paper 247*, "Asteroid and Comet Flux in the Neighborhood of Earth"
- Shoemaker, E.M., Wolfe, R.F., Shoemaker, C.S., Bowell, E., and Muinonen, K. (1991).
Unpublished *Proceedings of the San Juan Capistrano Conference on Near-Earth Asteroids*

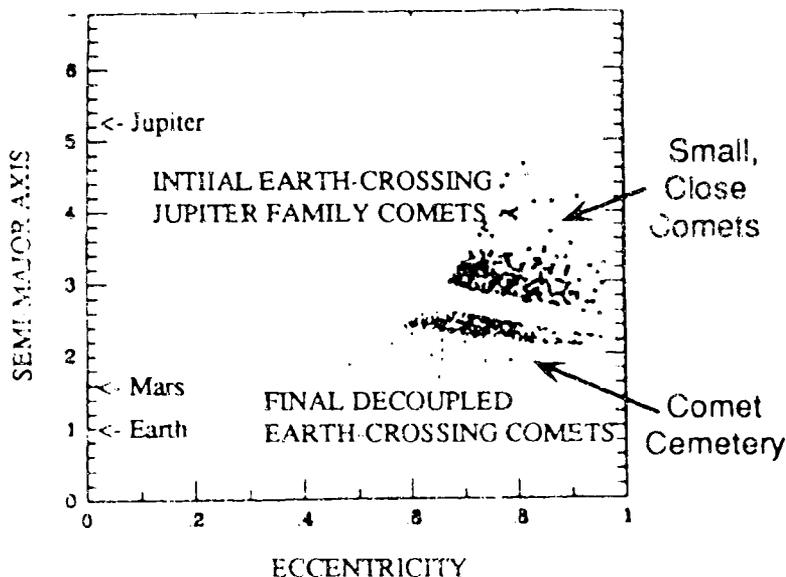
Discovery in Near-Earth Space: = Fuel, Food, Shelter & Close



Formation of Never-Far Comets
(Yeomans-Wetherill Formation)
- H₂O, CO₂, CO, NH₃
- carbon organics

DISCOVERY IN NEAR-EARTH SPACE Anthony Zuppero Idaho National Engineering Laboratory

Never-Far Comets: Some Always Very Close



From: Wetherill, G.W., "End Products of Cometary Evolution: Cometary Origin of Earth-Crossing Bodies of Asteroidal Appearance" Figure 5, page 547, R. L. Newburn, Jr. et al. (eds), Comets in the Post Halley Era, Vol. 1, 1991 Kluwer Academic Publishers

The discovery in 1991 of a km sized object containing what appears to be so much water ice that asymmetric evaporation pressure is changing its orbit, and at the same distance from the Sun as Earth, was like discovering a gushing oil well.

This discussion shows that 1. we apparently found rocket fuel objects in the space near Earth; 2. the objects are "close" compared to planets and asteroids; 3. they are "easy" to access and exploit, in the sense of the complexity of space machinery; and 4. an affordable prospecting plan can have small early costs.

- fuel
- close
- easy
- prospecting plan

The objects are comet cores. Observations of the comet Halley lead us to believe that comet cores contain water ice (~85%), CO and CO₂ (~10%), ammonia (~0.5%), some percent stones or dirt, and are covered by a layer of sooty tar with thickness between 0.1 and 500 meters. These are the raw materials to make rocket fuel, plant food and construction material.

Comet cores belong to formations whose objects are never far from Earth (never-far comets, NFC's, †). The Jupiter Family of comets feeds the formation. This family contains about 150 active comets and are also "never far" because their farthest distance from the Sun is typically near Jupiter's orbit. A typical closest approach is somewhere between Mercury and just past Mars.

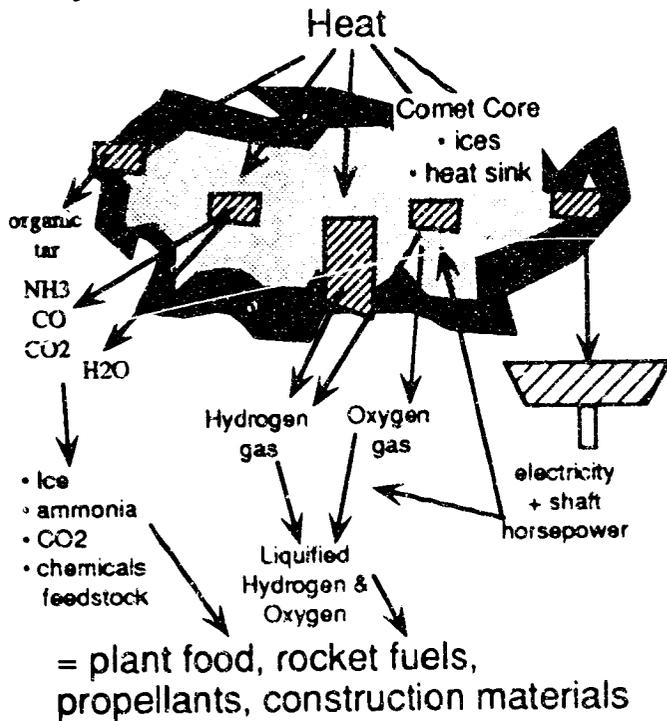
Wetherill* predicted the formation. He calculated that an entire formation of spent comets should exist with average semi-major axes of 2.2 AU (Earth is at 1 AU from the Sun) and with high eccentricities, above 0.5 (Earth has near 0). The gravity of the planets modifies the semi-major axes of the Jupiter Family comets so that they either crash into a planet, or become ejected from the Solar System by encountering Jupiter or Saturn, or migrate to the Comet Cemetery. When Jupiter Family comets die, some go to the Comet Cemetery.

Yeomans* found that Icarus at 1 AU and Apollo, at about 1.47 AU both have orbit features unique to comets.

In other words, he found what appear to be billion-ton steaming fuel objects in the predicted formation, near Earth.

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 17Feb92

Comet Cores Are Very Convenient Resources



Comet cores are fuel, extremely useful and valuable, massive and accessible because of low gravity.

Their water ice is the basis for rocket fuels and propellants. The water, CO₂ and ammonia are the three key plant foods. The ice and tar mixtures are easily thawed and frozen into space structures.

Heat alone liberates water. Heat alone converts a mix of soot and water into hydrogen and other gasses.

Passing water over 1200 kelvin carbon (soot, tar) taken from the comet outside and heated by a nuclear or solar source drives the "gas shift reaction," which produces CO and H₂ directly.

Passing steam through a turbine using the ice heat sink produces the shaft pumping power needed to compress and liquefy these gasses on the comet. The comet ices provide the heat sink needed for the refrigeration process.

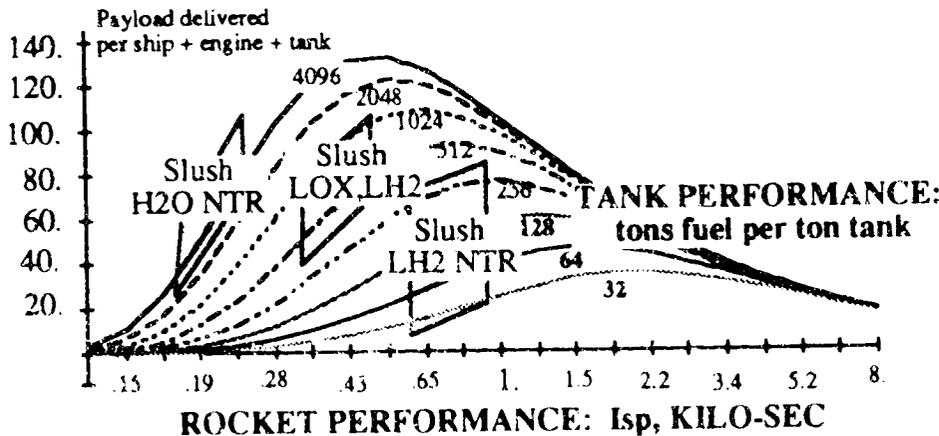
Heat sinks designed to work in the vacuum of space weigh too much, and we don't need them on a comet. This simplicity is crucial for industrial or commercial space processing.

Even though a 1 km sized object contains about 1 Billion metric tons of material, its gravity is so low that a space tanker needs only small retro rockets to land on or leave it. A Billion tons is about 100 000 times what we have launched in the history of space (10 000 tons). A space tanker hauling 20 times this amount away from such a small comet core would need a rocket with only 10 tons thrust.

It would take a 1 000 years to exhaust just one such comet if we extracted a Million tons per year. A Million tons would make and fuel 10 space ships each holding 10 000 workers going on safe, fast trips to comet cores. Only people, seeds and tools need be launched. The comet cores would provide the food, fuel and shelter.

Simple Fuels From Comets Can All Give Big Payback Ratios

PAYBACK RATIO



Minimum ΔV 6300 m/s
Run time 18 1/2 hours
Power 1600 Mega Watts

Engine wet weight 10 tons
Number engines 3
Ship structure weight 53 tons

Ship, less payload & tanks 103 tons
Efficiency 0.93
Energy to Fuel 5.04E+14 Joules

Or, liquid hydrogen and oxygen can be used in conventional, non-nuclear rockets. Electricity would be produced from the comet water turbines. It would split the water into hydrogen and oxygen gasses. The gasses would be compressed and cooled as for the liquid hydrogen rocket. This would allow us to keep the nuclear systems in deep space and yet deliver pure rocket fuels to Earth orbits.

The never far comets are "easy" to access because their materials can be simply converted into familiar rocket fuels or propellants, and in mass quantities. For example, water from comet ice can be used as a nuclear heated steam rocket. The reactor would operate at a somewhat "low" temperature of 1200 Celsius, develop a "low" specific impulse (Isp) of 235 seconds, consume 20 times more water than the mass of payload delivered, and still deliver 100 times as much as the space tug sent out to get the payload.

Or, liquid hydrogen can be used in a nuclear thermal rocket, like a NERVA rocket. Hydrogen gas would be produced in kiloton quantities by passing 1 000 Celsius water through orange-hot, 1 000 Celsius soot. It would be compressed and liquefied using pumps powered by comet water turbines using the -50 Celsius comet ice as heat sink. No electric generators would be needed. And the resulting rocket would provide the high mission velocity required for human transport.

Earth Capture ΔV Reasonable for Never Far Comets & NEO's

Some Comets In Jupiter Family	Closest Approach to Sun,					ΔV km/s
	1.2	4.8	2.9	8.6	0.6	
	Farthest Distance From Sun, A.U.					
	Orbit plane, degrees					
	Earth capture V_{∞}					
	Velocity at comet					
	km/s					
P/du	1.2	4.8	2.9	8.6	0.6	5.5
P/Finlay	1.0	6.1	3.7	9.3	0.2	5.9
P/Neujmin 2	1.3	4.9	5.4	8.7	0.9	5.9
P/Tuttle-Giacobini-Kresak	1.1	5.1	9.2	9.2	0.5	6.0
P/Howell	1.4	4.9	4.4	8.7	1.2	6.2
P/Haneda-Campos	1.3	5.6	4.9	9.1	0.8	6.2
P/Schwassmann-Wachmann 3	0.9	5.2	11.4	9.4	0.6	6.3
P/Wirtanen	1.1	5.1	11.7	9.4	0.6	6.4
P/Churyumov-Gerasimenko	1.3	5.7	7.1	9.3	0.9	6.5
P/Forbes	1.4	5.3	7.2	9.1	1.3	6.6
P/Tritton	1.4	5.4	7.0	9.2	1.2	6.7
P/Wild	1.6	5.3	3.2	8.9	1.5	6.7
P/Kopff	1.6	5.3	4.7	9.0	1.5	6.8
P/Clark	1.6	4.7	9.5	8.9	1.7	6.9
P/Tempel 1	1.5	4.7	10.6	9.0	1.5	6.9
P/du Toit-Neujmin-Delponte	1.7	5.2	2.9	8.8	1.8	6.9
Comet Cemetery						
Apollo	0.6	2.3	6.3	5.7	2.2	4.5
Adonis	0.4	3.3	1.4	7.1	3.2	6.7
Icarus	0.2	2.0	22.9	7.8	7.2	11.3
Near Earth Asteroids						
Ra-Shalom (type	0.5	1.2	15.8	4.4	3.0	4.5
1988 TA (type	0.8	2.5	2.7	5.8	1.2	5.6
1979 VA (type	1.0	4.3	2.8	8.2	0.1	4.6
1986 JK (type	0.9	4.7	2.1	8.5	0.4	5.2
1987 PA (type	1.2	4.3	16.1	9.4	1.2	6.9
1983 SA (type	1.2	7.2	30.8	13.4	1.7	11.9
More						
P/Boethin	1.1	9.1	5.2	10.3	0.4	7.1
P/Kohoutek	1.8	5.3	5.9	9.0	1.9	7.3
P/Schwassman-Wachmann 2	2.1	4.8	3.8	8.6	2.6	7.5
P/Kojima	2.4	5.5	0.9	9.0	2.8	8.1
P/Bowell-Skiff	2.0	10.8	3.8	10.6	1.3	8.3

How far away are the Never Far Comets? "Close."

The ΔV needed to bring a load back to an orbit around Earth from one of them is one answer. We have to know the ΔV to design a space tanker to haul fuels or materials back from the objects. If the total ΔV is less than about 7 km/s then the object is "close."

The mission consists of a thrust at the comet to leave it on a head toward Earth and of another thrust at Earth to cause capture. The thrust at the comet is the easier of the two because it can be performed over a long time, of order months, and because it is usually smaller, with a velocity at the comet of order less than 2 km/s.

The thrust at Earth capture is more difficult because it should be performed all at once and at the point of closest Earth approach.

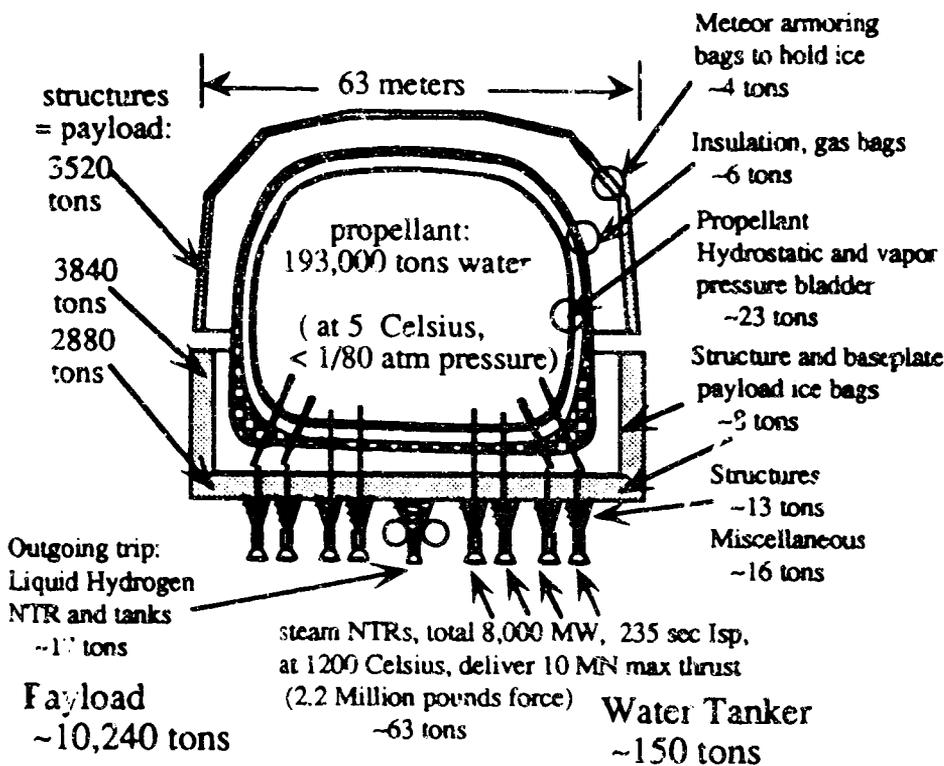
The Earth capture velocity, V_{∞} , can be achieved by a thrust developing a much smaller velocity if the thrust is performed at closest approach. A real vehicle carrying a large, 10 000 ton payload would take several hours of thrusting, which is imperfect. A somewhat imperfect maneuver can result in a capture ΔV that is as little as 50% more than the smaller, minimum ΔV .

