MSFC-2040

Near Earth Object (NEO) Mitigation Options Using Exploration Technologies

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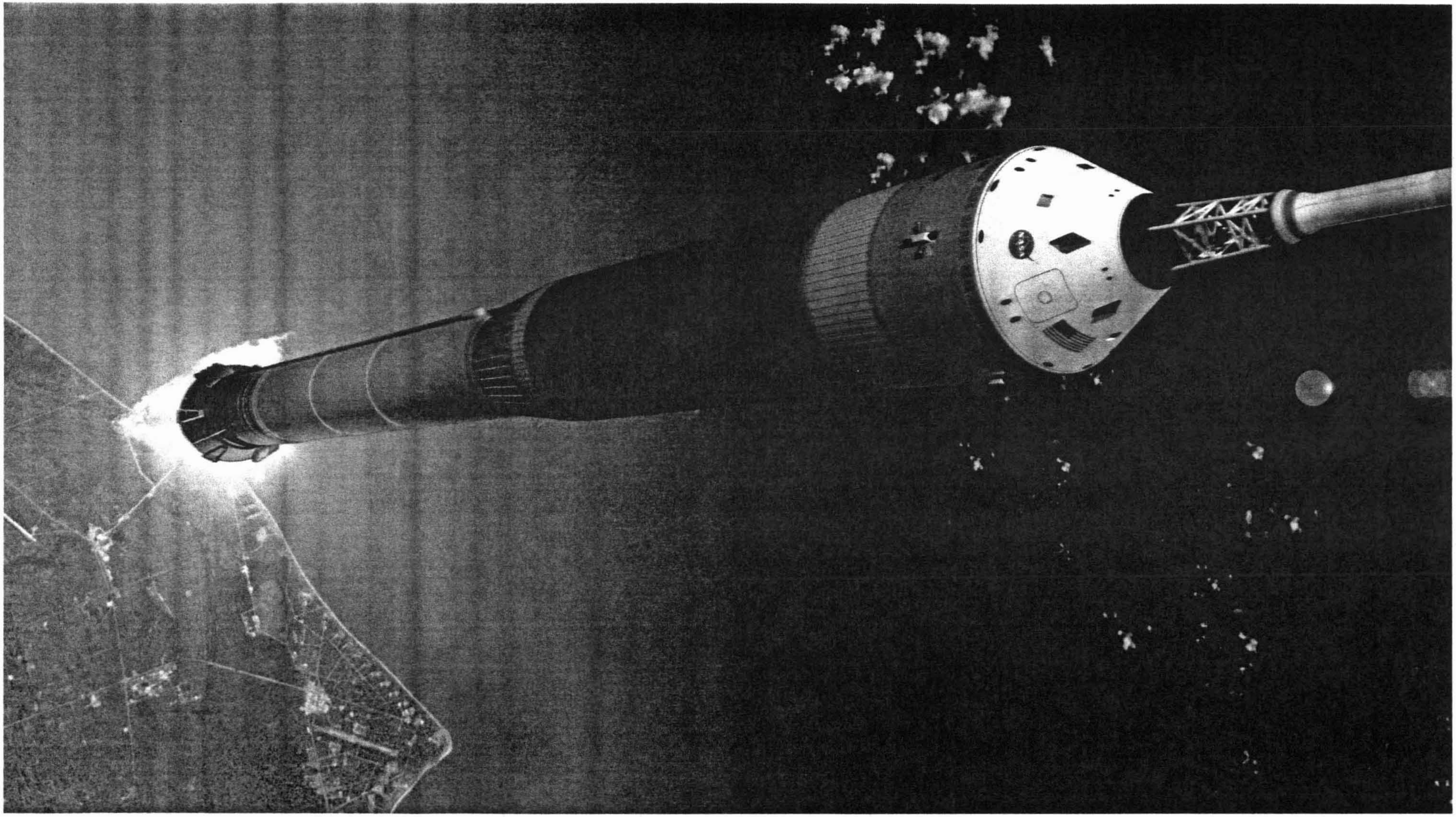
Outline

- Impetus
- Operational concept
- Exploration vehicles
- Groundrules and assumptions
- Observer stack design
- Interceptor stack design
- Interceptor options
  - Nuclear Interceptor design
  - Kinetic Interceptor design
  - Solar Collector design
- Comparative Analysis
- Conclusions/Future Work

Impetus

- Consider use of new launch vehicles in the effort of defense against NEO's.
- Leverage expertise in launch vehicle design, spacecraft design, astronomy and planetary science and missile defense in the Huntsville area.
- Build relationships with principal investigators of deflection technologies worldwide.
- Build on previous efforts in planetary defense.
- Build relationships with others in this area.
- Demonstrate synergy between architectures needed for human/robotic exploration initiatives and for planetary defense

Exploration Vehicles



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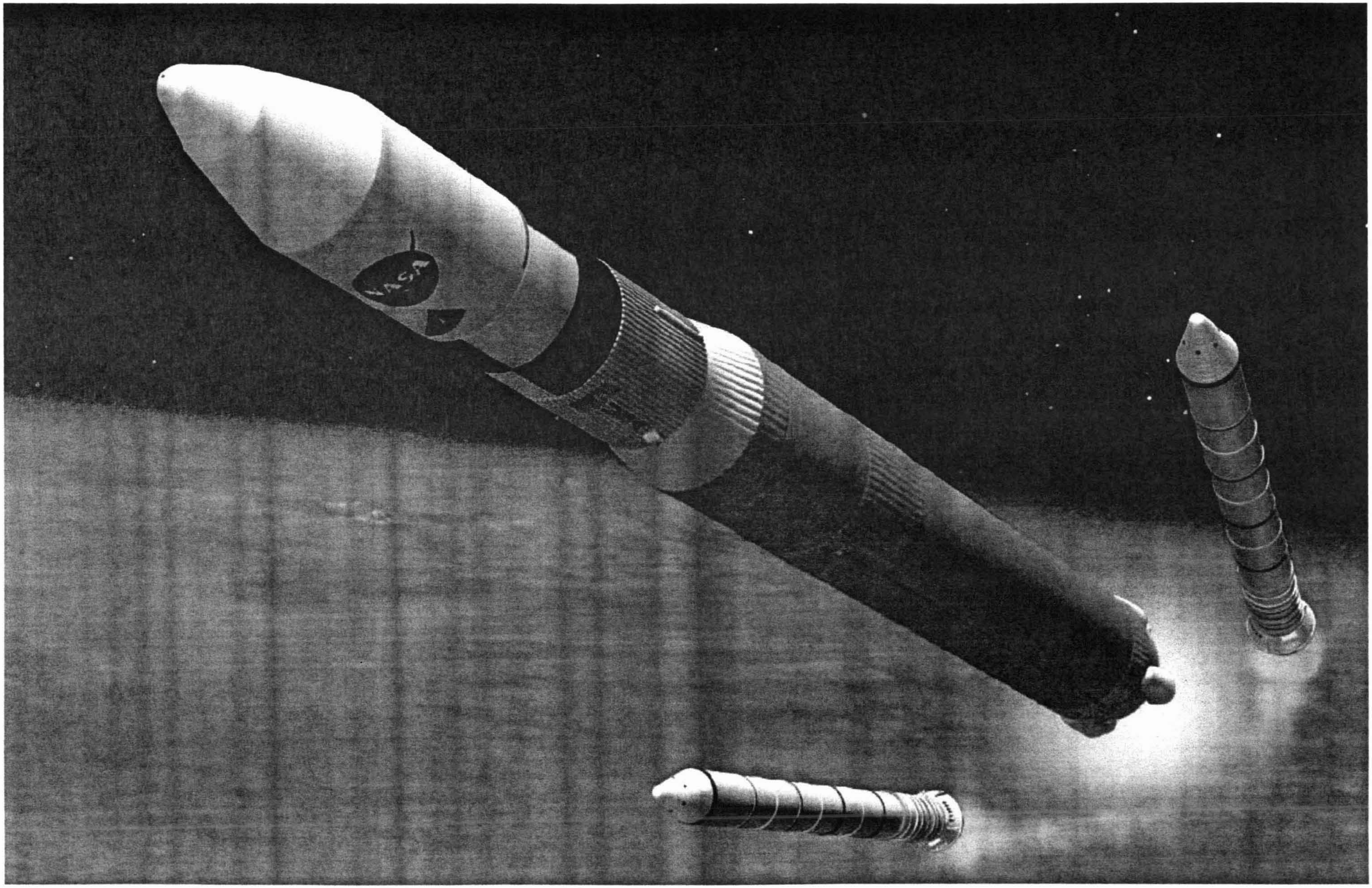
Exploration Vehicles



Exploration Vehicles

- Performance

Target Orbit/C3	Inclination	Ares I Payload	Ares V Payload
~30x100 nm	28.5	52,592 lbm[1]	n/a
~30x100 nm	51.6	49,260 lbm[1]	n/a
100x100 nm	28.5	n/a	105,487 lbm[2]
~2.6 km^2/s^2	n/a	n/a	134,483 lbm
-2.0 km^2/s^2	n/a	5146 lbm	133,585 lbm
0 km^2/s^2	n/a	n/a	129,600 lbm
10 km^2/s^2	n/a	n/a	111,262 lbm