The table gives the total ΔV for such imperfect maneuvers. It is the sum of the velocity at the comet and the velocity of an imperfect, 50%-over-minimum capture maneuver that achieves V_{∞} .

Note that a good fraction of the objects in the table have less than about 7 km/s ΔV . This means at least a dozen known fuel objects are "close."

Some day.....

Simple Tanker Can Use Water Propellant To Deliver 10,000 Ton Payloads



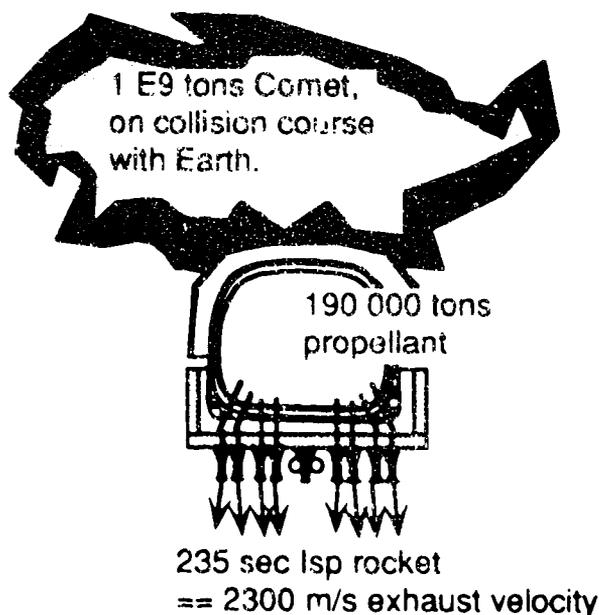
The comets are "easy" because we can design simple ships to use comet ice as payload, structure and propellant. Such a ship would deliver about 100 times its weight as useful payload to an Earth orbit.

The comet water is exceptionally convenient because we can use it directly in a nuclear reactor. We must only be sure to very carefully clean it from rocks, dirt and minerals. It is also very convenient because we can contain liquid, cold water in very low weight bladders. The water has very low vapor pressure. It is very convenient again because it freezes easily in the cold of space into a moderately hard structural material. Bladders shaped like the structure we want can form the water into rigid ice containers, shields and platforms.

This example shows that about 23 tons of bladders would hold about 190 000 tons of water propellant. Another 4 tons of bags would hold 10 000 tons of ice to be used as meteor and debris shields, and also make up the 10 000 ton payload and a ship platform. The rocket engines would be nuclear reactors heating water into steam, and the steam would go directly into the rocket nozzle.

Though this is an inefficient use of an abundant resource (comet ice) it may turn out to be the most efficient use of expensive, launched hardware.

Tanker Could Push Killer Comet Out Of Earth-collision Orbit



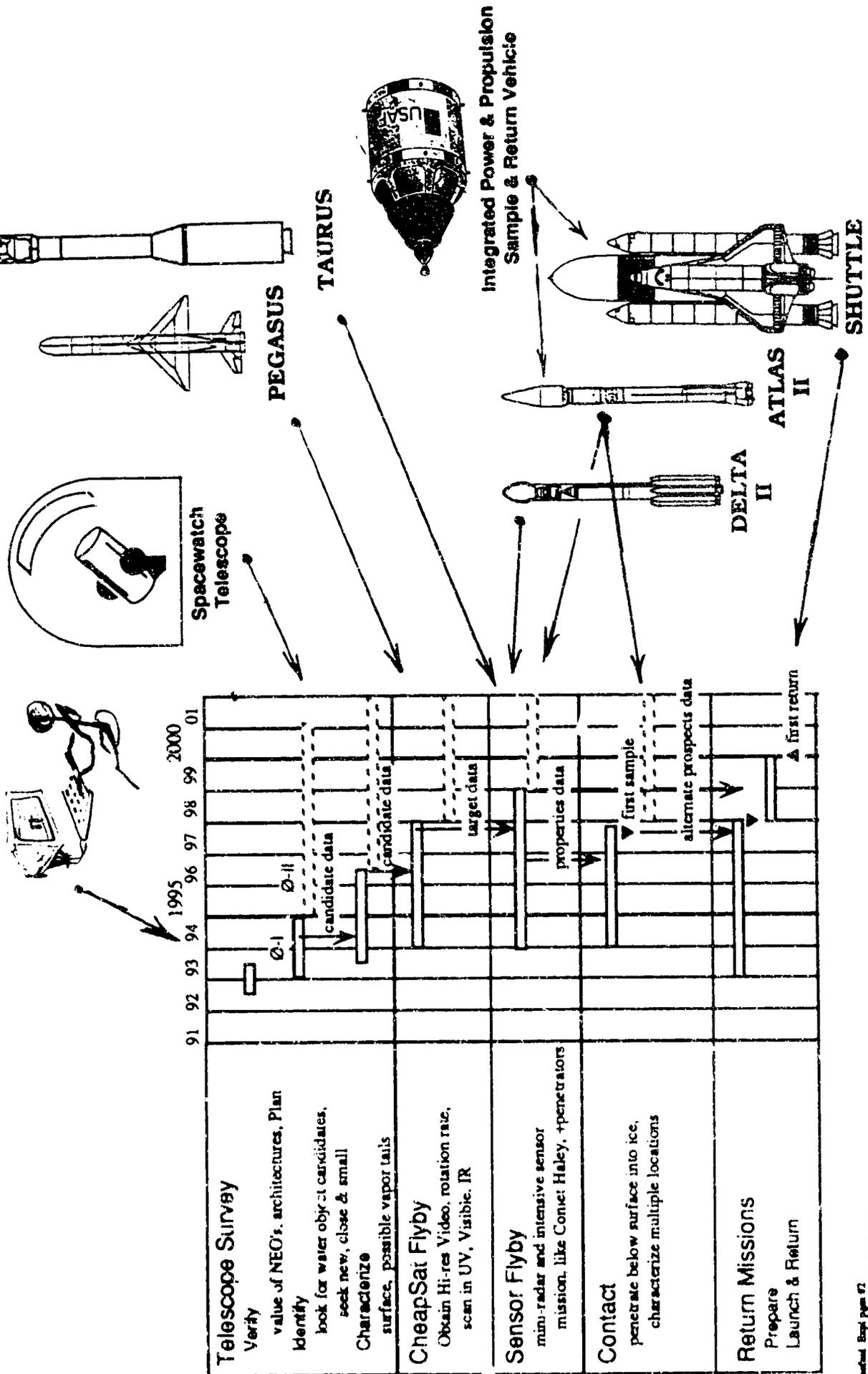
The tanker can push the comet out of an orbit that would otherwise hit Earth.

The Tanker would just push against the comet instead of pushing itself into an Earth orbit. The 190 000 tons of propellant exhaust moving at 2300 m/s would cause a 0.44 m/s change in the comet orbital velocity.

Though this may seem small it is more than enough to insure that the comet orbit misses Earth if it is performed one orbit early. For example, a 0.43 m/s ΔV change in aphelion velocity of the Never-Far-Comet P/Schwassmann-Wachmann 3 would cause it's perhelion to change by 3 Earth Radii. Since its perhelion is inside the orbit of Earth this could assure a near miss. Three Earth radii is close, but no collision.

We would need about a dozen years notice.

Near-Earth-Object-fuel (neofuel) Prospecting & Assay Plan: "One Step At A Time"



LASER DEFLECTION OF NEO's

Claude Phipps, Los Alamos National Laboratory

NASA Near Earth Object Interception Workshop

Paper F3, Candidate Technology Alternatives, J. Powell, presiding

The energy density of kinetic objects with relative velocities in the 5 – 50 km/s range typical of NEO's exceeds that of hot chemical reactions, more nearly resembling the energy density of laser-ablation plasmas. When warning time is short (as it will usually be prior to accurate NEO orbit determinations), efficient response dictates addressing the NEO with an energy density similar to its own. We will introduce the idea that the smaller NEO's (which, collectively, produce the most blast damage) can be deflected with high-energy, Earth-based pulsed lasers – especially if the NEO has a well-defined orbit which permits it to be deflected a year or so in advance of collision.

The Ground-based Laser Alternative

While nuclear explosives can deflect even the largest NEO's, and their use may be dictated by economics for the largest ones, hazards during launch as well as construction are unacceptable if alternatives exist. Mass drivers have the disadvantage of requiring installation on the NEO, an awkward task with relative velocities of 5 – 50 km/s. Lasers have the advantage of instant response, can be non-polluting, and can deliver energy at an operating cost of about \$2/MJ. Laser disadvantages are mainly those of achieving the required range, requiring either expensive short-wavelength lasers for conventional optics, or a breakthrough in larger optics to use cheaper infrared gas lasers. Just such a potential breakthrough is provided by the gas lens concept of M. Michaelis¹. We will focus on the approach we believe will be most fruitful in each circumstance, e.g., cheap DF lasers with gas lenses or ultraviolet KrF lasers.

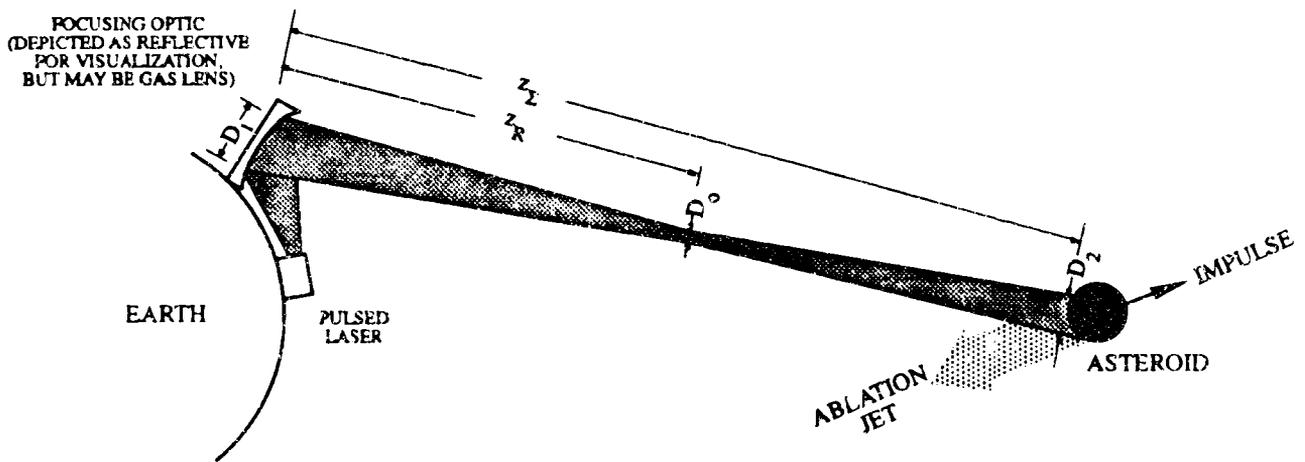
Range

A major consideration in choosing laser wavelength is focusing optic size, which is directly determined by the necessary range. For propagation of a laser beam which is "μ-times diffraction-limited", Kogelnik-Li theory gives for the Rayleigh range to the beam waist:

$$z_R = \frac{\pi D_0^2}{4\mu\lambda} \quad \text{cm} \quad [1]$$

Where D_1 is the Earth-based optic diameter, and λ is the laser wavelength, the minimum irradiation spot diameter at the beam waist D_0 will be $D_1/\sqrt{2}$ when the launch mirror is located a distance z_R from the beam waist. We can let the laser spot on the NEO have diameter $D_2 > D_0$ at the cost of increased laser energy (determined by the necessity for achieving surface plasma formation threshold on the NEO surface), for which case we obtain an increased range

$$z_{\Sigma} = z_R \left\{ 1 + \sqrt{(D_2/D_0)^2 - 1} \right\} \text{ cm.} \quad [2]$$



In the following table, we list the results of calculations for 5 cases at infrared and ultraviolet laser wavelengths, assuming normal optics or gas lenses and a beam quality factor $\mu=3$. Note that the table shows minimum single-pulse energy for the laser to achieve significant momentum coupling to the NEO.

Laser Range with Normal Optics [$D_1=10$ m] or Gas Lenses [$D_1=1$ km] and Pulse Energy Needed with Target dia. D_2 and Pulsewidth τ to Reach Minimum Intensity for listed C_m

Wavelength λ (μm)	Range z_{Σ} [beam quality $\mu=3$]	Launch Beam dia. D_1 (m)	Target Beam dia. D_2 (m)	Energy per Pulse W_L (J)	Pulse Duration τ (ns)	Target Intensity I_s (GW/cm^2)	Coupling Coefficient C_m ($\text{d}\cdot\text{s}^2$)
4	50,000 km	10 m	107	2.2 GJ	50	0.5	2.1
0.248	50,000 km	10 m	7.1	10 MJ	50	0.5	4.8
4	0.22 AU	1 km	710	100 GJ	50	0.5	2.1
0.248	0.22 AU	1 km	31	190 MJ	50	0.5	4.8
0.248	3.5 AU	1 km	710	100 GJ	50	0.5	4.8

The cases shown illustrate the importance of the successful development of gas-lens technology (or, possibly, of certain phased-array mirror concepts) as enablers for laser NEO deflection. Further, even though 4- μm laser energy is less costly than ultraviolet energy, the Table shows that much less of the short-wavelength, short-pulse energy is required to give efficient momentum coupling by laser ablation at the NEO surface. This must be considered "uncooperative" in the sense that we cannot enhance the coupling coefficient, nor mount a receiving mirror on the NEO to capture and concentrate the laser beam as we would do in, e.g., the case of laser-stabilization of geosynchronous satellites. The energy is, by Eq. [1], essentially proportional to λ^2 , with other conditions fixed. In forming the Table, we have held the quantity $I \lambda \sqrt{\tau}$ constant, as an approximation to the threshold for vacuum plasma formation.

In the 4th row of the Table, we have used focusing – that is, the launch mirror is positioned several times z_R from the beam waist. For the case represented in that row, 50,000 laser shots of 190 MJ (10 Hz, 80 minutes) are necessary to give a transverse velocity increment of 5 m/s to a 37-m-diameter stony NEO with density 3.4 g/cm³. These figures are consistent with the expected first-time detection distance for a NEO of this size on a collision course with Earth at 25 km/s relative velocity, and with its successful deflection². In this size range, we believe lasers can be built which deliver laser energy at an operating cost of 50¢ – \$2 per MJ. For this case, then, the cost of deflection would be \$5 – \$20M. A significant fraction of this cost is the cost of electricity in the KrF laser case – about 40 GW continuous power for 80 minutes. Of course, the capital cost of the laser facility would be quite high, perhaps as much as \$20B for a KrF laser. Since KrF does not penetrate the atmosphere, the laser would best be constructed and operated on the moon or on a geosynchronous platform.

In contrast, the shorter-range DF laser is more efficient in converting electricity to light and costs less to build, as well, per unit output. We conceive of a system in which D and F are electrolytically recycled with high efficiency. The overall electrical efficiency of this system is then close to the laser's chemical efficiency of 20%. In addition, DF laser physics permits us to propagate relatively high output intensity (4 GW/cm²), leading to a small laser device for the energy³, and the electrical driving point efficiency is extremely high (200 – 1,000%) because it is a chemical laser. For these reasons, the

capital cost of a 190-MJ-per-pulse DF laser would likely be an order of magnitude smaller at about \$2B, an advantage which fails to offset the limited range, as the cases illustrated in rows 3 and 4 of the Table demonstrate.