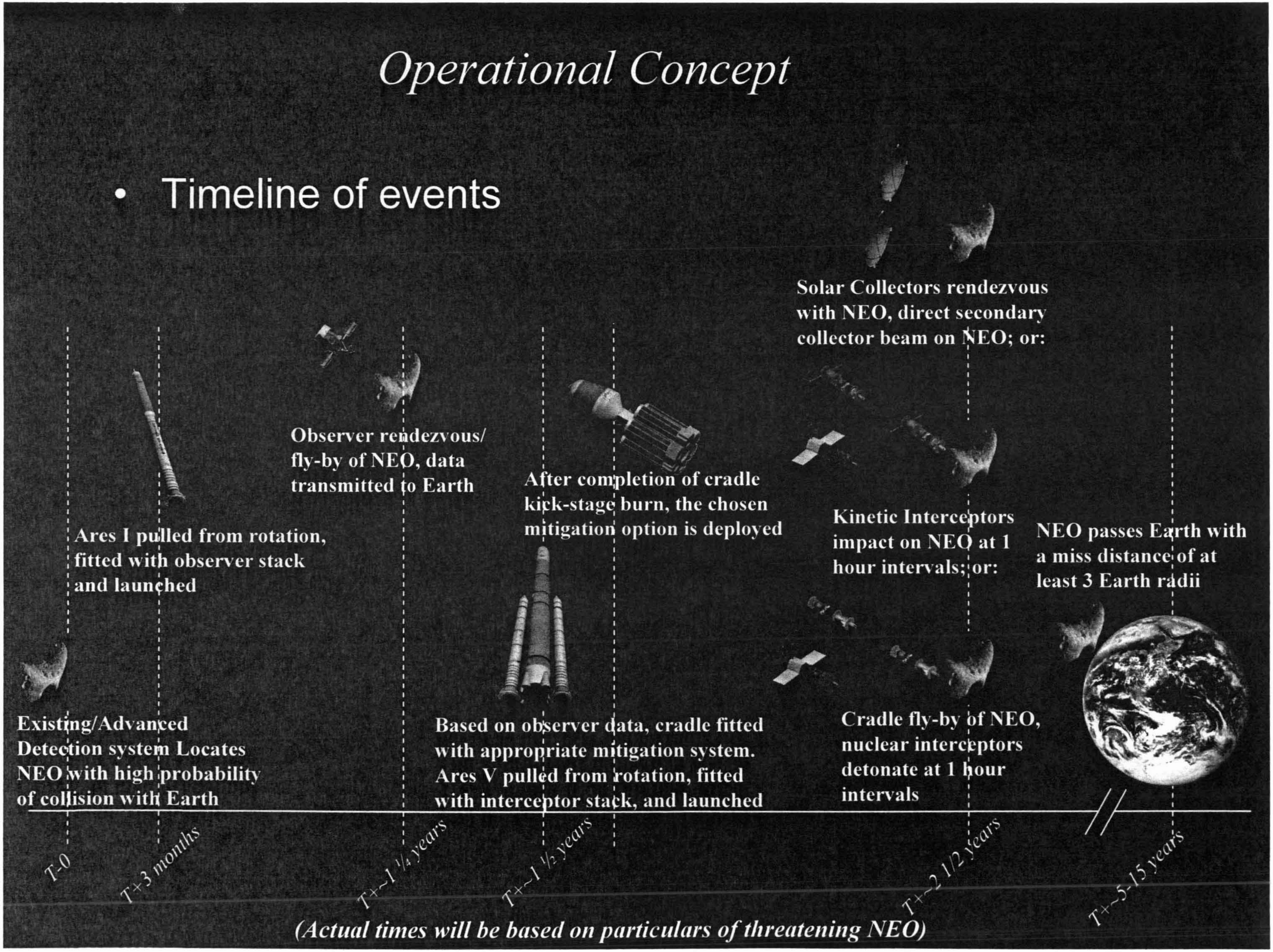
(1) Ares I payload includes 10% performance margin, Payload provides circularization ΔV
(2) Ares V payloads to LEO orbits are based on a partially burned Earth Departure Stage (EDS)

Groundrules and Assumptions

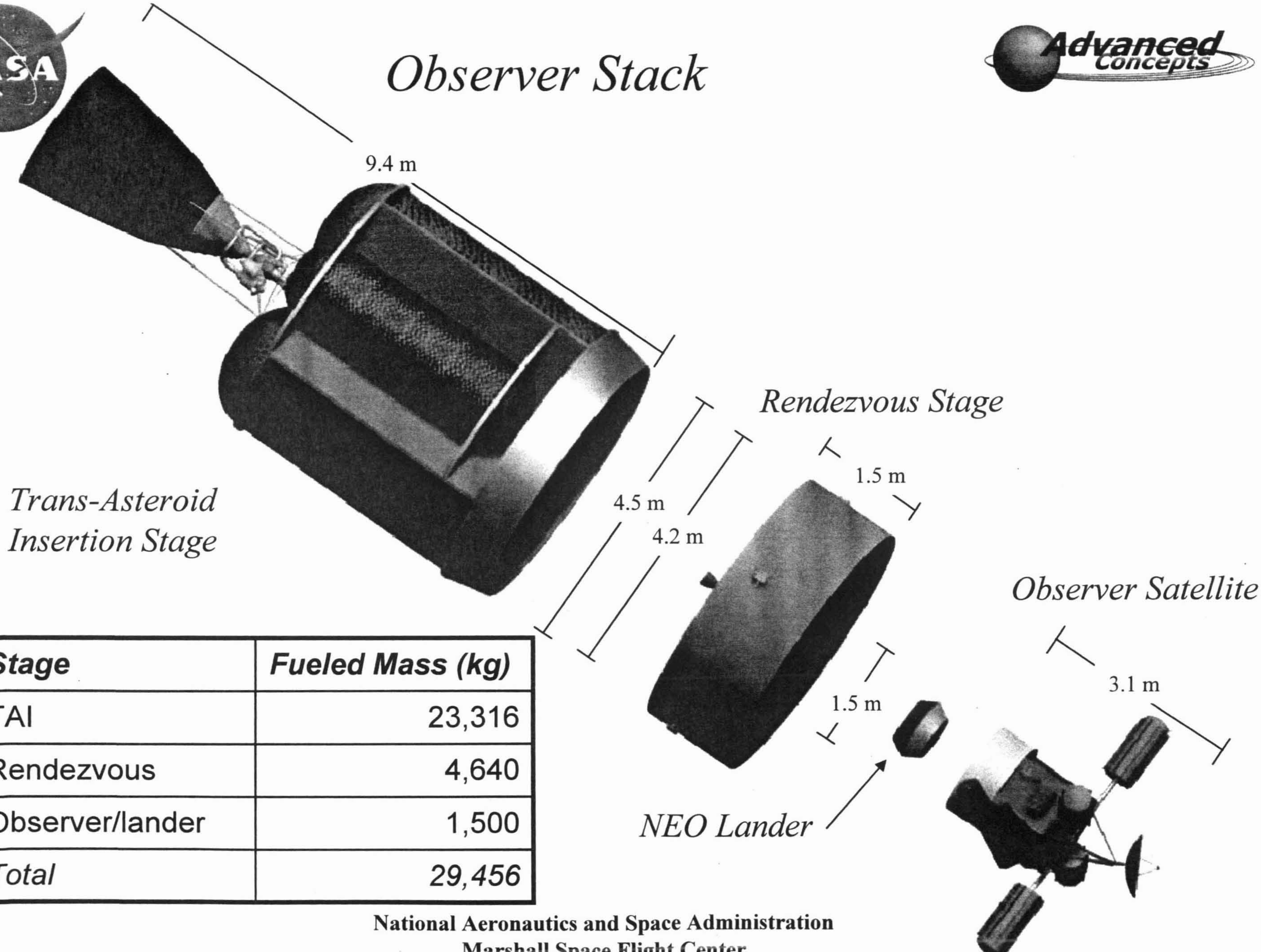
- Funding limited for research and development of planetary defense architecture
  - Technology Readiness Level of 5 or above
  - Use of planned exploration architecture advantageous
- Exploration Vehicles
  - Ares I available in 2014
  - Ares V available in 2020
- Assume potentially hazardous NEO detected after 2018
- Only publicly available information to be used in this study.
- Planetary Defense architecture components standing ready
  - Architecture to use the full capabilities of the exploration vehicles.
  - Architecture to defeat as much of the threat posed by NEO's as possible given above constraints.

Groundrules and Assumptions

- Three different mitigation options baselined for this study
  - Nuclear standoff explosion
  - Kinetic Interceptor
  - Solar Collector
- Not suggesting these are the only viable options
- Limited scope based on:
  - Short term study, requiring that we consider options for which we had previous experience
  - The chosen options allow consideration of nuclear/non-nuclear, intercept/rendezvous scenarios, short term/long term operation
  - The chosen options that have potential applications for future resource utilization
- Baseline architecture can potentially accommodate other mitigation options


Operational Concept
• Timeline of events
Existing/Advanced Detection system Locates NEO with high probability of collision with Earth
Ares I pulled from rotation, fitted with observer stack and launched
Observer rendezvous/ fly-by of NEO, data transmitted to Earth
Based on observer data, cradle fitted with appropriate mitigation system. Ares V pulled from rotation, fitted with interceptor stack, and launched
After completion of cradle kick-stage burn, the chosen mitigation option is deployed
Solar Collectors rendezvous with NEO, direct secondary collector beam on NEO; or:
Kinetic Interceptors impact on NEO at 1 hour intervals; or:
Cradle fly-by of NEO, nuclear interceptors detonate at 1 hour intervals
NEO passes Earth with a miss distance of at least 3 Earth radii
T-0
T+3 months
T+~1 1/4 years
T+~1 1/2 years
T+~2 1/2 years
T+~5-15 years
(Actual times will be based on particulars of threatening NEO)

Observer Stack



Stage	***Fueled Mass (kg)***
TAI	23,316
Rendezvous	4,640
Observer/lander	1,500
Total	*29,456*

Observer Stack

- Design
  - TAI stage
    - intended for Earth escape
  - Rendezvous stage
    - used to match orbit with NEO
    - can be used for additional DV for fly-by burn when rendezvous not possible
  - Observer satellite
    - Next generation Deep Impact probe
    - Solar panels replaced with RTG's for operation past Mars orbit
    - Impactor from Deep Impact replaced with lander
- Performance

Propulsion System	Thrust (lbf)/ No. of Engines	Nominal Isp (seconds)	ΔV capability (m/s)	Propellant (kg)
Lox/LH2	24750/1	465.5	4150	13,860
Hydrazine/ N2O4	1000/1	330	2000	2165
Hydrazine	5/16	234	60	107

Observer Stack

- Observer measurements and methodology
  - All measurements have redundant instruments
  - Operational plan
    - Lander separates from observer and approaches NEO
    - As lander prepares for landing it fires several weights around NEO
    - Observer tracks weights, calculates NEO mass from deflection angle of weights
    - Lander moors to NEO. Low thrust engine keeps lander pressed against NEO
    - Observer launches several explosive charges to impact NEO in different locations.
    - Lander measures seismic response and triangulates voids in NEO structure.
    - Other sensors on lander and observer makes continuous readings. Observer relays lander data to Earth

Observer Stack

- Observer measurements and methodology
  - Table of instruments and measurements on observer

Category	***Instruments***	***Planned measurements***
Optical	Laser Ranger	Orbital elements
	Narrow Field CCD	surface mapping, geometry, dust environment
	Wide Field CCD	Dust environment, geometry, potential satellites
	Spectrometer	Composition, density
Radar	MARSIS radar sounder	Density, internal structure
	Dual mode radar/data link	Internal structure
Other	Gravity sensor	Mass, gravitational field

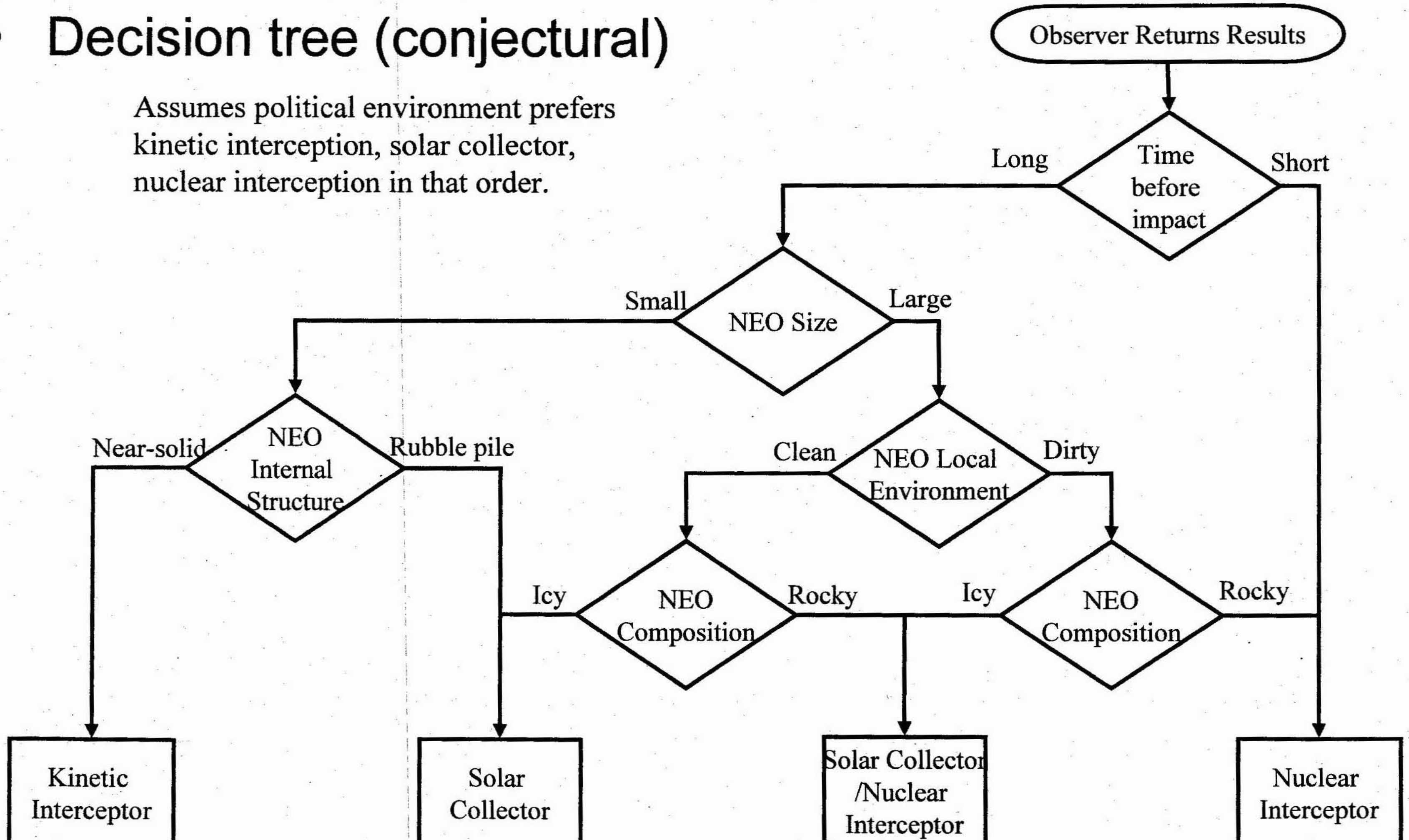
  - Instruments and measurements on lander

Instruments	***Planned measurements***
Chemical analysis package	Composition
Seismic sensor	Internal structure
Fly-by balls	Mass, Gravitational field

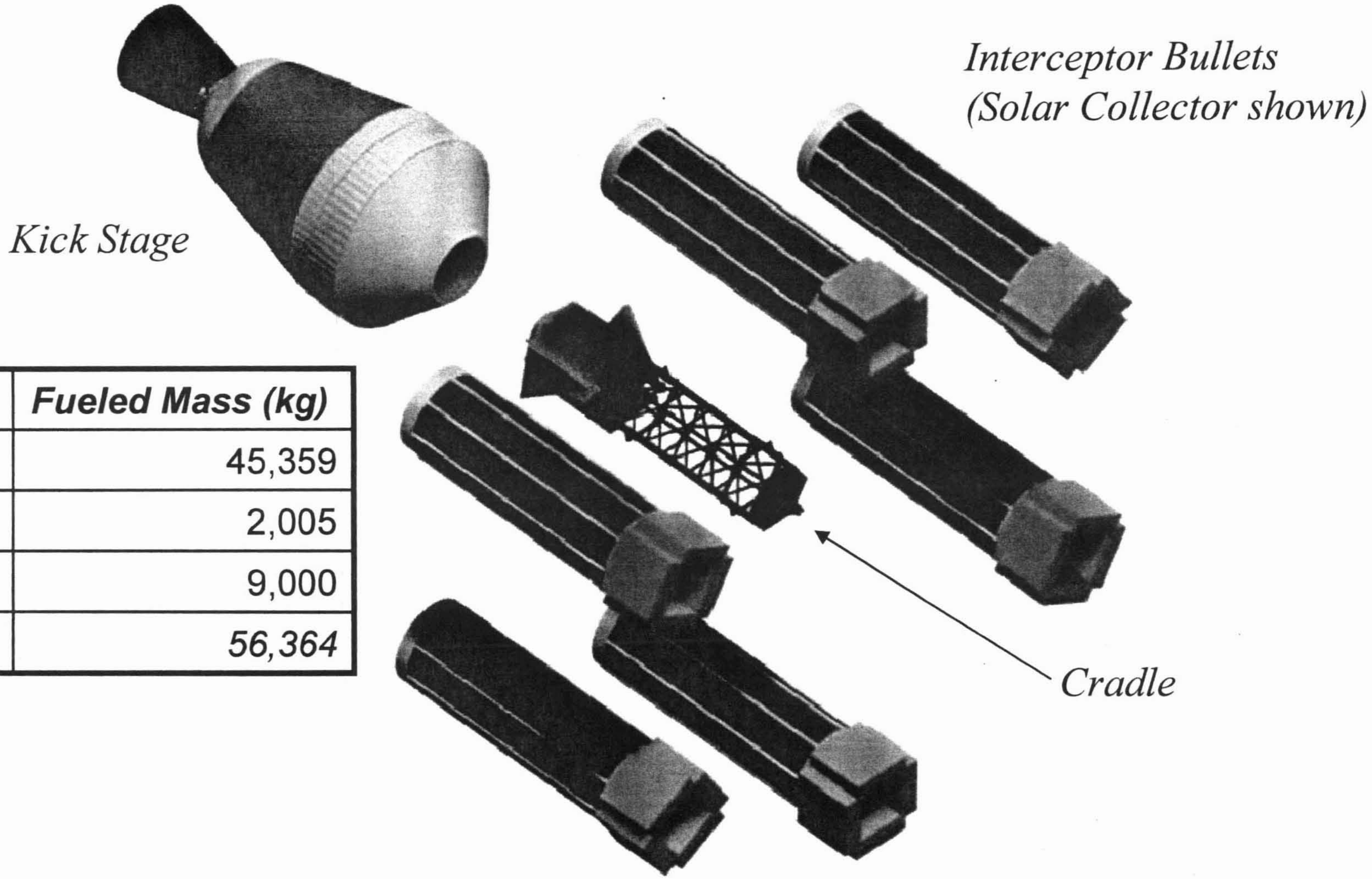
Observer Stack

- Decision tree (conjectural)

Assumes political environment prefers kinetic interception, solar collector, nuclear interception in that order.