Laser Searchlight

Most of the time, the laser would not be used for deflection. To justify cost of construction, we inquire whether the laser could be useful for searching the skies for NEO's. Using the same case described in row 4 of the preceding Table, and assuming reflectivity R into 2π steradians and that the laser footprint D_2 is smaller than the NEO, the size of the received signal expressed in photons – where W_L and λ are defined as before, z is range and D_p is receiver diameter in consistent units – is:

$$B = 6.3 \times 10^{21} \frac{R D_R^2 W_L \lambda}{z^2} \quad \text{photons.} \quad [3]$$

It is seen that a 190-MJ-per-pulse, 50-ns KrF laser will deliver a 50-ns pulse containing $100 R$ photons into a receiving aperture of diameter D_R (m) meters at a range $z_{\text{DET}} = 3.6 D_R$ (m) AU. Laser intensity on the NEO surface would obviously exceed solar illumination intensity within the laser bandwidth by many orders of magnitude at any reasonable range. As the Table shows, the laser footprint D_2 is smaller than a 30-m-diameter NEO when z is smaller than 0.22 AU. For larger or farther NEO's, increased receiver diameter is necessary to compensate, e.g., 5-m-diameter for $z_{\text{DET}} = 1$ AU.

However, for the case we are discussing (row 4 of the Table), the time to search 1 sterad at 10Hz laser repetition rate is 4.5×10^8 yr! The laser would only be useful for searching a very specific area of sky. The laser *would* be useful for accurately tracking an NEO which has been located by some other means, or for determining its surface elemental composition by Laser Induced Breakdown Spectroscopy (LIBS).

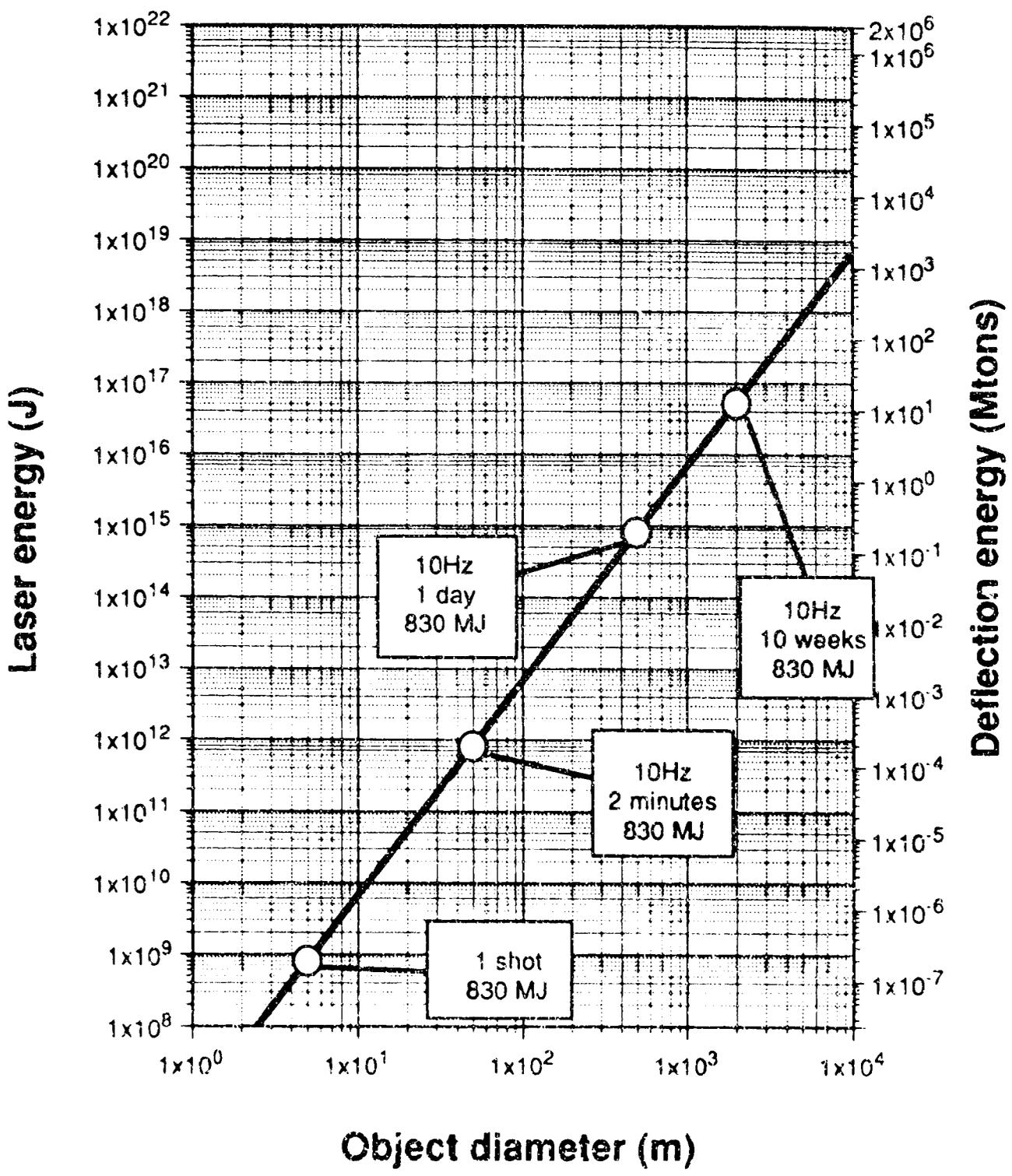
The following Figure reproduces calculations which show how many pulses of an 830-MJ laser operating at 10Hz are required to provide $\Delta v = 10$ cm/s vs. NEO diameter, consistent with 1-year collision warning time, and accurate NEO orbit determination.

References

1. M. M. Michaelis, et al., "A gas-lens telescope," *Nature*, 353, 547 (1991)
2. C. R. Phipps, "Dynamics of NEO Interception," Proceedings of this conference
3. C. R. Phipps, "Conceptual design of a 170-MJ hydrogen fluoride laser for fusion," *Laser and Particle Beams*, 7, 835 (1989)

Required laser energy (J) for Providing enough Δv to avoid collision with 1 year prediction

(Calculation based on $C_m = 2.5 \text{ dyne}\cdot\text{s/J}$, $\rho = 1\text{g/cc}$ and $\Delta v = 10 \text{ cm/s}$)



7. FUTURE DIRECTION FOR RESEARCH

VALUE OF SPACE DEFENSES

by

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ABSTRACT

The economic value of defenses against near-Earth object (NEO) impacts is bounded by calculating the expected losses in their absence, which illustrates the contributions from NEOs of different sizes and the sensitivity of expected losses to impact frequencies. For nominal impact frequencies, damage durations of a few decades, and normal economic costing, small NEOs make little contribution, intermediate size NEOs make a bounded but potentially significant contribution, and large NEOs make a bounded but large contribution. Increased persistence of damage with NEO size shifts emphasis to the largest NEOs and greatly increases expected losses and the value of warning and defenses. Currently, uncertainties appear to be larger than mean values of losses for all but the largest NEOs.

1. Introduction

This report discusses the value of defenses against near-Earth objects (NEOs) by calculating the value of the losses expected in their absence, which are estimated from the product of their impact frequency and expected loss, summed over all NEO sizes. It gives an approximate calculation of those expected losses, using simplified models for NEO impact frequencies and damage. Its goal is not to estimate these losses precisely, but to illustrate the contributions made by NEOs of different sizes, show the sensitivity of expected losses to imperfectly known empirical information, and suggest fruitful areas for further theory and experiments.

Section 2 adapts a standard damage model to estimate the area of destruction from a NEO of given mass and energy. Section 3 estimates the expected loss for a given area of destruction. Section 4 uses empirical data to model the probability density function for the NEO impact frequency, varying the power law fit to show the sensitivity of the losses to experimental uncertainties. Sections 5-7 convolve it with the expected loss as a function of diameter for small, intermediate, and large NEOs, respectively, to calculate their contributions to the total expected loss. Section 8 studies the effect of variable persistence of damage; Section 9 assesses the sensitivity of results to experimental uncertainties; and Section 10 summarizes the main insights.

2. NEO Damage Radius, Area, and Fraction

Hills and Goda argue that stony NEOs tens to hundreds of meters in diameter can cause damage on the ground, even if they break up in the atmosphere during entry, by depositing much of their kinetic energy in the atmosphere as they rapidly decelerate at an altitude of about an atmospheric scale height.¹ The strong shock produced by this energy deposition gives an approximate radius of catastrophic destruction of

$$R = bY^{1/3}, \quad (1)$$

where $Y = mV^2/2$ is the kinetic energy of a NEO of mass m and velocity V and $b = 0.047 \text{ (m-s}^2/\text{kg)}^{1/3}$ corresponds to an over-pressure of 2 psi, which would destroy most buildings.² If the NEO's density is $\mu = 3 \text{ kg/m}^3$, and its diameter is D , its mass is $m = 4\mu(D/2)^3$, and Eq. (1) gives

$$R = b(\mu V^2/4)^{1/3}D, \quad (2)$$

which is proportional to D . In this approximation, the damage radius depends only on the NEO's energy. R also depends on the NEO's composition, through the stresses that it can withstand during reentry. Those complications are studied by Hills and Goda; this note primarily treats stony NEOs, which comprise about 95% of the objects striking the Earth.

The scaling of damage radius R with initial NEO radius $r = D/2$ is shown by Fig. 1. The points are taken from Hills and Goda's predictions for stony NEO velocities of 11.2, 20, and 30 km/s; the straight lines are from Eq. (2) for those velocities. The scaling damage radii lie close to the detailed predictions for small r , but exceed them by 10-30% for large r and small V , which is adequate for the rough economic analyses below. The Tunguska event is interpreted by Hills and Goda to have been a stony meteorite with $V = 20 \text{ km/s}$, $D = 80 \text{ m}$, and $Y = 40 \text{ MT}$. For those conditions the detailed and scaling results give 44 and 50 km, respectively, for the radius of destruction. Preliminary Skywatch data suggests a shift to a higher fraction of higher-velocity, long-period comets at large radii, which would reduce the discrepancy.³

The scaling of Eq. (1) is only approximate; blast waves cannot remain spherical over distances large compared to the thickness of the Earth's atmosphere. Damage out to the radius R of Eq. (2) corresponds to destruction of a fraction of the Earth's surface of about

$$f = \pi R^2/4\pi R_e^2 = b^2(\mu V^2/32R_e^3)^{2/3}D^2 = CD^2, \quad (3)$$

where R_e is the Earth's radius and $C = 6 \times 10^{-10}/\text{m}^2$ for a typical V of 20 km/s. This result is intended for use for $f \ll 1$, but a rough estimate of the NEO diameter required for catastrophic destruction can be obtained by taking f to be unity, which gives $D = 1/\sqrt{C} = 40 \text{ km}$, which is consistent with the values inferred by others from the limited data and theory available, apart from unquantified global climatic impacts.⁴

3. Expected Loss

The US GNP is about \$5T/yr, which is about a quarter of the Earth's total gross product, G , that is used as a surrogate for the total loss. With warning, evacuation and preparation could reduce loss of life and limit damage to the loss of production for the period of time required for recovery. For an impact that renders a fraction f of the Earth's surface unproductive for a time T , a geometrical phase-space estimate of the expected loss is fGT . Sections 4 through 7 assume a recovery time of $T = 20$ years for NEOs of all diameters, which is also the reciprocal of the real interest rate of 5%/yr used by governments to discount or capitalize losses of comparable uncertainty. Section 8 studies the impact of variable persistence of damage with NEO diameter.

4. Impact Frequency Distribution

Morrison's "Impact Hazard" presents summary figures of NEO impact frequency data, which show that over 9 orders of magnitude in energy, the impact frequency can be approximated by a combination of power laws. Figure 2 is the second figure from Morrison's paper, with two lines added to show that its impact frequencies scale as $1/Y$ for Y smaller than about 10 MT, and as $1/Y^{2/3}$ for Y between about 10 and 10^6 MT.⁵ Each range can thus be represented by a power law approximation to the cumulative probability density function for the number of impacts per year by NEOs with diameters greater than D , which is

$$N(D) = \int_D^{D_{\max}} dx n(x) = K_{\alpha} D^{-\alpha}, \quad (4)$$

where $D_{\max} = 2$ km is the maximum diameter of NEOs that do not do catastrophic, global damage, and K_{α} is a constant, whose value depends on the value of α . For the scaling in Eq. (2), $Y \propto D^3$, so Morrison's figures imply $\alpha = 3$ for $Y < 10$ MT—or $D < 40$ m—and $\alpha = 2$ for D up to about 2 km. Because the data is sparse and its interpretation is not without controversy, α is carried as a parameter below. Differentiating Eq. (4) gives the NEO impact frequency probability density function

$$n(D) = -dN/dD = \alpha K_{\alpha} D^{-(\alpha+1)}, \quad (5)$$

which falls off with diameter one power more strongly with D than does frequency N . Morrison's figures can also be used to estimate the constant in Eq. (4). Inverting it yields

$$K_{\alpha} = D^{\alpha} N(D). \quad (6)$$

For $D = 20$ m, Morrison's second figure gives a collision frequency of $N = 0.01/\text{yr}$. That diameter is at the 1 MT break between the two power laws; hence, it can be used to evaluate consistent values of the constants for each range. For $\alpha = 3$, these parameters give $K_3 = ND^3 = (20 \text{ m})^3 0.01/\text{yr} = 80 \text{ m}^3/\text{yr}$. For $\alpha = 2$ they give $K_2 = ND^2 = (20 \text{ m})^2 0.01/\text{yr} = 4 \text{ m}^2/\text{yr}$. These constants, when inserted into Eq. (5), then determine the NEO impact frequency probability density function needed to estimate economic losses.

5. Expected Loss from Small NEOs

Integrating the expected loss over the NEO impact distribution function gives the expected loss from a given range of NEO diameters, which this section does for the smallest NEOs. According to the Hills-Goda calculations the smallest stony NEOs that can cause damage on the ground have a minimum diameter of about $D_{HG} \approx 50$ m. That is above the transitional diameter of $D_T \approx 20$ m, which separates the two power laws in Morrison's figures. Thus, stony NEOs in the $\alpha = 3$ range make no contribution at all to the expected loss.

Metallic meteoroids of diameters down to $D_{HGmet} \approx 6$ m, which is well below D_T , could cause damage, but they are greatly reduced in number.⁶ If it is assumed that they comprise a fraction $\beta \approx 0.1$ of the NEO total and that their collision frequency in the $\alpha = 3$ range is $\beta K_3 D^{-3}$, their expected loss is the integral of the loss, fGT , over NEO diameters from D_{HGmet} to D_T :

$$L_{small} = \int_{D_{HGmet}}^{D_T} dx \beta n(x) f(x) G T$$

$$= \alpha \beta K_3 CGT [(D_T)^{2-\alpha} - (D_{HGmet})^{2-\alpha}] / (2 - \alpha), \quad (7)$$

for $\alpha \neq 2$. For $\alpha = 3$, the loss from small NEOs reduces to

$$L_{small} \approx 3\beta K_3 CGT [1/D_{HGmet} - 1/D_T], \quad (8)$$

which is sensitive to the smallest NEOs that can cause serious damage. For the loss parameters of Section 3, the numerical value of the loss is about

$$L_{small} = 3 \times 0.1 \times 80 \text{ m}^3/\text{yr} \times 6 \times 10^{-10}/\text{m}^2 \times 20 \text{ T/yr} \times 20 \text{ yr} [1/6 \text{ m} - 1/20 \text{ m}] = \$0.7 \text{ M/yr}, \quad (9)$$

which would only justify a research program on NEO defense against small metallic NEOs of about that magnitude. Since such NEOs would be difficult to detect, it is unlikely that useful warning, let alone defenses, could be developed for that amount. If the sensor system was only able to detect NEOs down to 10 m in diameter, it would be unable to detect most of the small NEOs, and its value in warning would drop to $\approx \$0.2 \text{ M/yr}$.