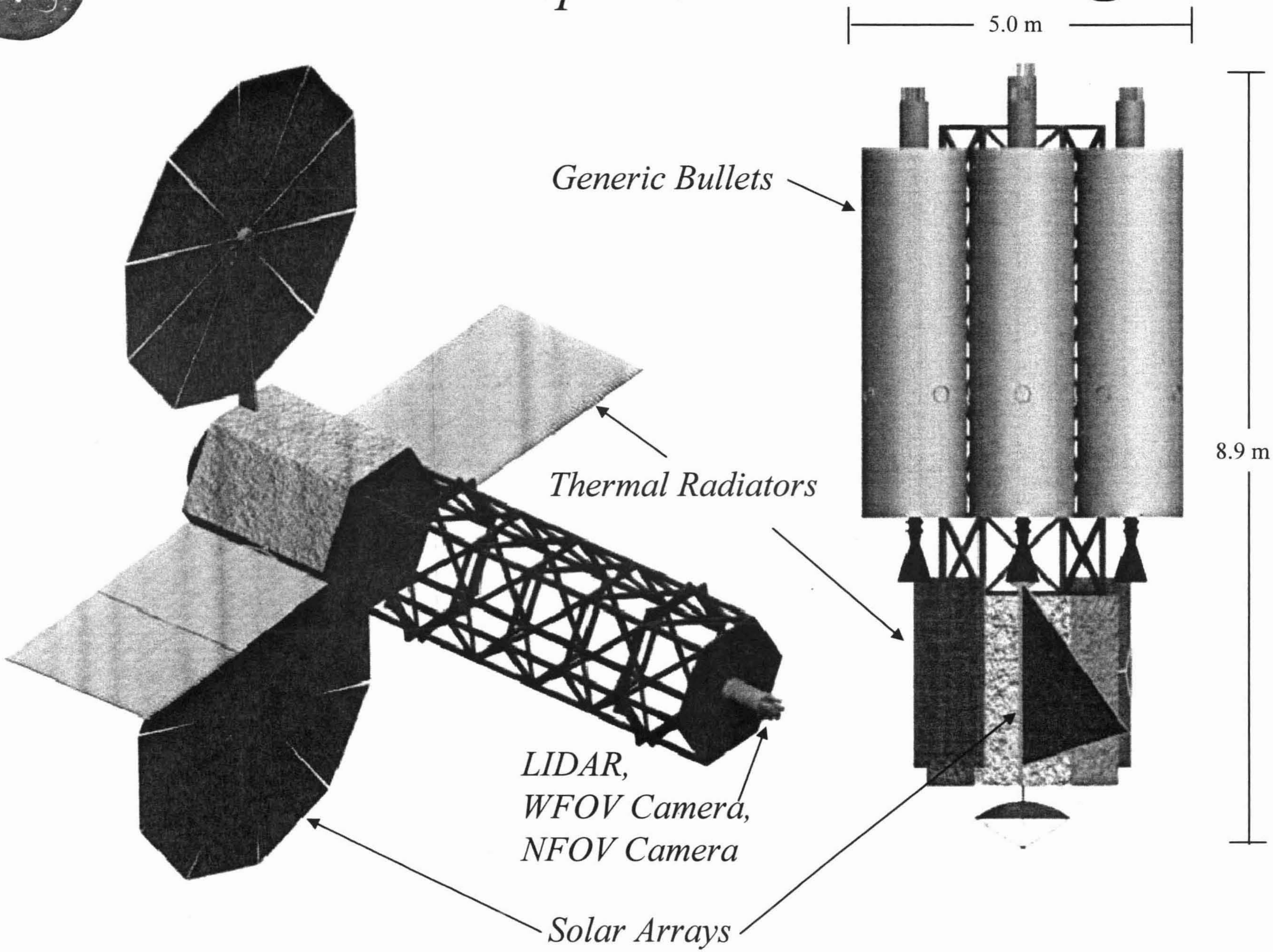


Interceptor Stack



Stage	*Fueled Mass (kg)*
Kick	45,359
Cradle	2,005
Bullets (6)	9,000
Total	*56,364*

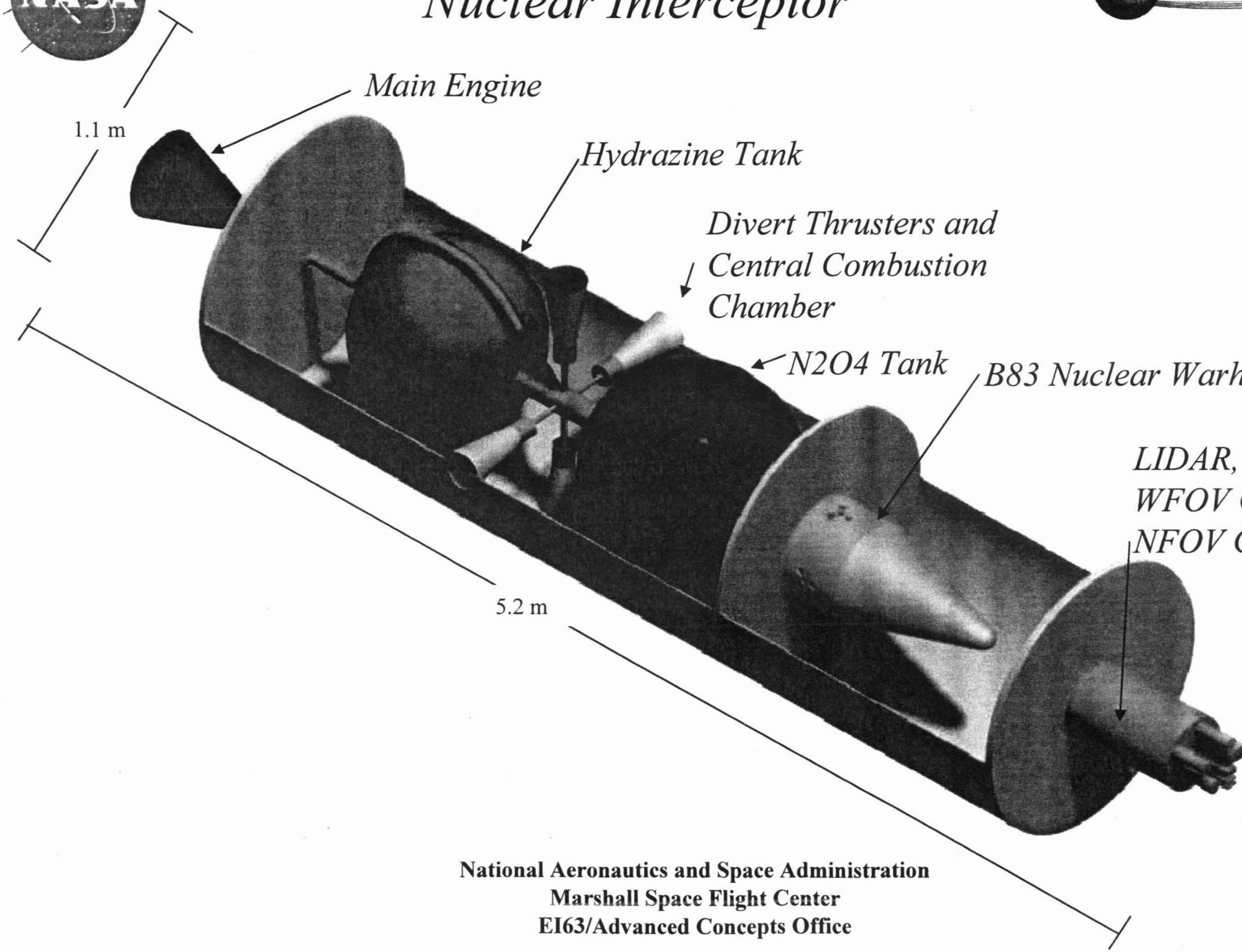
Interceptor Stack



Interceptor Stack

- Design and Performance
  - Ares V Earth Departure Stage (EDS)
    - Half full (approx.) of propellant at Low Earth Orbit. ΔV – 3940 m/s
  - Interceptor Kick-Stage
    - Lox/LH2 upper stage ignites immediately after EDS burnout and separation. ΔV – 4650 m/s
  - Cradle
    - Cradle carries six "bullets", each bullet weighing 1500 kg
    - Cradle has sufficient power to maintain bullets until release
    - Cradle radar locates NEO to within 1 km (some redundancy with observer) communicates location to bullets
  - Bullets
    - Can be nuclear interceptor, kinetic interceptor, or solar collector
    - Handles terminal intercept when within 5000 km of NEO

Nuclear Interceptor



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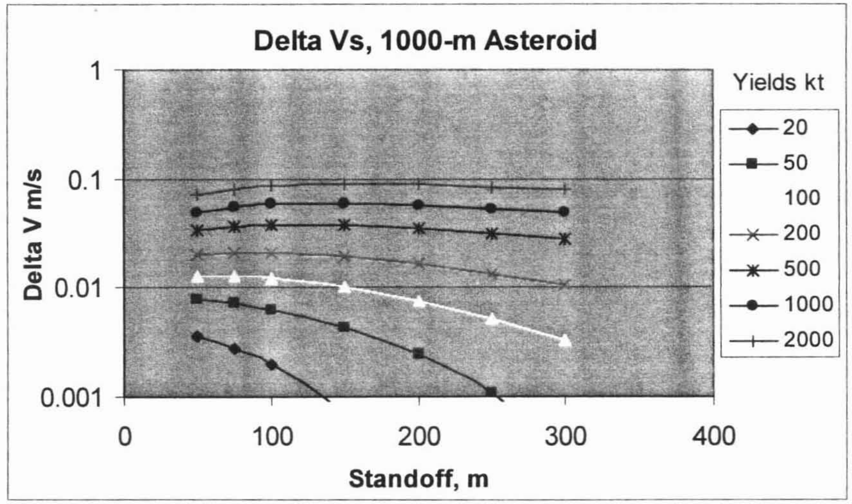
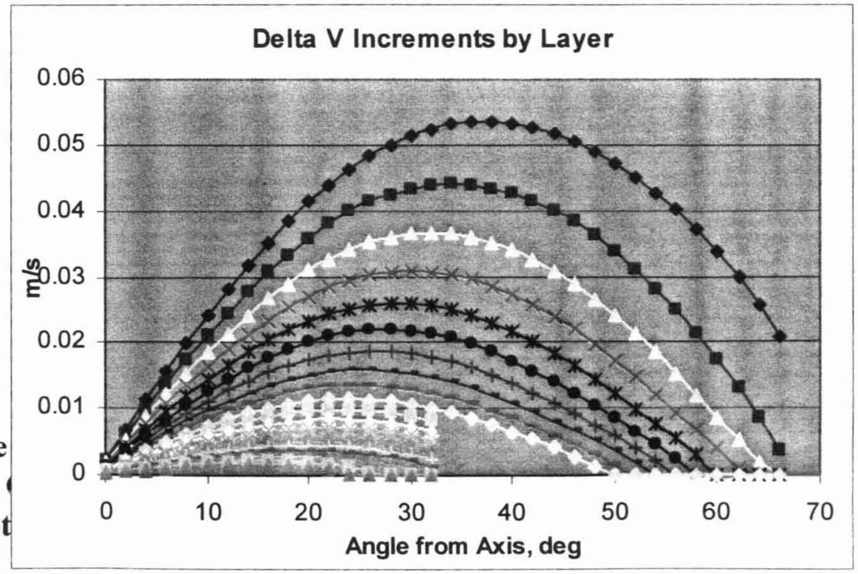
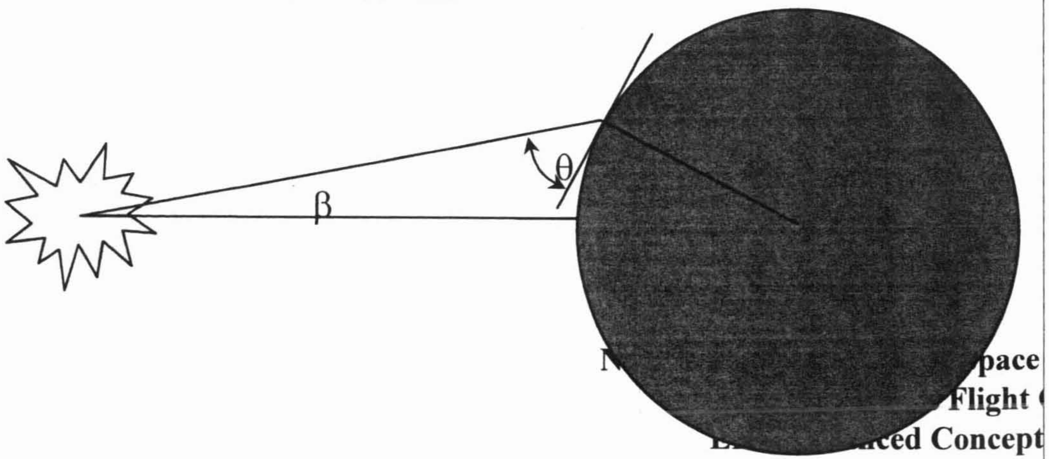
Nuclear Interceptor

- Physics of Nuclear Deflection
  - Explosion at optimum standoff distance from NEO
  - Explosion to cover maximum surface that can be ablated
  - Only X-ray interaction with NEO considered here
  - Monte Carlo model of X-ray penetration and absorption
  - Spectral ejection of vaporized material