6. Expected Loss from Intermediate NEOs

For NEOs with intermediate diameters, $D_T \approx 20$ m to $D_{max} \approx 2$ km, Morrison's figures indicate that the impact frequency is characterized by a power law with $\alpha = 2$. Hills and Goda's calculations apply for stony NEOs with diameters from $D_{HG} \approx 50$ m up to a maximum of about 250 m. NEOs of greater diameters survive to impact the ground, so their damage mechanisms shift to a combination of conventional hypervelocity impact, which have been studied extensively,⁷ and novel mechanisms such as Tsunamis and other phenomena, which have not.⁸ Nevertheless, the analysis below assumes that the damage radius continues to scale as Eq. (2) for NEO diameters all the way up to $D_{max} \approx 2$ km, an assumption that is apparently also shared by other analyses.⁹ With this scaling the expected loss from intermediate size NEOs is

$$\begin{aligned}
L_{\text{inter}} &= \int_{DT}^{D_{\text{max}}} dx n(x) f(x) GT \\
&= \int_{DHG}^{D_{\text{max}}} dx n(x) f(x) GT = 2K_2CGT \ln(D_{\text{max}}/DHG) \\
&= 2 \times 4 \text{ m}^2/\text{yr} \times 6 \times 10^{-10}/\text{m}^2 \times \$20\text{T}/\text{yr} \times 20 \text{ yr} \ln(2 \text{ km}/50 \text{ m}) = \$7\text{M}/\text{yr}, \quad (10)
\end{aligned}$$

which justifies a more substantial premium. Moreover, it is quite uncertain. The actual losses could be much higher, as discussed in Section 9 on the sensitivity of results to uncertainties in the data. Note that the intermediate loss is equally sensitive to NEOs of all diameters; each octave in diameter contributes about equally. Thus, NEOs of all sizes must be detected and protected against for maximum benefit. If defenses were developed that could only detect NEOs larger than 300 m in a timely manner or could only intercept NEOs smaller than 300 m in diameter, the expected loss and resulting value of the defenses would be cut about in half.

7. Expected Loss from Large NEOs

In general, the expected loss from the largest NEOs is treated as the product of an infinite loss and a small—possibly zero—probability.¹⁰ The standard economic model used here assumes, instead, that with warning and evacuation, loss of life could be limited, and the damage from even large NEOs could be bounded by the economic value of the facilities destroyed, the supplies needed to survive the recovery, and the production lost during the time it took the Earth's atmosphere and civilization to recover, which is given by the product of the Earth's product G and the recovery time of about 20 years as assumed above. In that case the loss from large NEOs is

$$L_{\text{large}} = \int_{D_{\text{max}}}^{\infty} dx n(x) f(x) GT = GT \int_{D_{\text{max}}}^{\infty} dx n(x) = GTN(D_{\text{max}}). \quad (11)$$

Morrison's figures give a collision frequency for the NEOs of diameter D_{max} of about one impact every million years, or $N(D_{\text{max}}) = 10^{-6}$. Thus, the expected loss from large NEOs is about

$$L_{\text{large}} = \$20\text{T}/\text{yr} \times 20 \text{ yr} \times 10^{-6}/\text{yr} = \$200\text{M}/\text{yr}. \quad (12)$$

This is about a factor $\$200\text{M}/\text{yr} / \$7\text{M}/\text{yr} \approx 30$ times larger than the nominal losses from the intermediate sized NEOs discussed in the previous section. Indeed, the losses for the largest NEOs can be treated by extending D_{max} to include the possibility of NEOs a few hundred kilometers in diameter. Then the benefits of intercepting larger objects would increase with their size roughly as could the energies, technologies, and costs of the means required to intercept them.

This argument must ultimately break down for NEOs of sizes that could literally fracture the Earth and dissipate its atmosphere, but that would require NEO diameters orders of magnitudes greater than the few kilometers Chapman associates with global catastrophe, by which he actually just means global climate impact. Within the context of the standard model used here, insurance can be purchased and is valuable for NEOs of those sizes. The truly catastrophic events would occur on time scales perhaps $100^2 = 10^4$ time longer than those of the D_{max} -sized NEOs of current concern. They could literally require placing life away from the Earth.

would give an expected loss of about \$60M/yr from intermediate size NEOs, which would appear to justify a significant program for them, too. If that constant is used to evaluate large NEOs, their losses would increase to about $8 \times \$200\text{M/yr} = \1.6B/yr . With persistence of damage, they could be even larger.

In addition to this uncertainty about the absolute magnitude of the collision frequency, there is also more recent data from the Spacewatch program that questions even the break points in the collision frequency data. Figure 3 gives its collision frequency as a function of diameter experiments as well as data from lunar craters, comet fragments, and bright meteors.¹¹ The scaling from Morrison's summary figures is also penciled in. The Spacewatch data merge well into Shoemaker's lunar crater data and Morrison's summary curves for NEOs with diameters greater than 100-300 m, but lie significantly above them for smaller NEOs. At a diameter of 30 m, the discrepancy amounts to about a factor of 1,000. If confirmed, the Spacewatch data would tend to enhance the losses from small and intermediate NEOs relative to that from large ones.

The impact can be assessed with slight modifications of the analysis above. Section 5 indicates that for small stony NEOs, although their collision frequency is greatly increased, their contribution would still be negligible, since none of the small NEOs in this range would produce damage on the surface. But the impact of metallic NEOs would be increased by the ratio of the collision frequencies, which is about a factor of 10^3 , to about

$$LSW_{\text{smallmet}} = 10^3 \times \$0.7\text{M/yr} = \$700\text{M/yr}, \quad (16)$$

which is quite large; although, as noted above, this estimate depends directly on the assumed fraction of metallic NEOs at small diameters, which is not treated carefully here.

The Spacewatch data essentially breaks the intermediate NEOs up into two groups, which are differentiated by the change of the power law at the transitional diameter of $DSW \approx 250$ m. The first group is from 20 to about 250 m; the second is from 250 m to 2 km. For the second group, the scaling is about $\alpha = 2$, as before, and the magnitude of their collision frequency is about the same as that in Morrison's figures, so the previous integration can be halved to produce a loss from the second group of intermediate stony NEOs of

$$LSW_{\text{inter2}} = \$3.5\text{M/yr}. \quad (17)$$

For the first group of NEOs with diameters from about 20 to 250 m, the scaling appears to be slightly stronger than $\alpha = 3$ out to the transitional diameter DSW . The loss from this first group of intermediate NEOs is given by modifying the limits of Eq. (10) to the interval DHG to DSW :

$$LSW_{\text{inter1}} = \int_{DHG}^{DSW} dx n(x) f(x) G T \\ = \alpha K_{SW} CGT [(DSW)^{2-\alpha} - (DHG)^{2-\alpha}] / (2 - \alpha), \quad (18)$$

for $\alpha \neq 2$, where K_{SW} is the collision frequency from the Spacewatch data. For $\alpha = 3$, it can be

8. Variable Persistence of Damage

The sections above assume a persistence of damage of $T = 20$ years for all NEO diameters. That probably overestimates the impact of small NEOs, for which damage could probably be reversed in a year or two, and underestimates the damage from large ones, for which it could persist thousands of years. Logically, T should increase with D . Just how it would increase is not known. The impact of varying T with R is illustrated below by assuming $T = T_0 f$, i.e., that T is proportional to D^2 or R^2 , which corresponds to diffusion-like recovery. The calculations take $T_0 = 1$ million years for near-total damage. Compared to the constant T calculations above, this assumption reduces the loss expected from small NEOs and increases the loss from large ones. The crossover diameter is where $f = CD^2 = T/T_0 = 20 \text{ yr}/10^6 \text{ yr}$, or $D = \sqrt{(2 \times 10^{-5} / 6 \times 10^{-10} / \text{m}^2)} = 180 \text{ m}$, which is at the upper end of the stony NEOs treated accurately by Hills and Goda. This variable T gives an expected loss of

$$L_{\text{var}} = \int DHG^{D_{\text{max}}} dx n(x) f(x) G T_0 f$$

$$= \alpha KGT_0 C^2 (D_{\text{max}}^{4-\alpha} - DHG^{4-\alpha}) / (4 - \alpha) \quad (13)$$

for $\alpha \neq 4$. For $\alpha < 4$ and variable persistence, the loss scales most strongly on the largest NEOs, and because $D_{\text{max}} \gg DHG$, it reduces to

$$L_{\text{var}} \approx \alpha KGT_0 C^2 D_{\text{max}}^{4-\alpha} / (4 - \alpha). \quad (14)$$

For the very large NEOs to which this estimate is most sensitive, α is 2 or less. For $\alpha = 2$ and the parameters above,

$$L_{\text{var}} = 2.4 \text{ m}^2 / \text{yr} \cdot \$20T / \text{yr} \cdot 10^6 \text{ yr} \cdot (6 \times 10^{-10} / \text{m}^2)^2 \cdot D_{\text{max}}^2 / 2 = \$30 / \text{m}^2 \cdot D_{\text{max}}^2, \quad (15)$$

which for $D_{\text{max}} = 2 \text{ km}$, gives a loss of about $\$120\text{M}/\text{yr}$. The losses would increase with the square of the diameter of larger NEOs. Thus, losses with persistence can be an order of magnitude larger than those from the largest NEOs ignoring persistence, which justify would justify an accordingly larger program, if those losses were unavoidable. With variable persistence, large programs would be justified even for modest maximum NEO diameters. Persistence of damage shifts the strongest scaling from the smallest to the largest NEOs and greatly increases the expected annual loss. More detailed calculations of global damage would essentially vary T_0 , presumably producing losses and values of defenses intermediate between the extremes in sections 7 and 8.

9. Sensitivity of Results

The results of sections 5 through 7 indicate that small NEOs produce small losses; intermediate NEOs produce intermediate losses; and large NEOs produce large losses. They are, however, uncertain due to the somewhat sparse and new data on impact frequencies as a function of size. While Morrison's figures imply $K = 4 \text{ m}^2 / \text{yr}$ in the $\alpha = 2$ range, the text states that "Bodies about 100 m diameter and larger strike, on average, several times per millennium," which implies a constant in the collision frequency of $K_2 = (100 \text{ m})^2 / 300 \text{ yr} = 33 \text{ m}^2 / \text{yr}$. That is larger than the value used in the estimates above by about a factor of about $3^{3/4} \approx 8$. The larger value

$(100 \text{ m})^3 \times 3 \times 10^{-3}/\text{yr} \approx 3 \times 10^3 \text{ m}^3/\text{yr}$, for which Eq. (18) reduces to

$$\begin{aligned} L_{\text{SWinter1}} &= 3K_{\text{SWCGT}}[1/(D_{\text{HG}}) - 1/(D_{\text{SW}})] \\ &= 3 \times 3 \times 10^3 \text{ m}^3/\text{yr} \times 6 \times 10^{-10}/\text{m}^2 \times \$20/\text{yr} \times 20 \text{ yr} [1/50 \text{ m} - 1/250 \text{ m}] = \$35 \text{ M}/\text{yr}, \quad (19) \end{aligned}$$

which increases the contribution from the first group of intermediate NEOs by about an order of magnitude over that from the estimate using Morrison's rates. As an aside, it might be noted that adding the metallic NEOs in this first group could roughly double this loss, because their ≈ 10 -fold smaller minimum diameter would just compensate for their ≈ 10 -fold smaller number. Ignoring them and adding Eqns. (17) and (18) for the two groups gives the total expected loss from the intermediate-size stony NEOs under the Spacewatch collision frequencies, which is

$$L_{\text{SWinter}} = L_{\text{SWinter1}} + L_{\text{SWinter2}} = \$35 \text{ M}/\text{yr} + \$3.5 \text{ M}/\text{yr} \approx \$39 \text{ M}/\text{yr}, \quad (20)$$

which is about a factor of $\$39 \text{ M}/\text{yr} / \$7 \text{ M}/\text{yr} \approx 6$ greater than the total estimated from Morrison's summary figures. Because the Spacewatch data does not alter the estimate of the loss from large NEOs given in Section 7, the ratio of the losses from intermediate and large NEOs becomes about $\$39 \text{ M}/\text{yr} / \$200 \text{ M}/\text{yr} \approx 20\%$ under the Spacewatch collision frequencies.

Thus, while Morrison's summary collision frequencies produce the result that small NEOs produce small losses; intermediate NEOs produce intermediate losses; and large NEOs produce large losses, current uncertainties in the data considerably complicate this simple evaluation. The uncertainties in the absolute magnitude of the collision frequencies discussed in Morrison's text would lead to losses from the intermediate size NEOs that were worth detecting and defending against. And the recent Spacewatch data produce both a different path to this conclusion and to a strong suggestion that the contribution from small metallic NEOs could be even larger, although it could be quite difficult and expensive to detect them. Unfortunately, this analysis does not serve to bound this seemingly dominant contribution from small metallic NEOs, since it assumes a fairly simple and monotonic scaling of damage radius on NEO diameter, which is appropriate for stony NEOs, whereas the Hills-Goda calculations indicate a complicated and non-monotonic behavior for small metallic NEOs that could produce significantly different scaling. It would certainly appear useful to take their curves for small metallic NEOs and carry out the type of analysis done here for stony NEOs.

While these sensitivity analyses are stimulating, about all that can be said with confidence is that on the basis of the collision frequency, composition, and calculational information now in hand, the error bars are as large or larger than the mean expected losses for all but the largest NEOs. The proper priorities for research to right this situation would appear to be to determine the collision frequency and composition more carefully for NEOs with diameters below about 250 m and to better estimate the extent and persistence of the damage from NEOs of diameters above a few kilometers. Lest it seem that intermediate NEOs with diameters between 250 and 2,000 m are

being ignored, it might be noted that their damage mechanisms do not appear to have been quantified at all, and all estimates just seem to assume the continuation of geometric damage radii in the face of obvious geometric arguments to the contrary. There would not seem to be any lack of fruitful areas for theory and experiment.

10. Summary and Conclusions

This note bounds the economic value of defenses against NEO impacts by calculating the expected losses in their absence by summing the product of their expected impact frequency and expected damage loss over all NEO diameters. The analysis is primarily directed towards stony NEOs, using the recent damage calculations of Hills and Goda. It uses a standard economic model of expected loss that produces a bounded contribution from NEOs of all sizes. This process illustrates the contributions from NEOs of different sizes and the sensitivity of total expected losses to composition and impact frequencies, suggesting fruitful areas for theory and experiments.

For nominal parameters, the analysis identifies three diameter ranges of interest. The smallest stony NEOs with diameters below about 20 m, where the collision frequency falls most rapidly with diameter, cause no damage according to Hills and Goda's detailed calculations. Small metallic NEOs might produce losses of about \$1M/yr, but that is probably too small to be of interest, given the difficulty of detecting them.

Intermediate stony NEOs with diameters from about 20 to 2,000 m appear to produce about equal contributions per octave to an expected annual loss of about \$7M/yr, which would justify defenses costing about that much. Defenses that could only detect large NEOs or intercept small ones would have proportionally reduced value.

The largest NEOs with diameters over about 2 km, which are usually associated with global damage, contribute an expected loss of about \$200M/yr, which dominates the analysis. When persistence of damage with NEO size is taken into account, it shifts emphasis even more strongly to the largest NEOs and increases the expected annual losses by an order of magnitude.

Unfortunately, these simple results are very sensitive to impact frequency data, which is sparse and new. The uncertainties in collision frequencies discussed in Morrison's text would lead to losses from the intermediate size NEOs that were worth detecting and defending against, and recent Spacewatch data produce both a different path to this conclusion and to a strong suggestion that the contribution from small metallic NEOs could be even larger, which this limited analysis cannot bound. It would appear useful to repeat it with Hills and Goda's detailed calculations for small metallic NEOs and the best data on the composition of small NEOs.

Currently, the error bars are as large or larger than the mean expected losses for all but the largest NEOs. It would appear appropriate to study the collision frequency and composition of NEOs with diameters below 250 m, to better estimate the extent and persistence of the damage from large NEOs, and to quantify the damage mechanisms of intermediate-size NEOs. There

seems to be no lack of fruitful areas for theory and experiment. Both will have to be significantly refined before the relative importance of NEOs of different sizes can be assessed with confidence.

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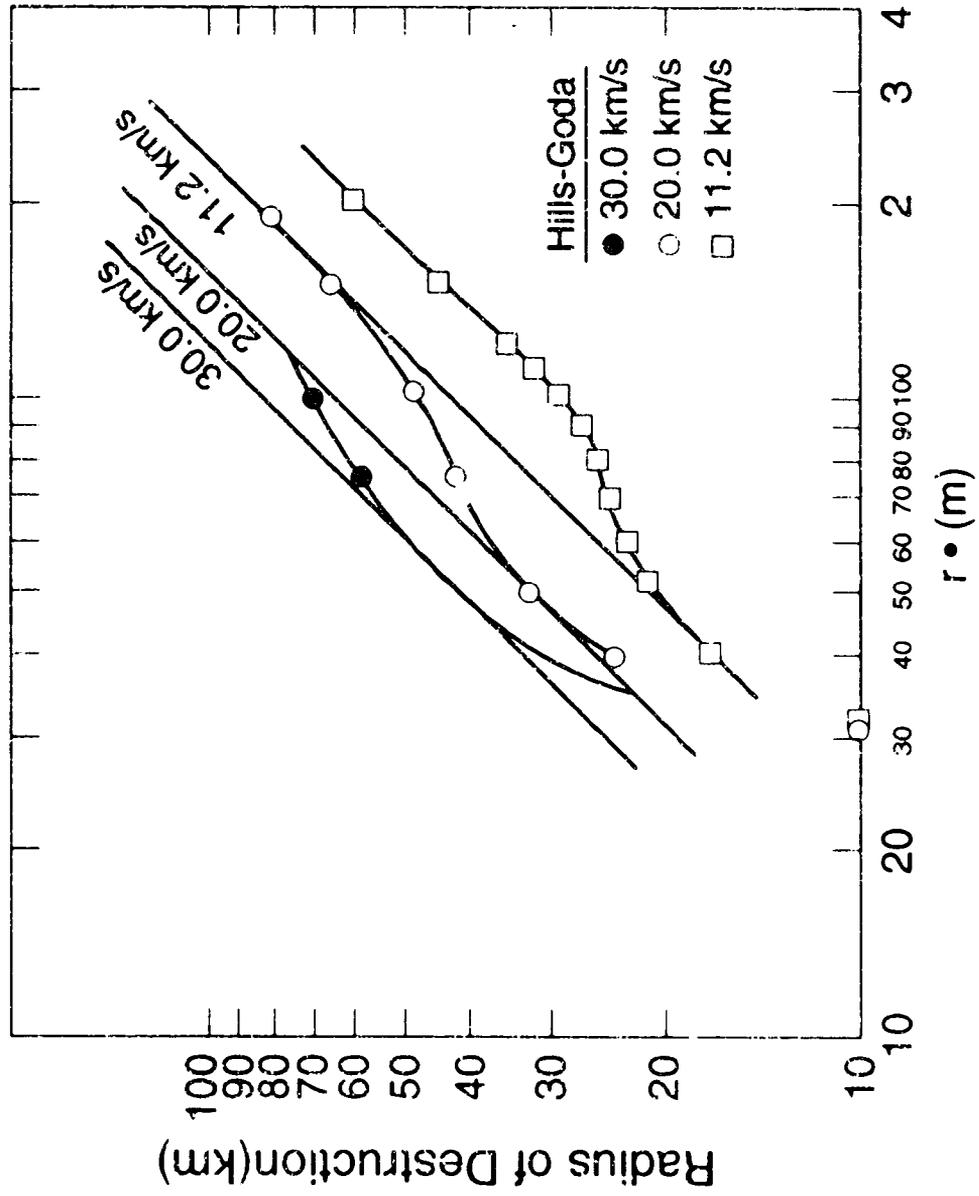


Fig. 1 Damage vs NEO Radii

FREQUENCY OF IMPACTS ON THE EARTH

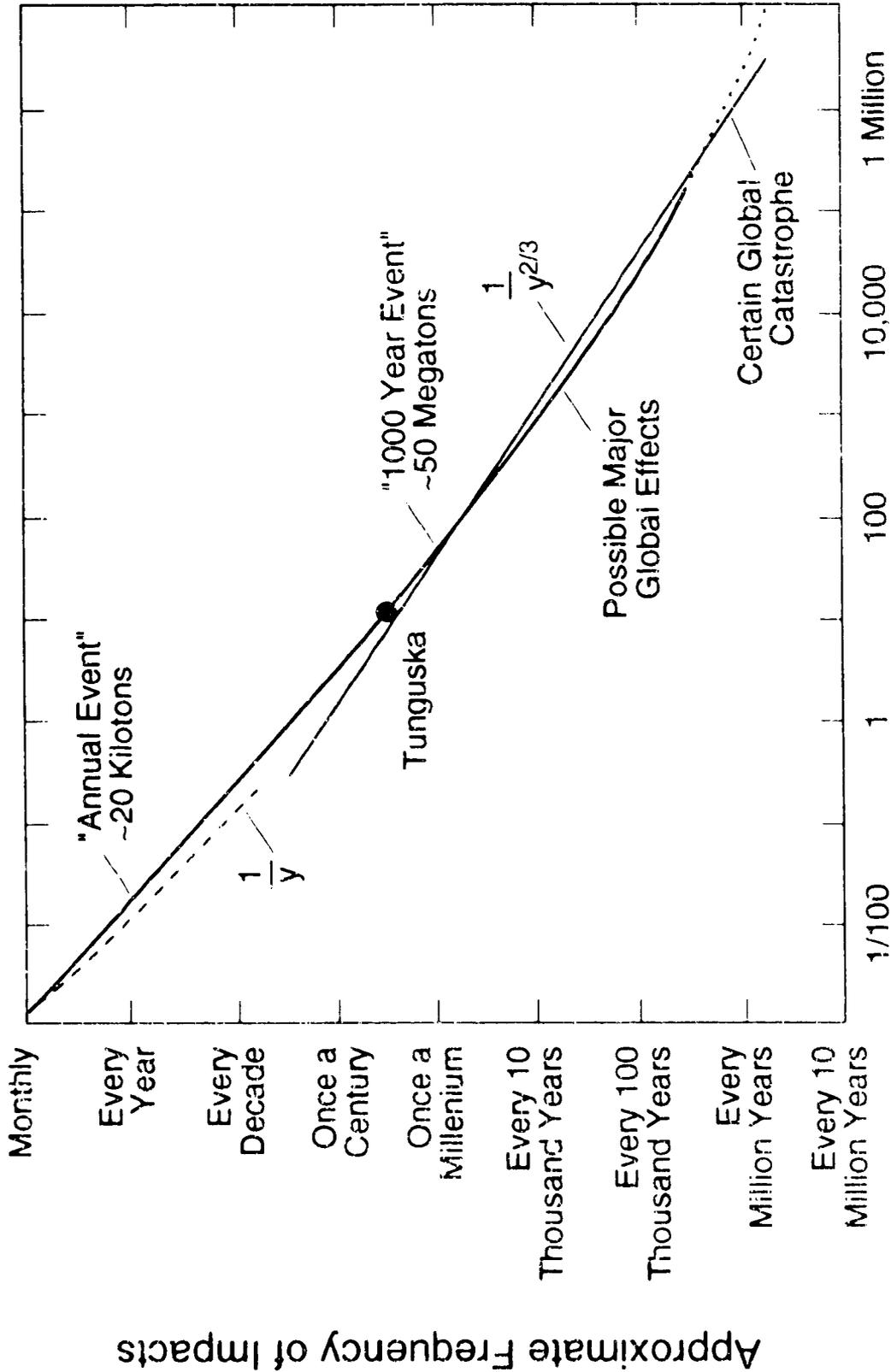


FIG. 2 Megatons TNT Equivalent Energy

(Source: Morrison "Morrison Impact Hazards")

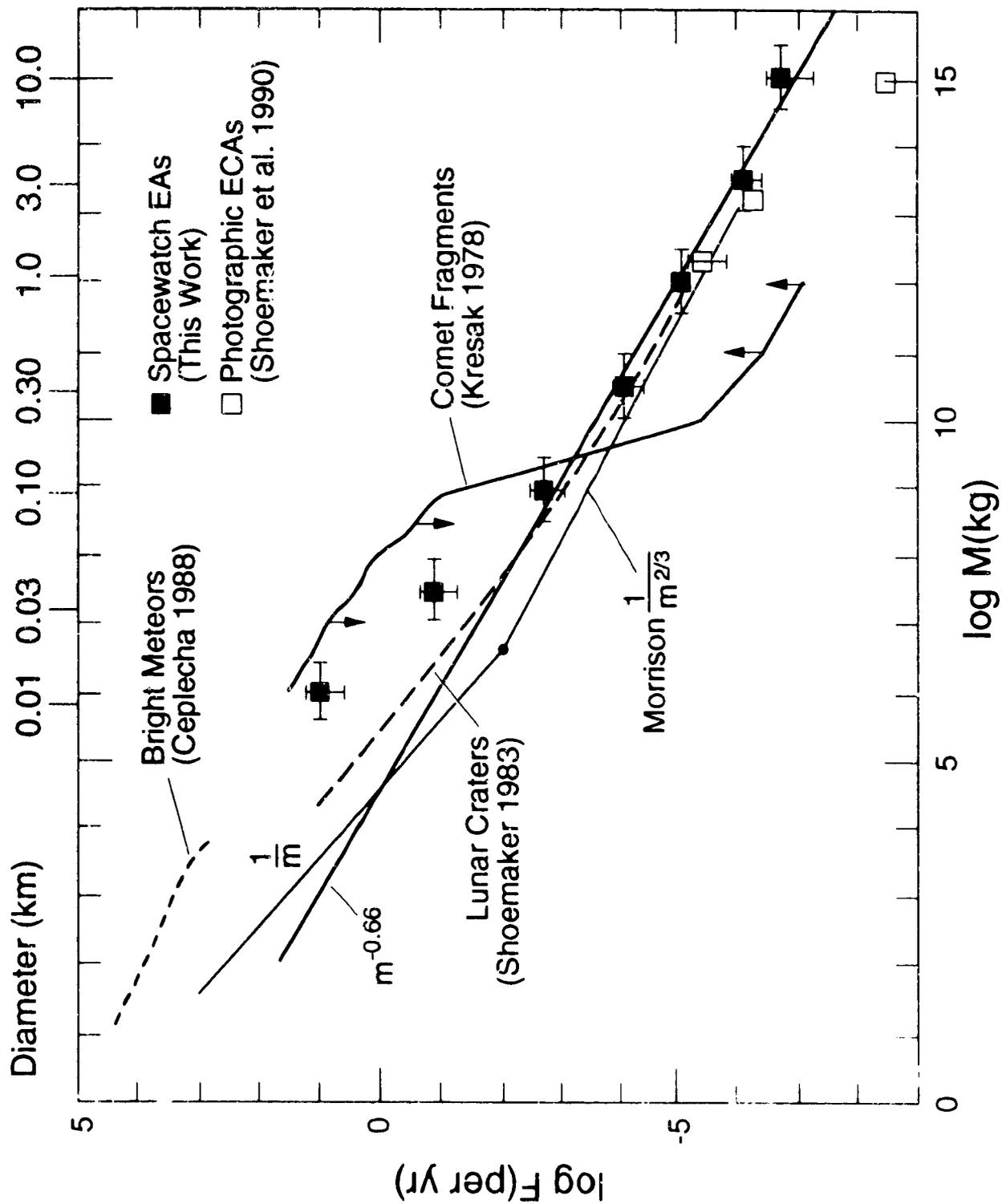


FIG. 3 Spacewatch and Related NEO Collision Frequencies

"Why Now?"
Text and paraphrase of an after-dinner speech by
Dr. Edward Teller
on the occasion of his 84th birthday
January 15, 1992
Los Alamos National Laboratory

There are two answers to the question "Why Now?"

In the last three years, very remarkable changes have occurred in the world. One of them is that I can visit Hungary. What has happened? Nobody present, nobody in the world, had foreseen it. Now, for the first time, incredible things can really happen, including international cooperation on a subject like defense against asteroids.

I cannot pass over, in talking about this subject, the indirect but powerful ways our national laboratories contributed to what has happened. Nuclear energy did not have the possibility of remaining undiscovered. That it has been discovered and has been used -- probably not without mistakes, but without major mistakes -- has persuaded people who had been previously impotent and unforthcoming to find leaders to take them one big step toward peace. That the Russian people stood up in incredible numbers to defend their own freedom and that of others...this was made possible by the magnificent fact that nuclear power rested in the hands of those who did not misuse it in a truly major way, in the hands of our government which is in fact dedicated to peace. I am encouraged in the argument that we can work on knowledge of every kind leading to higher technology in the confidence that people will use it properly.

The role of the national laboratories in bringing this about cannot go unmentioned. The big changes in the world give a reason for "why now," and "why here" (at Los Alamos).

There is another reason: a remarkable number of technological developments have made it possible to do something about meteorites. Computers, radar, lasers, nuclear energy...each of these has contributed. We are now facing a problem that before the Tunguska meteorite could not be addressed. These methods were not available. Now they are.

I would like to make my main statement. It will be brief, but the consequences are long. Here is my recommendation about what to do with the opportunity that is here. We must proceed in four separate phases, one at a time. We must give the lion's share of attention to the first phase: knowledge.

First, we should find out about meteorites. A lot is known today. Very much more remains to be found out. In what ways? Many are obvious. I'll mention two special points which have not received detailed emphasis as yet in this meeting. One is the incredible developments in Livermore in the improvement of lasers. We can now concentrate a lot of illumination in a narrow spectral region for a short time, with laser pulses a hundred times cheaper than before (in appropriately exaggerated terms of megabucks per megawatt). Powerful lasers have already been focused on the Moon. With the help of rockets, or even from the Earth, we can illuminate a meteorite that passes closer than the Moon. We could heat up the surface and watch it cool, yielding information about its conductivity. The importance of this subject is now evident to me today, much more than yesterday.

A second question. Shall we look at the meteorites from Earth or from space? I don't know. But I will give an argument to look at them from space, because it is not completely obvious. If we put the telescope on a (low) orbiting satellite, it can see all of the sky and with no disturbance from the atmosphere. Clearly one of the

important properties of meteorites is their changing brightness because of their rotation and changing position. These intensities can be measured from the ground. They can be measured more quantitatively if the atmospheric disturbances are corrected, but it is best if we are outside the atmosphere and no correction is needed.

We need to measure intensities to 0.1%, which can be done by charge coupled devices, CCDs. Unlike photographic plates, which are clumsy and old fashioned, CCDs report directly to a computer, and then you can perform miracles. With fifty bits to a hundred bits, you can get accurate positions of stars and spectral lines. The Sun changes its intensity by 1/2% to 1% every eleven years. We have similar information to date on a few dozen stars. Let's get stellar variability to 0.1% for a million of them, 10^8 bits. Ask the computer to check the catalog. We don't want to know this to find out about the long-term variation of energy production in stars -- it has been a million years from the production of energy to when it is emitted. What we see on the short term is due to hydrodynamics, which we don't understand (except for cepheid variables). We are ignorant about the smaller variation. Why do we want to know about them? I'll tell you after I find out. Galileo said, "Look first, then find out what the problems are." From space, you have a better possibility of learning about meteorites and also about this entirely different branch of science.

This project might be done internationally; a national effort would be difficult and expensive. But the public interest exists for this first step of knowledge.

The second step is experimentation. Every year, one of these potentially dangerous meteorites comes closer than the Moon. We should send out satellites to discover them, try to do what you would do for defense if you needed to, whether nuclear or non-nuclear. If we use a nuclear explosion while the meteorite departs, we can give an absolute guarantee that we will have no detectable radioactivity on the Earth. The celestial object could be stones, rubble piles, a comet, chondrites, iron meteorites -- whatever -- you take the best look at them and experiment. So if and

when a real danger occurs, you have already practiced. Do it internationally. The United States should pay less than half the cost; this is not to save dollars, but criticism from other nations would be much more constructive if they were paying. The planning, the money, the actions should all be international. If a threat occurs, the knowledge from our experimentation can be used.