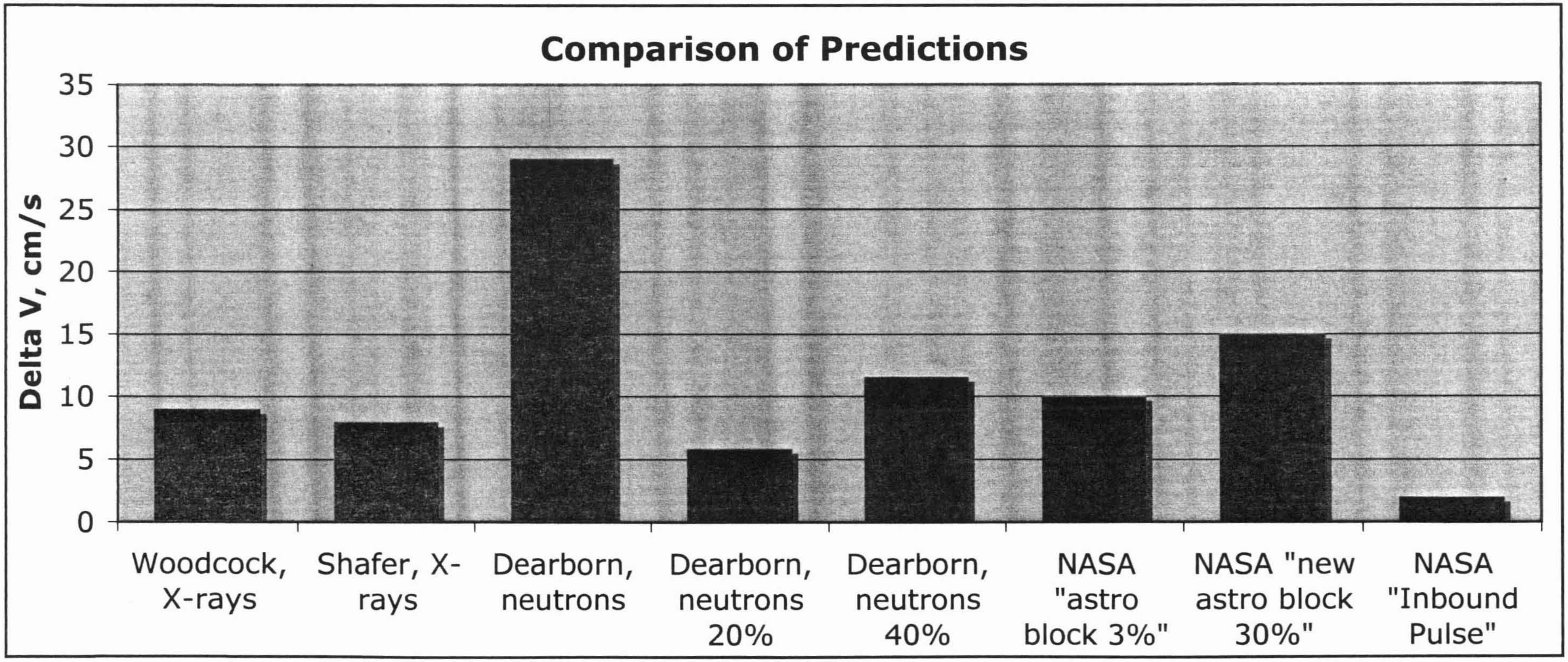






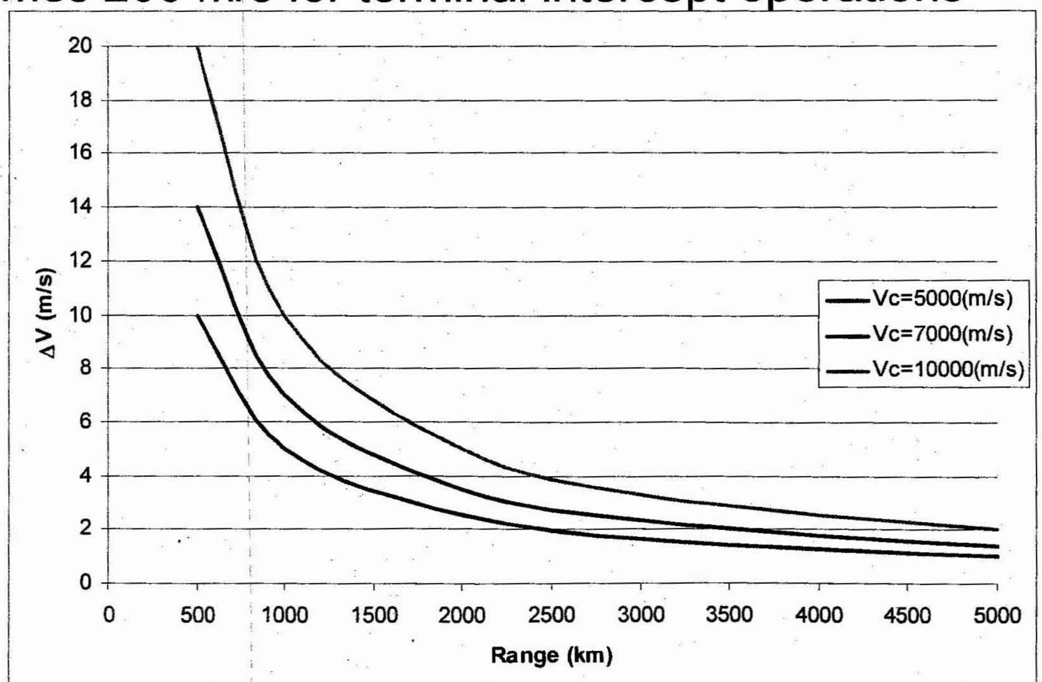
Nuclear Interceptor

- Prediction comparison against other models in literature



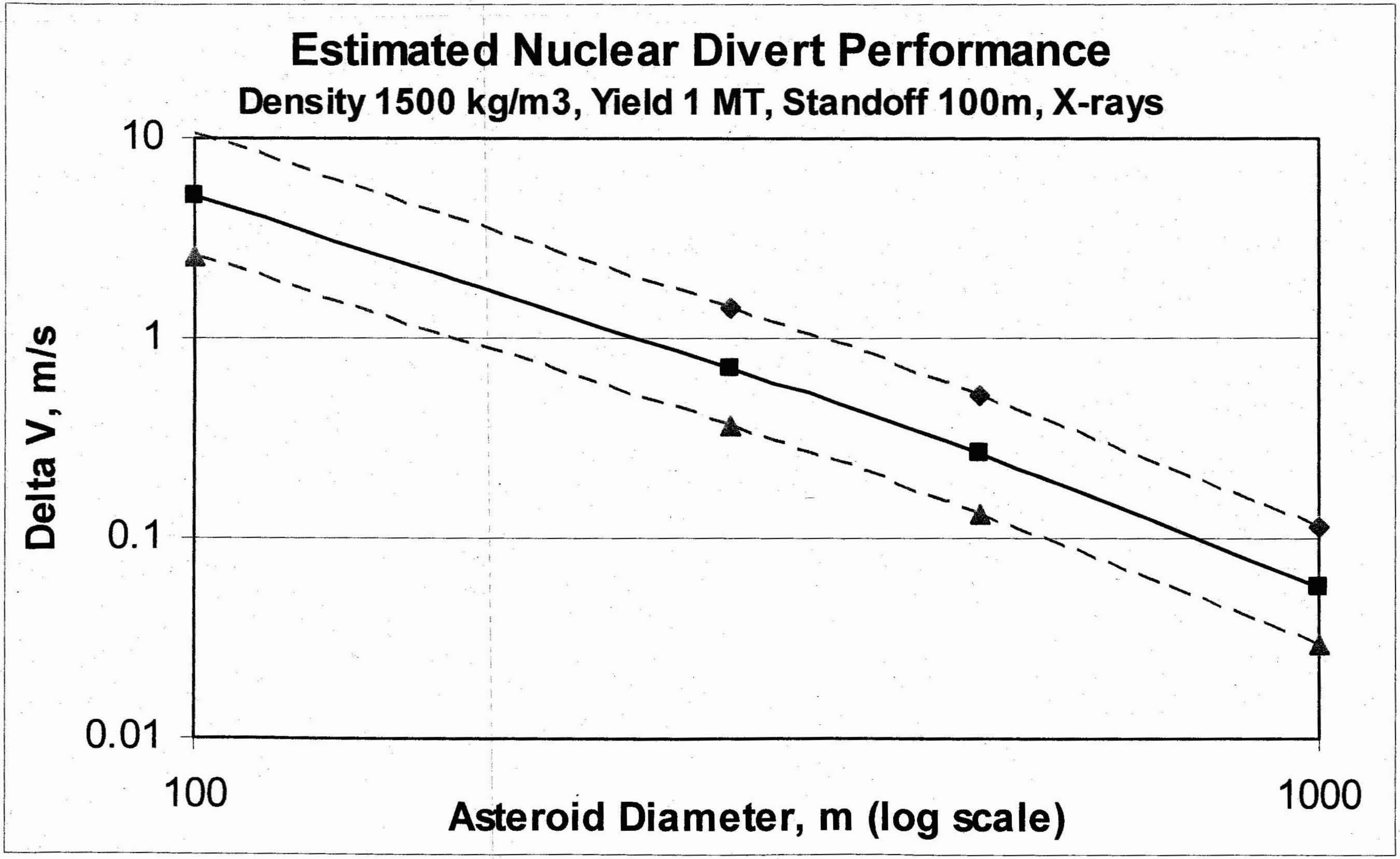
Nuclear Interceptor

- Terminal Intercept package
  - Bipropellant system, turns on inside 5000 km from target
  - Main combustion chamber on constantly, propellant diverted to appropriate thruster
  - LIDAR, WFOV, NFOV cameras guide to target
  - ΔV requirements for terminal intercept shown below. Design assumes 200 m/s for terminal intercept operations

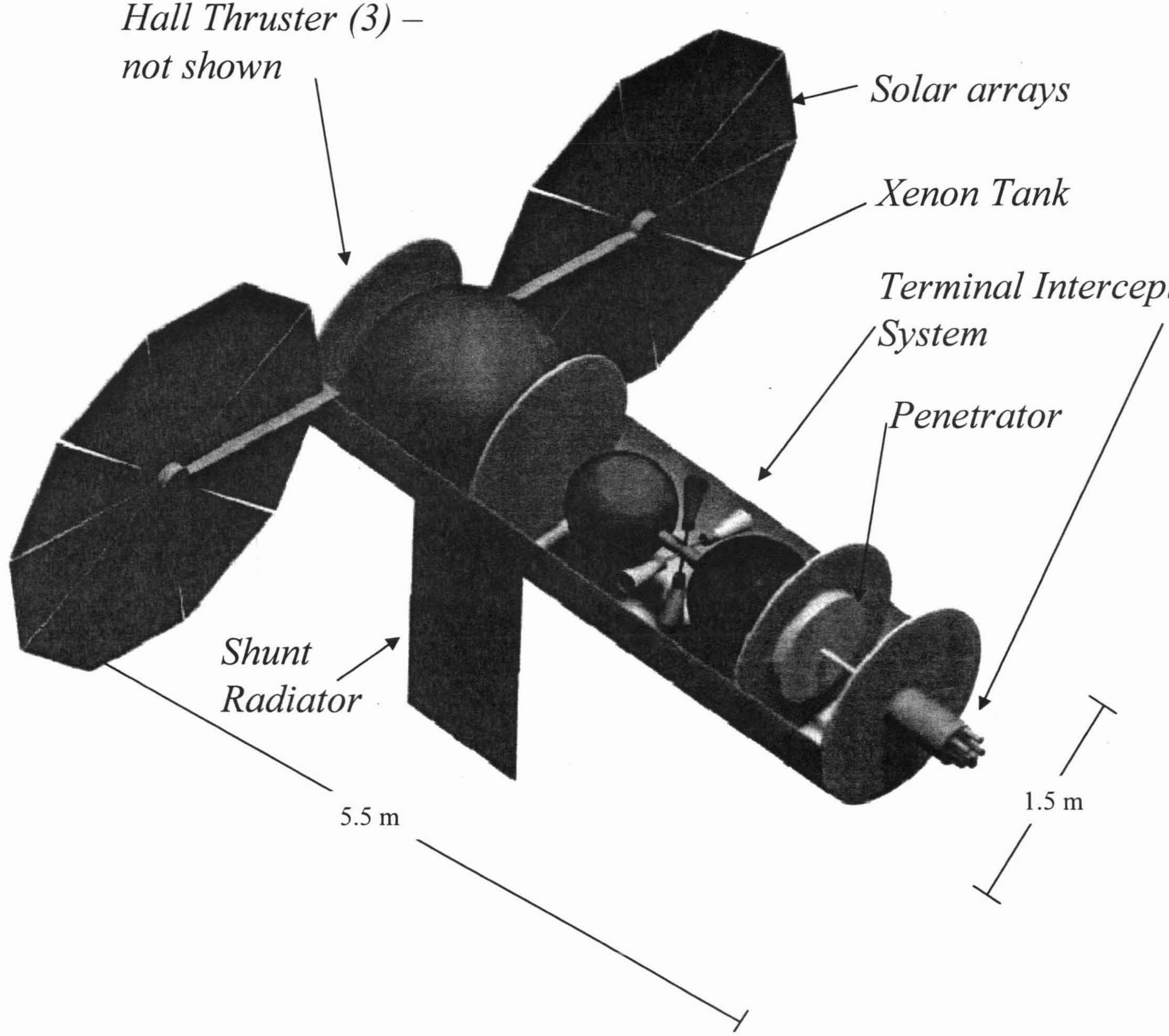


Nuclear Interceptor

- Nuclear Interceptor Effectiveness (single interceptor)