The third phase is defense against a meteorite that is going to hit. One might think about starting to make plans about who decides what to do when it happens. Perhaps, it is good to make plans. I'll say why it might not be good. I hope that we will have more than three months' notice, not about a hypothetical object, but about a real one that will hit. Maybe we should evacuate 1,000 people, or maybe we should use one of the methods we have already practiced. If the decision on how to decide is made in advance, it will be made by bureaucrats. If the threat is happening, the people will decide; I trust the people. After the object is deflected, then we can face step number four.

As step four, we can make plans for the safety of the whole future. It would be advantageous if the first use would be on a small meteorite. Actually, there is a 99% chance that a small one will come before a big one. So this is the optimal approach.

In this extraordinary time, which is the end of three years of miracles, we are looking into the possibility of a better future, because there are big and different changes for different people in 1992. This is a crisis for which the Chinese use a symbol composed of two parts which mean danger and opportunity. Defense against meteorites is one way to use the opportunity and avoid the danger.

I will make a more general remark about how the opportunity should be used. The right solution was proposed in early 1946 to the U.N. Its outstanding characteristic was to seek security in cooperation and openness (not secrecy). It was called the Lilienthal Report. It was proposed by Oppenheimer, who was not a right-winger; by Baruch, who was not a left-winger. It was presented to the United

Nations. All political parties supported it. But it came to nought due to the veto of Stalin. It involved an International Atomic Development Authority with limited but sufficient powers. I think we can succeed now.

We can solve the problem both of war and of meteorites. But we shall not lack problems. Man has been called a problem-solving animal. Man and woman should be called problem-creating animals. We will have new problems to solve.

7. PROGRAM/POLICY OPTIONS

7.1 *Categories of Impact Hazard and Corresponding Amelioration Effort*

The first of the two NASA-sponsored workshops found that there is a definite worldwide risk of dangerous effects from impacts on Earth by asteroids and comets larger than 1 km in diameter. Smaller objects produce more localized effects. Such impacts occur infrequently, but have potentially serious consequences that justify an effort at mitigation.

Three different categories of impacts merit attention:

- Large asteroids (greater than approximately 1 km diameter)
- Large, long-period comets
- Small asteroids and comets (approximately 50 m to 1 km diameter)

Most objects smaller than 50 m diameter break up, vaporize, and therefore deposit most of their energy very high in the atmosphere. A small percentage (3-5 percent) of such objects are of dense metallic composition and will strike the surface of the Earth, the larger ones producing craters.

Most large asteroids can be readily detected with an augmentation of current ground-based technology. If one were on a collision course with Earth, it probably would be found decades in advance of any collision, after which an orderly scheme of characterization and mitigation could be implemented. These large asteroids are judged to be the most dangerous NEOs in terms of global effects on life.

According to the first workshop, large long-period comets have approximately 20 times lower probability of Earth impact than do large asteroids. But because of their higher impact velocity, the overall hazard of serious global effects from comets may be about one-quarter as great as that from asteroid impacts. Most large long-period comets probably will not be detected until less than a year before collision. The response for mitigation must therefore be rapid, and comets may be inherently more difficult objects than asteroids to deflect. Both of these factors make mitigation efforts more expensive, more difficult, and potentially less certain.

During the next decade, small (50 m to 1 km) objects could be found only with an advanced technology approach to detection that, if they threatened collisions, would discover them just days to weeks before impact. (On a time scale of centuries, some of these smaller objects would eventually be found by the conventional survey for larger objects.) These smaller objects constitute a hazard only to local regions of the Earth, and the annualized average casualty rate is therefore lower than for the larger impacts, which have worldwide consequences. The impact of a small object in a heavily populated area would be an enormous catastrophe, however. As in the case of long-period comets, deflection/destruction assets would have to be already in place and thus might be controversial. For localized impacts evacuation might be a possible response.

7.2 *Levels of Effort and Sequence*

Both NASA-sponsored workshops concurred regarding the first element of a program for addressing the threat: identifying the threatening objects. The nature of the long-period comet threat is least well understood, particularly because of our lack of knowledge about the basic properties of comet nuclei. The environmental (not to mention economic) effects of impacts by large objects—whether asteroids or comets—are poorly understood because they

involve great extrapolations from known phenomena. Therefore, further study of the hazard is merited.

Prior to developing an operational mitigation system, it will be necessary to characterize the physical properties of the potentially threatening objects because of the extremely broad diversity of these objects (ranging from monolithic metallic objects to icy rubble piles). Of course, if an object is actually found to be on a collision course, it will become an urgent and high priority requirement to characterize it as well as possible in the available time.

The shorter the response time, the more difficult the mitigation. Therefore, it is prudent to consider improving the detection capability to increase the warning time before investing heavily in specific short-response mitigation systems.

Possible levels of programmatic effort depend on the new resources that the nation makes available to address the impact hazard. In order of increasing commitment of resources, these are

- (1) Observational, laboratory, and theoretical studies and analysis of the NEOs and of mitigation technologies (estimated cost, several million dollars per year)
- (2) Construction of dedicated telescopes and other instruments to dramatically increase the detection rate of NEOs, and augmented laboratory and theoretical studies (several tens of millions of dollars per year)
- (3) In addition to (2), robotic spacecraft missions to characterize a sample of NEOs that is representative of their broad diversity (about \$100 million per year). Such missions may evolve into preliminary experiments, as by kinetic impact, to perturb small NEOs and observe the results
- (4) Once the characterization effort and analyses of mitigation techniques have defined appropriate mitigation system requirements, an implementation decision can be made. Our present concepts of what an implementation phase might consist of include a launch infrastructure, an interceptor vehicle, a target acquisition capability, and nuclear explosive devices. An implementation program, including system tests, might cost several hundreds of millions to billions of dollars. More advanced and quite different mitigation systems may be developed on the time scale of two decades or more

7.3 Policy Framework

The nature of the hazard is global in scope. The United States is best situated to take a leadership role in developing an international program to detect the NEOs, characterize them, and mitigate the hazard. Recognizing the sensitive nature of this course of action and the dramatic international changes in recent years, it is appropriate and opportune to establish a climate of openness and international cooperation from the beginning.

Within the United States, the government-owned facilities, capabilities, and expertise for beginning this program are distributed primarily among three federal agencies—NASA, the Department of Energy (DOE), and the Department of Defense (DOD). Other agencies, such as the Federal Emergency Management Agency (FEMA) and the State Department, can also make significant contributions. The scientific and technical community will also be deeply involved. *The most sensible management of this effort is to form a national joint program office to implement the appropriate U.S. response to the NEO threat. At first, it may be most efficient to structure this as an augmentation to an existing structure of this type. Since the early phases of the recommended program primarily involve exploration and characterization*

of the bodies that pose the threat, it is natural and appropriate that NASA takes the lead within the context of the joint program office to begin this program. Eventually, during the implementation phase, prime responsibility may shift to another federal or international agency.

7.4 Conclusions of the Program/ Policy Options Working Group

The threat from impact of Earth-approaching objects was last formally addressed at a 1981 workshop in Snowmass, Colorado. In the decade since then, there has been a major shift in perception of the hazard to human life, arising in part from a vast increase in evidence linking extinction of species to impacts on Earth. Simultaneously there has been a great increase in the rate of discovery of NEOs, including some which have made near passes by the Earth. *The present workshop has concluded that there are technically credible approaches to preventing an impact catastrophe.*

Presently there is no organized program to address the NEO hazard. A decision to proceed should not be delayed in anticipation that new data will soon substantially modify our present understanding. The estimated level of threat merits a near-term response. We should begin now.

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Appendix B

MEMORANDUM

To: John Rather, Jurgen Rahe, and Gregory Canavan

From: Clark R. Chapman
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Date: 8 June 1992

Subject: "Near-Earth-Object Interception Workshop" Report



On June 3rd, I received the latest version of the report with a request for comments to be returned just two days later. I've worked on it as fast as I could. I have read the new version of the report and noted a number of changes. But I note, with considerable sadness, that you have ignored most of my suggestions -- both large and small ones -- that I provided in my memo of 8 April.

Answers to the questionnaire are provided at the end of this memo.

I find that the present report, while containing some important material, is generally biased and technically flawed. While I know that others may choose a different course, I consider the document to be so flawed that I do not wish my name associated with it. I note that you have tried to say in the new Preface that Chapters 2 through 7 are the responsibility of only the Working Groups that wrote them. I, however, think that inclusion of technically fallacious material or bizarre recommendations *anywhere* within the report casts a shadow over all participants in the Workshop. Since you have chosen to risk the loss of credibility that will result from your inattention to the criticisms of myself and others, I ask that my name be removed from the report. I will be happy to acknowledge in a broader forum that I attended the Workshop and devoted much effort to trying to help you prepare a responsible report, but that the ultimate product of the Workshop turned out to be skewed and seriously flawed.

I will make one last-ditch attempt to critique the report, in the hopes that you will be responsive. I will not repeat all of the constructive suggestions contained in my memo of 8 April, but will re-emphasize some of the most important ones.

Executive Summary

First, I have a *major procedural objection* to the Executive Summary. The Executive Summary of this draft report differs from the one that was submitted to the Congress. In particular, a direct comparison of the Executive Summary in the March 18th draft, the "Summary of the Findings of the NEO Interception Workshop" [text as provided April 1st by the

Space Subcommittee], and the latest draft Executive Summary reveals that objectionable material that *had been removed prior to submission to the Congress* has been re-inserted into the latest Executive Draft. For example, the words recommending "that an appropriate experimental program" be undertaken were deleted -- appropriately, I believe -- from the submission to Congress, but reinserted in the latest draft. Since these words generally refer to the controversial idea that tests (nuclear and otherwise) be undertaken to deflect asteroids, I think that this italicized recommendation is inappropriate. There are, of course, numerous other differences between the proposed Executive Summary and the one provided to the Congress. I think that this is most peculiar, and the Congress might find it to be peculiar, too.

Preface:

Pp iii-iv The Preface implies, in a fuzzy way, that Chapter 1 somehow represents a broader consensus than do the other Working Group chapters. This is false. As I describe below, Chapter 1 is seriously biased and *in no way* represents a consensus of the members of the Workshop. Quite the contrary: one of the major disagreements during the Workshop concerned the relative importance of the "Tunguska-class" impacts versus the larger ones. As has been extensively discussed in the course of developing the report subsequent to January, and as the *Detection Workshop Report* makes clear, the prime threat from impact comes from the objects about 1 km in diameter and larger. John Rather has not only superimposed his own biased and incorrect evaluation of the relative hazards in Chapter 1, but he has virtually ignored the larger objects altogether.

I cannot see how any member of the Steering Committee or participant in the Workshop can, in good conscience, agree with the representation of the Preface that Chapter 1 involves "an overall consolidation of opinions and technical results" nor agree that it "shows the full scope of the deliberations, results, and opinions."

Executive Summary:

Pg vi/vii: As elaborated on in my 8 April memo, it is by no means "futile" to search for and find potentially hazardous objects in the absence of potential nuclear technology for mitigation. Evacuation and non-nuclear alternatives could be very important, even if they aren't the *most effective* means of mitigation. This statement is not only in the "Energy Delivery" paragraph but remains, where Rather previously inserted it, in the "Program/Policy Options" paragraph. In particular, I object to its inclusion in the latter; as a participant in the "Program/Policy Options" group, I have been particularly cognizant of that chapter, and the statement about "futility" nowhere appears in that chapter and never did, so it should be excised from the Executive Summary.

Pg vii: In my 8 April critique, I objected to the inclusion of the phrase "eventually do deflection experiments" in step (3). The word "do" has now

been changed to "consider." This not only makes that sentence ungrammatical and nonsensical, it does not address the problem. The Policy group carefully considered a 4 element program. Items (1) through (3) were not ordered temporally but involved different magnitudes of funding. Item (4), implementation (including tests) was carefully selected to follow step (3). It was also carefully worded not to recommend implementation but, instead, to say that a "decision [on implementation and tests] could be made" at that time. John Rather, as Editor, unilaterally inserted a testing phase into step (3) and has left it there.

Section 1.

This is falsely represented to be a consensus "introduction and systems overview." It is not. The biggest arguments at the Los Alamos Workshop were between (a) those (like the Detection Workshop members) who argued that the greatest hazard is due to objects larger than about 1 km that would have *globally* destructive consequences and (b) those (like John Rather and Edward Teller) who argued that small Tunguska-scale impactors posed the greatest hazard. Teller et al. were simply in error. They had relied on a technically erroneous Livermore report by Lowell Wood, Rod Hyde, and Muriel Ishikawa (UCID-103771, May 1, 1990, "Cosmic Bombardment II"). At the Workshop, Hyde gave a talk that substantially corrected his previous errors, but John Rather seems not to have factored that into his considerations.

The present draft report contains new material (one lengthy paragraph beginning on pg. 4 plus two full-page diagrams, Figs. 1-3 and 1-4) that elaborates on correcting just one of the numerous errors in the original Livermore report (Wood et al. had ignored the fact that most small objects explode high in the atmosphere and have minimal consequences on the ground). This new material, while qualitatively correct, has not been peer-reviewed, despite its highly technical nature; it is peripheral to this report, merely correcting a single earlier error, and it should not be given such prominence in this report.

Despite correcting the one earlier error, Rather -- by conscious omission of essentially any discussion of >1 km bodies -- grossly distorts this report on the central issue: should the limited resources of the world be used to address the larger objects or the smaller ones? Elsewhere in this report (Section 7), Rather has now omitted the statement that had been in the original about the hazard of small impactors being less by several orders of magnitude than comparable natural hazards like earthquakes and cyclones.

Figures 1-3 and 1-4 do not even extend to sizes larger than 100 m and 400 m diameter, respectively. This is just one example of how the chapter is dominated by issues that wholly ignore the larger, more dangerous objects.

In order to illustrate that this imbalance in Section 1 is deliberate, I quote below what I wrote in my memo of April 8th; it is apparent that my comments were ignored:

"The report implicitly and explicitly emphasizes the importance of protecting Earth from small projectiles in the 10 to 100 m diameter range. In fact, such impacts have a high probability of doing no appreciable damage and, as John Pike has demonstrated, are down by several orders of magnitude compared with other natural disasters (e.g. earthquakes, floods, cyclones) in their chances for destroying life and property. Instead of emphasizing the qualitatively different, and quantitatively greater, hazard due to projectiles >1 km diameter, the italicized conclusion on page 4 says that it is "clearly sensible" to protect Earth from "these very rare but very deadly events" because the "stakes are so high." The context of this recommendation concerns 10 to 50 m objects, since the recommendation immediately follows three paragraphs discussing objects in the 10 m to 50 m diameter range (Tunguska, Revelstoke, and the Grand Teton fireball)."

"In view of the extensive discussions at Los Alamos about the qualitatively and quantitatively greater danger posed by civilization-threatening objects >1 km diameter, this conclusion appears to be intentionally misleading. Wood, Hyde, and others drew this erroneous conclusion in a Livermore report distributed in advance to Workshop members; the conclusion was echoed by Edward Teller during the first morning of the Workshop. Later discussion by many attendees emphasized the errors in that analysis, and the presentation of Hyde et al. at the Workshop corrected many of their earlier mistakes. Yet this report continues to emphasize the smaller impactors. The report should, instead, honestly describe the low overall danger from asteroid impact and the still lower danger from the smaller, more frequent impacts. It should also honestly describe the fact that the danger from the smaller impacts is down by several orders of magnitude compared with other natural disasters."

Fig. 1-5 of the new draft remains unchanged. I said in my 8 April memo that the figure should be annotated to emphasize that the "< 3 months" track is *much less likely* than the other tracks. Otherwise, it, too, gives undue emphasis to just those short-warning-time events that Rather would like to have his standing armada of interceptors waiting to shoot down.

I said before (8 April memo) that the discussion of precursor missions (e.g. Table 1-3) is very skimpy, does not adequately address mission objectives, does not distinguish between goals that can be met from the ground and those that require spacecraft missions, etc. The discussion remains inadequate in the latest draft.

I said before that the italicized recommendation (pg. 13) to build or retrofit radars for NEO purposes was costly and that the costs should be justified. No justification has been appended.

Section 3.

This chapter continues to discuss methods that have little or no utility or which are inappropriate. Section 3.2 states that kinetic energy interceptors are applicable mainly to small objects (< 70 or 100 m

diameter); but they are so small that they pose little hazard on the ground. The authors of Sect. 3 had evidently not seen the new Fig. 1-4.

Section 3.5, entitled "Consensus of the Energy Delivery/Materials Interaction Group Members." *I DEMAND that my name be removed from any connection with this FALSE representation.* As shown on pg. xi of this draft report, I was a member of that particular group. As I will quote below, my memo of 8 April emphatically disagrees with the conclusion that remains in the latest draft that "...we consider terminal defense to be as important as remote interdiction...[so] it will be imperative to have ground-based interceptors available for use on relatively short notice." While the wording has been changed from the original ("...it will be imperative to have an armada of interceptors on standby status...") the meaning is essentially the same. ("Ten" has been changed to "several," but these interceptors would still carry 100 megaton nuclear weapons.)

Not only have my objections been ignored in falsely reporting a "consensus," but -- in a new paragraph toward the end of this section -- the unsupported statement has been added that the hazard of accident or misuse of these weapons would be small compared with the hazard from those exceedingly rare asteroids or comets that might require their use. Unnamed "uninformed critics" (presumably people like me!) are taken to task for suggesting that these dangerous interceptors would be costly. Admittedly, cost is in the eye of the beholder, but no cost estimate has been provided in this report; by *my* reckoning, the cost of these interceptors is bound to greatly exceed the cost-to-benefit ratio appropriate to address this extremely low probability hazard.

As an (ex)-member of this group, I now quote below the objections in my 8 April memo, as proof that the material does NOT represent a consensus:

"The principal conclusion of this report (italicized although buried on pg. 20) is that "an armada of about 10 interceptors," each with "about 100 MT" fusion bombs, should be "on standby status." This is a preposterous recommendation. It would be extremely costly, would threaten accidental nuclear war, and would destabilize the world. The recommendation is out of all proportion to the minuscule threat of impact by a large, not-previously-discovered comet, which would be the only justification for such a "terminal defense" system."

and

"Having, as Chapter 3 describes it, "an armada of interceptors on standby status" presents a danger of misuse and/or accidental war -- which we thought had diminished due to the end of the Cold War -- that is enormous compared with the NEO hazard. It is inconceivable that the risks of such misuse/accident can be reliably reduced to less than those exceedingly small risks posed by the NEO's that might require such a system for mitigation."

and

"Pg. 20, italicized section. I strongly DISAGREE that "we consider terminal defense to be as important as remote interdiction." Furthermore, I disagree in the strongest possible way with the conclusion that "it is imperative to have an armada of interceptors on standby status." It would entail enormous cost and hazard of accident or misuse. The report nowhere develops the important conclusion that we need "about 10" interceptors nor why the bombs should be "about 100 MT.""

Section 4.

Very little revision has been done to this section. It still has two major problems. First, it presents an inadequate (I would also say incompetent) discussion of precursor missions. I have been a member of several past NASA and National Academy of Science committees that have prepared mission recommendations (including COMPLEX, the CRAF Science Working Group, and the NEAR study group) and am thoroughly familiar with how mission options should be evaluated in a report such as this one. As I wrote in my critique of 8 April:

"The report shows a bias toward SDIO spacecraft and ignores all NASA studies of NEO missions. This is a strange approach for what was to be a NASA recommendation to Congress. Table 1-3, which describes "strawman precursor mission measurements," is incompetent and for that reason alone should have no place in this report. It is dubious whether spacecraft developed by SDIO are capable of making the detailed measurements necessary to address our deficiency in knowledge about the physical natures of *comets*. This section of the report fails even to distinguish the kinds of measurements that could be made with groundbased optical or radar telescopes from those requiring spacecraft fly-by or rendezvous. To be useful, the strawman measurement requirements should be based on at least a preliminary assessment of what instruments would be necessary to achieve measurement goals dictated by the needs of the deflection technologies. Then it could be determined what the required instruments might be and whether or not inexpensive, lightweight spacecraft are capable of meeting the weight, power, and data-rate requirements of those instruments."

"The approach just described is the basis for the National Academy of Sciences COMPLEX recommendations for the study of comets and asteroids, in which it was argued that *rendezvous* rather than fly-by missions were probably necessary for the kind of in-depth study that we may expect will be necessary to achieve the kind of characterization that would be desired in the interception context. NASA has made many relevant studies of asteroid and comet missions in the past (e.g. CRAF, NEAR, the Discovery Program). At a minimum, this section of the report should draw on, or else contradict, those earlier studies. The reliance (pg. 23) on an apparently unpublished, possibly secret study by a "NASA/SDIO workshop" is inappropriate."

Minimal improvements to this section have been made in the latest draft.

Second, the report contains material related to a crazy and dangerous option of outfitting the world's arsenal of rockets with the world's arsenal of nuclear weapons in order to address an aspect of the NEO hazard. As I wrote in my critique of 8 April:

"Sect. 4.3: OMIT THIS SECTION on destroying large incoming objects on short notice. This is a greatly watered down and obscure version of the idiotic proposal in the draft of this section that proposed having more than 1,000 missiles on standby, equipped with a significant fraction of the world's nuclear arsenal. This was strongly objected to on the final day of the Workshop and the consensus was that the recommendation would be deleted from the report; later that day, Pete Rustan assured me personally that it would be deleted. Despite shortening and removal of many of the lightning-rod words, this material is no less defensible in its muted version than it was in the original. It is a place-holder for a totally crazy idea and should be omitted."

Section 6.

This section is an outrageous, often technically incompetent, and generally irrelevant embarrassment to everyone involved in the Workshop. I know that many Workshop attendees have criticized this section, yet it remains virtually unchanged from the previous draft. I won't repeat here all of my technical criticisms, but my overall reaction to this section bears repeating:

"The listing of a variety of highly speculative and/or irresponsible technologies in Chapter 6 is inappropriate. While I do not dispute the "bottom line" conclusion of this chapter, great emphasis given here to such concepts as "Super Orion" and "anti-matter" detract from the credibility of this report and/or lend undeserved credibility to these speculative and/or irresponsible technologies. I would not oppose a one-sentence mention of each of the options evaluated by this sub-group, but the material as it stands has *no place* in a serious government report. Let the amplification occur in the separate Los Alamos Lab proceedings."

Section 7.

Pg 45: The report of the Program/Policy Options group has been deliberately distorted to emphasize John Rather's skewed goals of addressing smaller, less dangerous impactors. The major change that has been made to this chapter since the last draft is the omission of an important sentence ("These objects constitute a hazard only to a local region on Earth; the annualized casualty rate is much lower than for the larger impacts and orders of magnitude less than for other natural disasters such as floods and earthquakes.") and replacement by several sentences which change "much lower" to just "lower", omits the potent comparison with other natural hazards, and then states that such an impact by a small object could be "an enormous catastrophe." These changes represent one part of a deliberate attempt to tilt this report in

favor of using military technologies to address what are, in reality, the *less-threatening*, smaller objects.

Appendix C

Memorandum

To: Gregory Canavan

From: Clark R. Chapman
Planetary Science Inst./SAIC
2421 E. 6th St.
Tucson, AZ 85719 USA

Date: 3 December 1992

Subject: Updated Comments on Interception Workshop Reports

Thank you for inviting me to submit comments for inclusion in the Proceedings of the Interception Workshop. I have accepted your suggestion to include my memo of 8 June 1992 as an Appendix to the Proceedings. I have accepted your suggestion to include my memo of 3 June 1992 as an appendix to the proceedings. That memo was the second of two critiques that I addressed to John Rather and others connected with preparation of the official report of the Workshop. I see evidence in the draft Proceedings that you have dealt with a number of the criticisms raised in my memo. Although these Proceedings reproduce parts of the latest draft of the Rather Report, you have sensibly removed some of the most offensive portions. I wish that John Rather had been similarly responsive earlier in this process.

As of the date of this memo it appears that -- in addition to the Proceedings -- an official report in the Interception Workshop will be published by NASA and transmitted to the Congress in the next week or two. I would hope that the official Rather Report would correct the technical flaws and absurd recommendations that were present in the last draft made available to me, similar to the changes you have made in these Proceedings, my understanding is that further modifications of the report will be minor (including excision of my name from the report). Therefore, I feel that it may serve a useful purpose to have my critique of that report published in the Proceedings: for example, in the latest draft, you have retained - unjustifiably, in my view -- a large amount of questionable speculation and pure nonsense in the section on "Current and Future Technologies".)

I would like to add a few observations about the impact hazard from the perspective of another six months since I wrote my critique.

Publicity in the Mass Media

The impact hazard has received considerable publicity in the news media, chiefly in response to an announcement by Dr. Brian Marsden, of the International Astronomical Union's Central Bureau, that Comet Swift/Tuttle has a tiny but possibly finite chance of encountering the Earth early in the 22nd century. I believe that Marsden's original announcement was not well considered, and I understand that he now agrees that the impact probability is far smaller than the 1 in 10,000 chance that he estimated for The New York Times. Regardless, there was extraordinary amplification of the impending disaster in the popular media, including a cover story in Newsweek. I think it is incumbent on everyone involved in commenting on the asteroid/comet impact hazard to emphasize the extremely low probabilities of impact and to do whatever is possible to restrain the news media from their tendency to sensationalize this subject. The public, and national policy leaders, need sober assessments of this hazard so that they may consider responding to it based on rational comparisons with many other potential priorities. If proponents of particular responses -- ranging from telescopes to SDI defense systems -- exaggerate this threat based on self-serving motives, then it will surely backfire. There is already much cynicism among the public and the pundits, some of it well justified in my view.

What Should We Worry About: Big Impacts or Small Impacts?

One of the major debates that took place at Los Alamos concerned the relative importance of two classes of impactors:

A. The "Tunguska class" of impactor may be defined as those objects that are large enough to cause a local disaster and impact frequently enough to have a modest chance of doing so during our lifetimes. The minimum size for this class (excluding rare metallic projectiles) is about 50 - 60 m, according to Hills and Goda in this volume. Such impacts, with energies of 10 - 15 MT, occur at least every two centuries and perhaps as often as every few decades, somewhere on the Earth. We might take the maximum size of the "Tunguska class" to be the 10,000-year impactor, which approaches a 1% chance of occurring during a human lifetime. Such objects are about 200 to 300 m in diameter and would explode with an energy exceeding 1,000 MT.

B. The "globally catastrophic class" of impactor has been defined in the Detection Workshop Report (Morrison, 1992) as one big enough to cause a global climate change (from stratospheric dust) equivalent to that studied for "nuclear winter." Although estimates of the threshold for global effects are uncertain, the Detection Workshop Report considers it to be in the range 0.5 to 5 km, probably near 2 km. Such impacts occur on Earth approximately every 1 million years with an explosive force exceeding half-a-million MT.

At the Workshop, discussion was strongly biased towards the importance of Tunguska-class impactors. This was due, chiefly, to a technically erroneous analysis by Wood, Hyde, and others that had been distributed prior to the Workshop. That analysis failed to consider the atmospheric shield that protects us from the smallest impactors and drew absurd conclusions about mortality due to frequent, small events that -- in fact -- never kill anyone. The latest draft of the Rather Report included corrected calculations by Hills and Goda on atmospheric shielding, but retained an overall bias towards interception of small projectiles. These Proceedings include more sensible analyses of the relative importance of the two classes of impactors.

My own view is that the Tunguska-class impactors are *not worth the cost of insurance*, if by "insurance" we mean implementation of programs that identify most threatening projectiles and intercept them (for purposes of diverting or destroying them). I think that globally-catastrophic impactors *may be worth the cost of insurance*, by which I mean implementation of a telescopic survey like the proposed Spaceguard Survey, followed by implementation of an intercept mission *only* if a threatening object is found. Let me describe my reasoning:

The damage from a Tunguska-class event will usually be minimal (if it is an airburst over the ocean, or if it is a groundburst in an uninhabited portion of the world, like Tunguska in 1908). With very low probability ($\ll 1\%$ of Tunguska-class events, occurring no more often than every few thousand years and more likely much less often than that), a population center might be struck, in which case the death and destruction would be massive. Even such a local tragedy, however, would be unlikely to cause more death or destruction than some of the other major natural disasters of the 20th century. For purposes of comparison, there have been 11 natural disasters during the 20th century that have killed more than 100,000 persons each (4 earthquakes, 4 floods, 2 droughts, and 1 cyclone); estimated deaths exceeded 1 million for several of these disasters.

The analysis by Canavan in the chapter on "Values..." implicitly assumes that a small impactor will have economic consequences in proportion to the fractional area of the Earth that is within the radius for destruction. This is very unrealistic because the economic value of portions of the Earth's surface is highly skewed, just as is the population. The most likely loss from a Tunguska-class impactor is probably zero.

The benefit/cost ratio is particularly poor for insurance against Tunguska-class impactors not only because of the modest hazard but because of the high expense of effective interception. Detection of Tunguska-class impactors, while technically feasible, is nevertheless a real challenge, involving far more expensive technology than that necessary to detect globally-catastrophic impactors. Moreover, it is unlikely that most Tunguska-class impactors can be detected years before impact. Therefore, the "insurance program" would have to include development and implementation of an intercept capability that could respond in near-real-time. Whether or not an "on-the-launch-pad" capability is required, the costs of a defensive system against these objects would be appreciable.

The available numbers suggest that the inherent hazard of globally catastrophic impactors is at least an order of magnitude greater than for the Tunguska-class impactors. On the other hand, if the preliminary results of the Spacewatch Program are correct about an enhanced number of 50 - 100 m objects, and if the threshold for global catastrophe is near the upper end of the range of uncertainties, then the annualized risk of fatalities might actually be dominated by Tunguska-class impactors. I would still argue, however, that the globally catastrophic impactors deserve our attention far beyond their strictly numerical hazard. That is for the simple reason that *if civilization is threatened, then all of history and everything that is important to us is at risk*. Human society can recover from devastating plagues and wars that kill tens of millions and destroy whole nations. But we may be unable to recover, as a civilization, from a globally-destructive impact disaster -- even though the destruction falls far short of what would render our species extinct. This is the kind of hazard that bears thinking about because of the profound consequences if we are unable to recover from the disaster. (In a sense, this attribute is partly handled by the "persistence" analysis in the chapter on "Values..." by Canavan.) A large portion of this "ultimate risk" can be insured against through construction of a network of telescopes at moderate cost and *without* development of an intercept capability (unless and until a threatening object is actually found, which is very unlikely). Therefore, the benefit/cost ratio is dramatically higher for the globally catastrophic case than for the Tunguska-class case even if the numerical risks were similar.

THE SCIENCE OF DOOM

It comes screaming out of the sky like the Scud from hell, bigger than a mountain and packed with more energy than the world's entire nuclear arsenal. It hits the atmosphere at 100 times the velocity of a speeding bullet, and less than a second later smacks into the ground with an explosive force of 100 million megatons of TNT. The shock wave from the crash landing, traveling 20,000 miles an hour, levels everything within 150 miles. Simultaneously a plume of vaporized stone shoots up from the impact site, blasting a hole through the atmosphere and venting hot debris. The vaporized rock cools, condensing back into hundreds of millions of tiny stones. As they streak to the ground, over the next hour, they heat up, and soon the very air glows hot pink. Steam hisses from green leaves, buildings and even trees burst into flame. Nitrogen and oxygen in the atmosphere combine into nitric acid, and surviving life, crawling out of a burrow or cave, gets pelted with a rain as caustic as the acid in a car battery.

That's what astronomer Henry Melosh of the University of Arizona calculates would happen if something six miles across fell from space and smacked into Earth. Six miles is the size of the comet believed to have hit the planet 65 million years ago, killing off the dinosaurs and two thirds of all life. Six miles also happens to be the probable size of the Swift-Tuttle comet. Swift-Tuttle is the peripatetic frozen dirt ball

Space is filled with objects that threaten Earth. Researchers are scrambling to ensure that worlds don't collide.