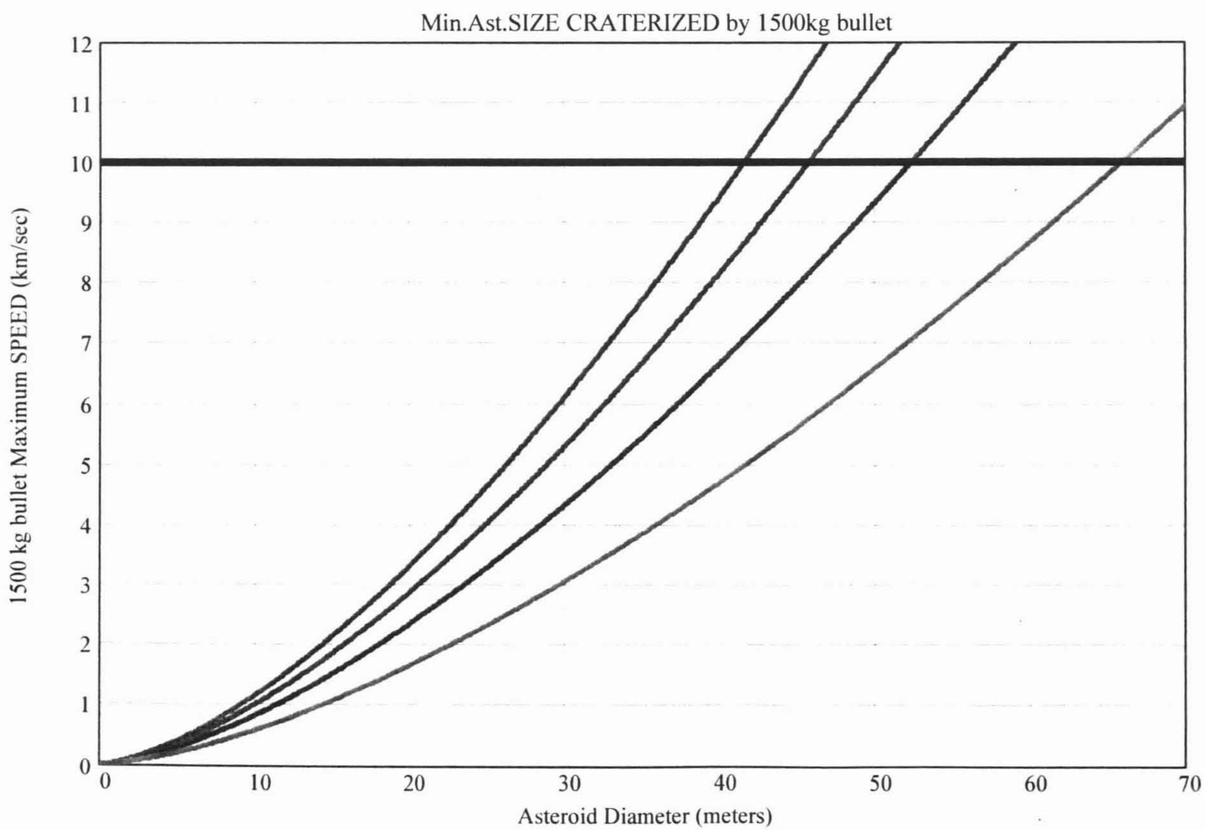


Kinetic Interceptor



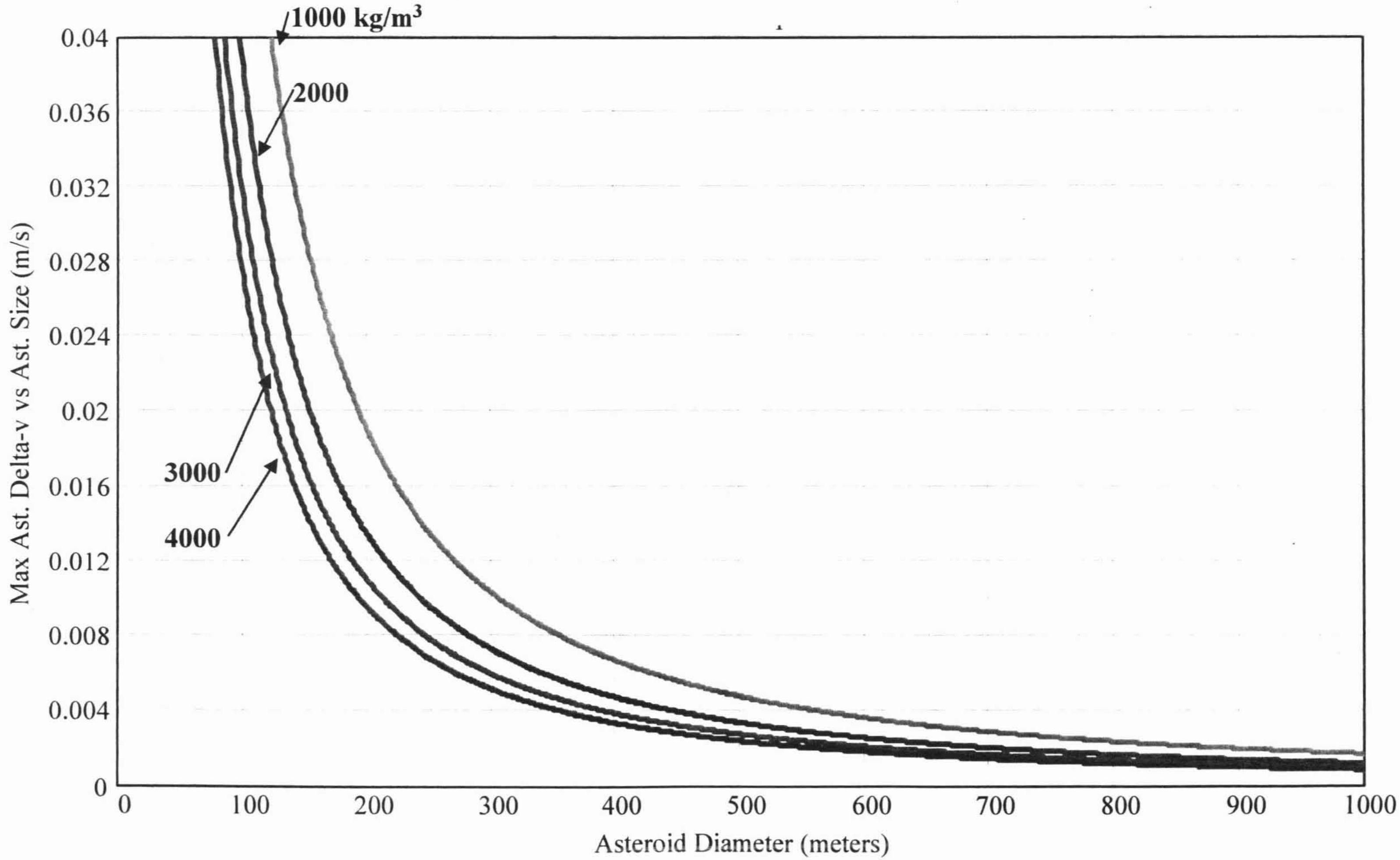
Kinetic Interceptor

- Physics of Kinetic Interception
  - Made estimate of maximum impact velocity without fracture
  - Assume inelastic collision of kinetic interceptor with NEO
  - Momentum from potential ejecta not included

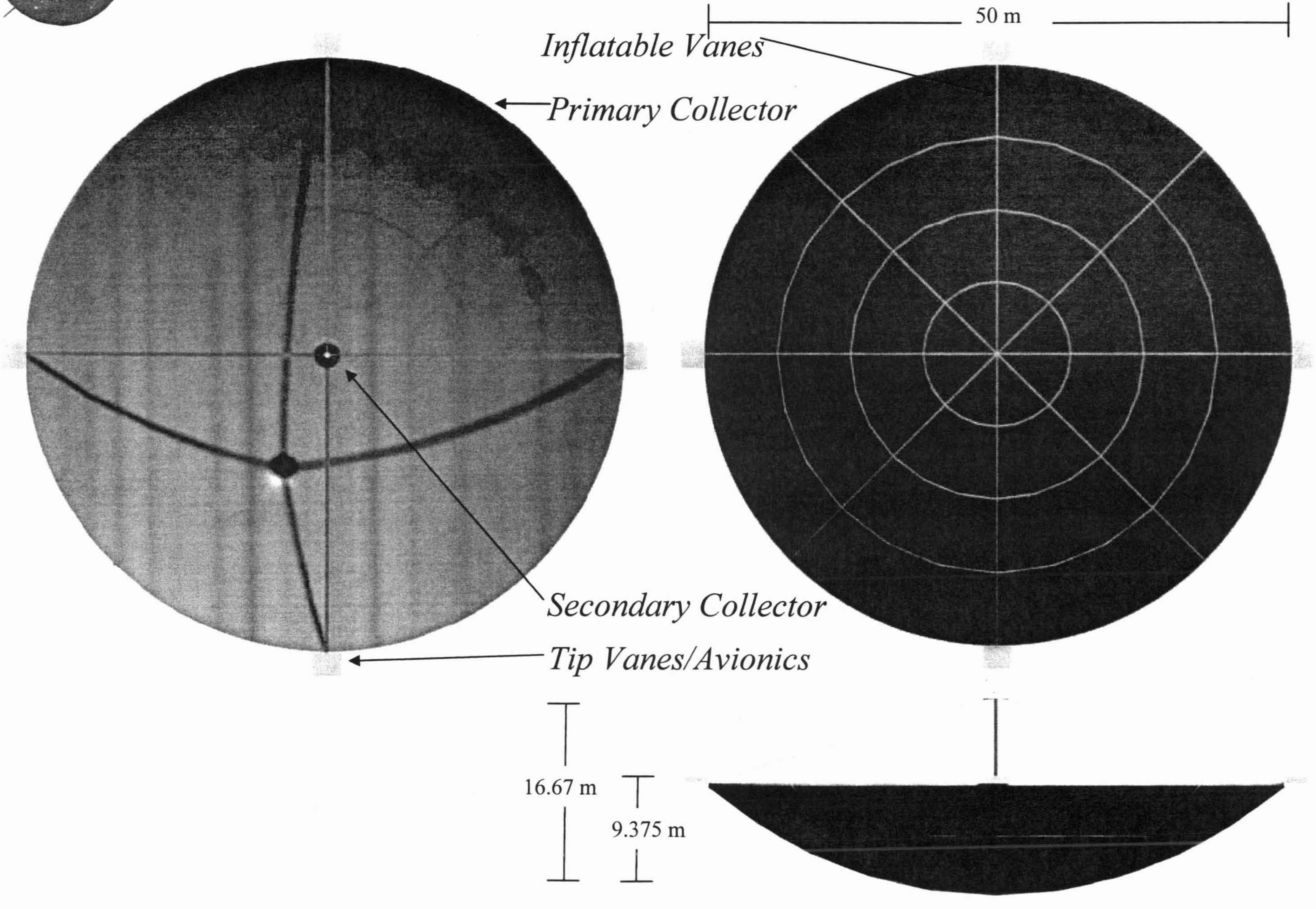


Kinetic Interceptor

- Kinetic Interceptor Effectiveness (single interceptor)