BY SHARON BEGLEY

that an astronomer last month declared has a 1-in-10,000 chance of hitting Earth on Aug. 14, 2126.

All an astronomer need do is spy the pockmarked surfaces of planets and our own moon to realize that it's a cosmic shooting gallery out there. Mercury, Venus, Earth and dozens of moons have been cratered over the eons by a blizzard of falling asteroids, comets and other stuff that can't manage to stay in its own orbital lane. But it dawned on scientists only recently—in the 1940s—that this pinball chaos hasn't stopped. An estimated 20 tons of particles, most no bigger than grains of sand, fall on the ground each day. Of course, sometimes the missiles are bigger than sand grains. Thousands of meteorites as big as a lump of coal fall every year, usually harmlessly. But one smashed through



A deadly collision could suck out the atmosphere, scorch the Earth and shroud the planet in dust

a garage roof in Illinois in 1938, and another totaled a car in a New York City suburb last month (no injuries in either case). Ironically, the misses are more worrisome than the hits. On March 23, 1989, an asteroid a half mile across missed Earth by just 700,000 miles. No one saw it coming; if it had arrived a mere six hours later it might have wiped out civilization. "Earth runs its course about the sun in a swarm of asteroids," says astronomer Donald Yeomans of NASA's Jet Pro

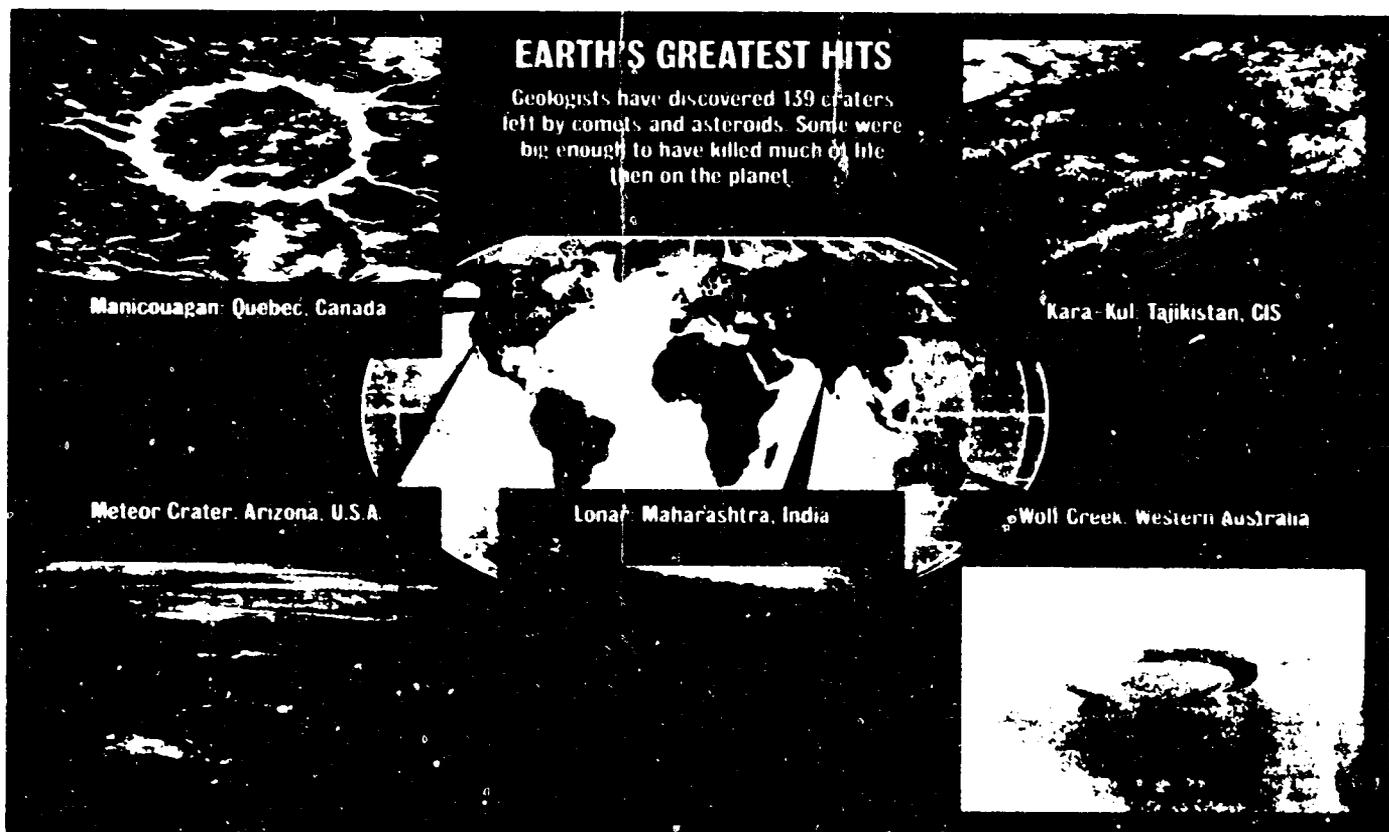
Halley (after the 17th-century English astronomer who predicted its return). But no one knows how many never-before-seen comets are heading our way. "For those coming in from the far reaches of the solar system (for the first time), we have virtually no chance of seeing them until they get close," says astronomer Clark Chapman of Science Applications International Corp. in Tucson, Ariz. "We could discover every asteroid and still 10 percent of the threatening objects wouldn't be found" until they were literally upon us.

Comet Swift-Tuttle is not among that 10 percent—it's been observed at least twice before—but it could still pose a considerable threat. Last seen in 1862, it was spotted by a Japanese amateur astronomer again in late September. On Nov. 7 it passed within 110 million miles of Earth—not even a close call. (Swift-Tuttle causes the Perseid meteor showers every August, as it orbits the sun, little bits flake off. When Earth crosses this path, the litter streams through the atmosphere and glows.) Brian Marsden, of the Harvard-Smithsonian Center for Astrophysics has calculated that

distances [14 million miles] on August 5, 2126. There is no evidence for a threat from Swift-Tuttle in 2126 nor from any other known comet or asteroid in the next 200 years." But Marsden still thinks the grandchildren of today's toddlers might be in for a nasty shock in their old age. "There are still unanswered questions," he says. "That's why I've said to astronomers, 'Get more observations.'"

Swift-Tuttle is only one of thousands of potential doomsday rocks. It's not exactly prudent to wait for the sky to fall, so in January the NASA panel called for the creation of an early warning system. Using six two- or three-meter telescopes, astronomers could spot more than 90 percent of the asteroids bigger than about a half mile. It would cost \$50 million to build "the Spaceguard Survey" and \$10 million a year to run it. That's a 4-cents-per-American insurance policy. But there could still be unpleasant surprises. There's no practical way to get an early warning about smaller asteroids or many comets.

Once astronomers calculate orbits for the thousands of asteroids



PHOTOS COURTESY OF J. NARA PRASAD, G. S. SINGH ET AL.

Swift-Tuttle will return, after swinging out past Pluto in a 134-year orbit on Aug. 14, 2126. On that visit, it will come much closer to Earth than it did this year. And Marsden said last month, because Swift-Tuttle's jets might nudge it ever so slightly off its appointed course, it might even hit Earth.

Ever since, the doomsday faxes and E-mail have been flying at the speed of light. Scientists don't dispute that comets erupt with jets as the sun warms their surface. Like thrusters on a spaceship, the eruptions shift the comet's orbit ever so slightly. But is there reason to think Swift-Tuttle's jets will push it onto a collision course? To see, JPL's Yeomans used the observations of 1992 and 1862 to calculate Swift-Tuttle's orbit. Using that orbit, he calculated how close the comet would have come to the sun in its previous visit in 1737, assuming no mysterious course-altering jets. Bingo, he nailed the actual orbit to within a day (the 1737 orbit was recorded by a Jesuit missionary in China). This seemed to establish that so far, at least, Swift-Tuttle's orbit has not been shaped by jets of the kind or strength that might cause a collision in 2126. Yeomans concludes: "The comet will pass no closer to the Earth than 60 lunar

and comets whose paths intersect Earth's, they will almost certainly find a few that are on a collision course. The extent of Earth's danger depends, of course, on the size of the object likely to strike it:

■ **Truck size:** Such collisions come at least every decade. But anything smaller than 30 feet across or so, though packing the wallop of 50,000 tons of TNT, usually fragments and burns up in the atmosphere. Such an asteroid or comet may produce a "meteoric fireball"—a burst of light and heat—but it's usually too high in the atmosphere to cause significant damage.

■ **Building size:** A rocky asteroid with a diameter between 30 and 300 feet blows up in a blinding flash when it smacks into the atmosphere, as did the comet or asteroid that exploded over Tunguska, Siberia, one June morning in 1908. Exploding five miles up with the force of 12 megatons, it annihilated reindeer 30 miles away, ignited the clothes of a man 60 miles away and leveled more than 700 square miles of Siberian forest. A sturdier asteroid, one made of nickel and iron rather than stone, would plunge to the ground without exploding. If one the size of the Tunguska rock hit

the rural United States, calculates John Pike, director of space policy for the Federation of American Scientists, it could kill almost 70,000 people and cause \$4 billion in property damage. It could also flatten buildings 12 miles away, according to the NASA panel. If it hit an urban area, there would be upwards of 300,000 deaths. If it hit in a seismic zone, it could trigger earthquakes topping 7.5 on the Richter scale.

■ **Mountain size:** Objects larger than 300 feet across hit Earth once every 5,000 years or so. If an asteroid 600 feet across fell in the mid-Atlantic Ocean, calculates astrophysicist Jack Hills of Los Alamos National Laboratory, it would produce a massive tidal wave, 600 feet high, on both the European and North American coasts. Hills speculates that just such a hit wiped out the fabled Atlantis. Larger asteroids, half a mile across, hit every 300,000 years. That kind of collision, says Pike, "would surely rank as the greatest catastrophe in human history." Thanks to the cloud of dust thrown up by this million-megaton explosion, there would be no crops anywhere for a year. In contrast, a comet of this size, since its ice and frozen gases fragment easily, would probably break up in the atmosphere and explode like the Tunguska hit.

■ **City size:** Asteroids or comets larger than three miles across, like Swift-Tuttle, hit every 10 million to 30 million years. According to one calculation, if the dinosaur comet—thought to have been about six miles across—hit in the Gulf of Mexico, it would have created a wave three miles high. Nine hundred miles away, the mammoth wall of water would still be 1,500 feet high. Such an asteroid landing in the Gulf of Mexico would cause floods in Kansas City. The impact would make entire continents burst into flame, block sunlight and make agriculture impossible. Humans might go the way of the trilobites.

At a conference this year at Los Alamos, researchers had no shortage of ideas about how to protect against cosmic catastrophe. Some of the more ingenious came from weapons scientists. Shooting down a comet is not so different from shooting down an ICBM (except that the ICBM is closer, and thus easier to spot, and slower, so easier to hit). And given the promised demise of the Star Wars program under the Clinton administration, shifting over to anti-comet defense may not be a bad career move.

At the conference, Edward Teller called for the development of a bomb 10,000 times more powerful than anything in today's arsenal. One researcher might dropping antimatter onto the threatening asteroid or comet would do the trick: when antimatter meets matter, they annihilate each other in a puff of pure energy. (He didn't specify how to get antimatter up to the asteroid, since at the moment rockets are made of matter, not antimatter, and so would be destroyed as soon as the antimatter cargo was loaded.) Or, a rocket could drop a "solar sail" onto an asteroid or comet; the sail would catch the charged particles constantly streaming out from the sun and thus alter the object's course, carrying the threat safely past Pluto. No one has figured out how to deliver the sail, though. Dropping a heat source of some kind onto a comet looks good on paper, too: the heat would induce jets that, like thrusters, would

steer the comet away from Earth (an asteroid doesn't have enough volatile ingredients to make jets). But jets are not predictable. They might accelerate the comet toward Earth.

Such sticking points help explain why the motto of the Los Alamos conference was, as one enthusiast cheered, "Nukes forever!" So far, the only source of energy powerful enough to deflect a mountain-size rock traveling at 15 miles per second—54,000 miles an hour—is nuclear. The basic idea is to use a massive explosion to deflect the asteroid or comet from its earthbound path. The sooner the better: a push of even a few hundred feet, if applied millions of miles away, could work. Waiting until the killer rock was closing in would require more energy than any nuclear weapon ever built.

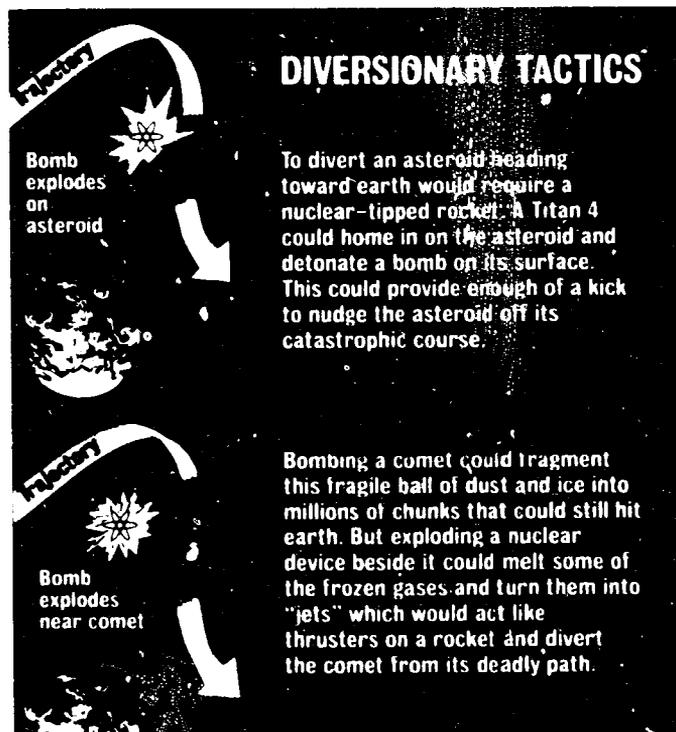
Where to deliver the bomb depends on what the object is. A comet is fragile. A blast on the surface could shatter it into huge pieces that together could kill even more earthlings than the original. The

NASA panel therefore endorsed a "stand off" blast (diagram). One or more nuclear-tipped missiles, launched on an American Titan 4 or a Russian Energia rocket, would home in on the comet optically or by radar. The missiles would be programmed to explode the bombs beside the comet, kicking it off its earthbound path either directly or by inducing orbit-altering jets.

No one would argue against deflecting an asteroid or comet capable of dooming all agriculture for a year, let alone one able to cause the extinction of mankind. "But there is deep disagreement over whether we should also protect against the impacts that happen every decade or so, like Tunguska," says Clark Chapman. "Even these small events can kill people, but they are a thousand times less likely to do so than are quakes, floods and the other things that kill people all

the time." Expense is one factor. Because an early warning system could not detect objects 150 feet across more than a few weeks ahead of their arrival, to protect against them would require keeping dozens of nuclear-tipped rockets fueled up, armed and ready to go 24 hours a day. That would cost several billion dollars a year. Even then, success against a fast closing object would be far from certain, especially since the rockets would get only one chance to score a hit. Keeping nuclear-tipped rockets at the ready would also be dangerous. Accidents happen. Terrorists happen, too.

During a human lifetime, there's roughly a 1 in 10,000 chance that Earth will be hit by something big enough to wipe out crops worldwide and possibly force survivors to return to the ways of Stone Age hunter-gatherers. Those are the odds of dying from anesthesia during surgery, dying in a car crash in any six-month period or dying of cancer from breathing the automobile exhaust on the Los Angeles freeway every day. Killer asteroids and comets are out there. And someday, one will be on a collision course with Earth. Of all the species that ever crawled, walked, flew or swam on Earth, an estimated two thirds became extinct because of an impact from space. Mankind may yet meet that fate, too. But we're the only species that can even contemplate it and, just maybe, do something to prevent it. ■



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