Solar Collector

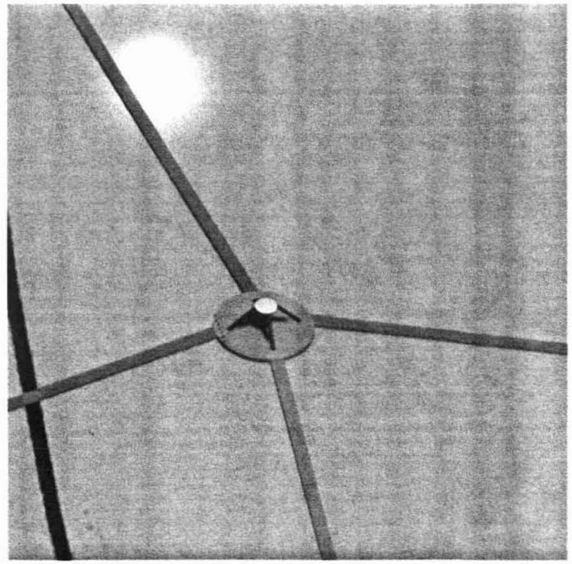


Solar Collector

- Physics of Solar Collector
  - Primary collector always faces sun
  - Estimate of performance assumes 1 AU distance from sun
  - Secondary collector located at focus
  - Beam from secondary directed on NEO
  - Beam penetration into crust vaporizing material
  - Ejecta transmits momentum to NEO
  - Secondary collector sized to
    - Handle aberration from non-uniformities in parabolic primary
    - Non-point source for sun
    - Secondary not perpendicular to focus plane from primary
  - Collector efficiency estimated at 50% incident on primary

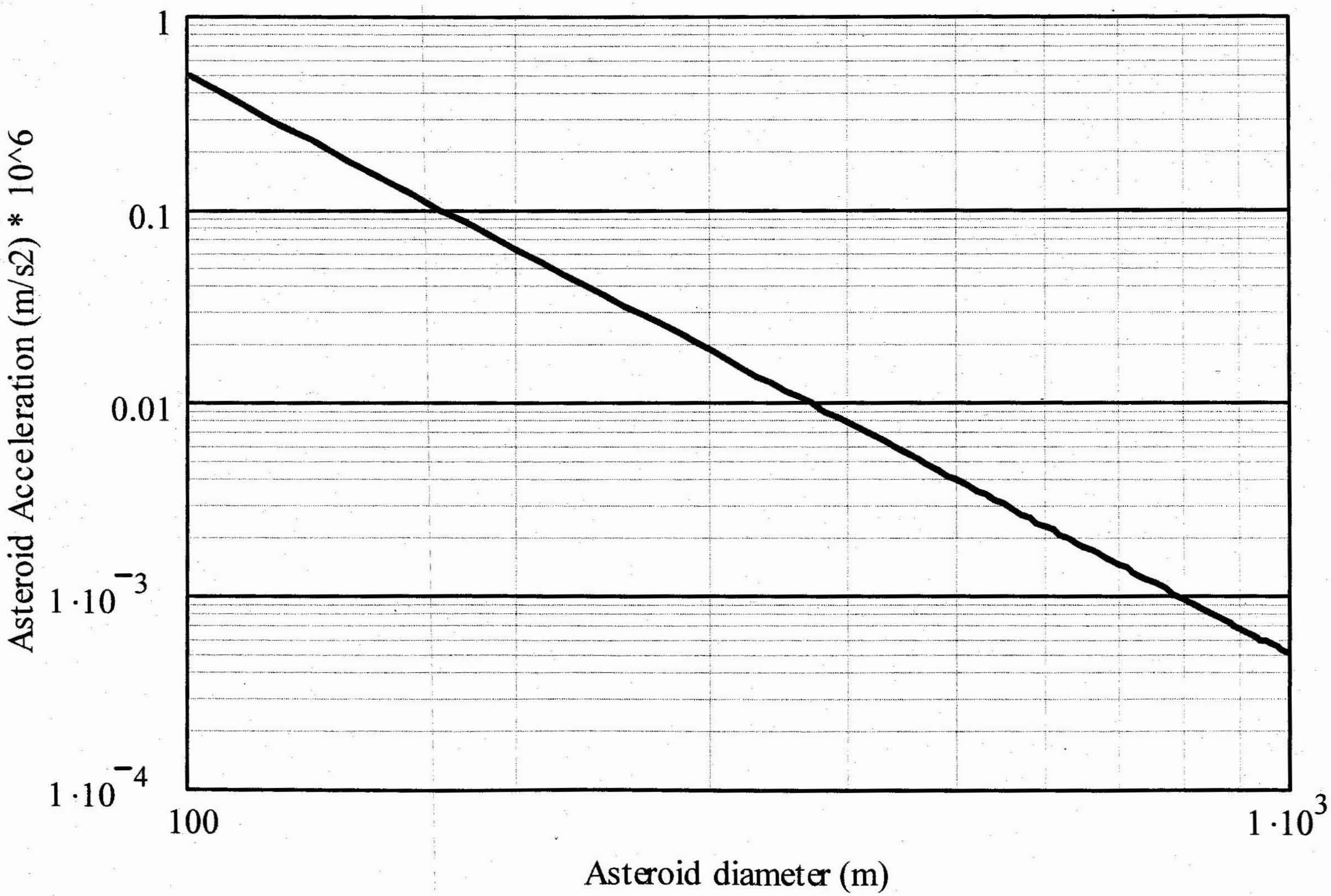
Solar Collector

- Design
  - Primary collector
    - made of solar sail materials
    - Folded “parachute-like” to fit in allowable bullet volume
    - Inflated using vanes along major seams, nitrogen gas cures thin film laminate vanes after inflation
  - Secondary collector
    - Thin film of gold layered on beryllium plating
    - Niobium heat pipes with potassium working fluid mounted on back side of beryllium plating to radiate away heat
    - 0.5 m sun shield mounted 0.5 m away from secondary
  - Tip vanes
    - Solar arrays double as tip vanes for attitude control.
    - Redundant communications and avionics systems at all four tip vanes



Solar Collector

- Solar Collector Effectiveness (single collector)



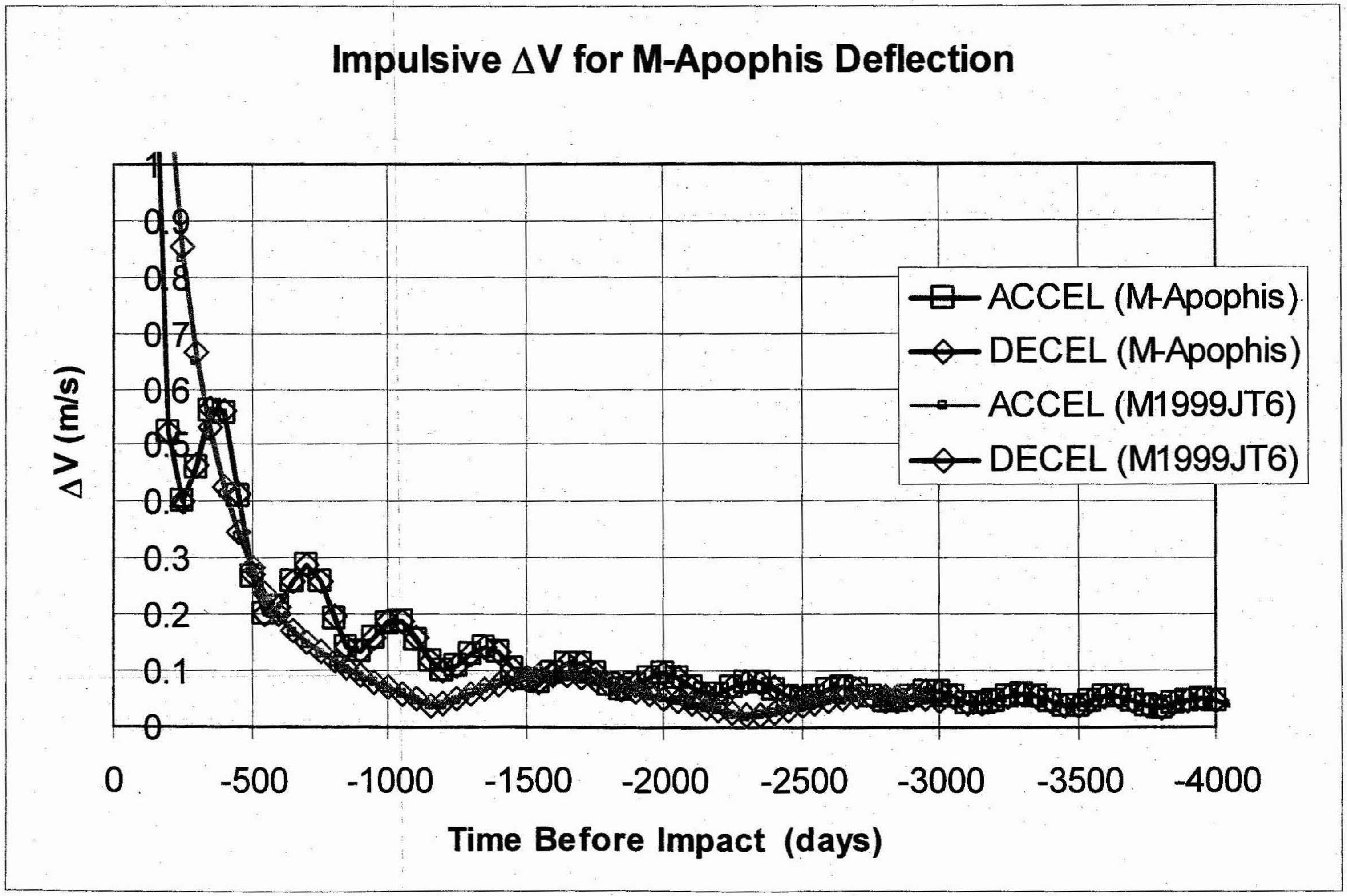
Comparative Analysis

- Baseline NEO was assumed to have an orbit similar to Apophis
- Orbit was modified to cause Apophis to impact Earth on April 22, 2029 12:10:10.73

Orbital Element	***Original***	***Modified***
Semi-major axis (m)	137986931.808626	137978976.28259
Eccentricity	0.19114698829234	0.19091399221024
Inclination (deg)	3.34145210222811	3.333348213097
Right ascension of the ascending node (deg)	203.874080430574	212.35750466471
Argument of perigee (deg)	126.695719648246	127.46966492194
Mean anomaly (deg)	137.86541454524	127.25811549492

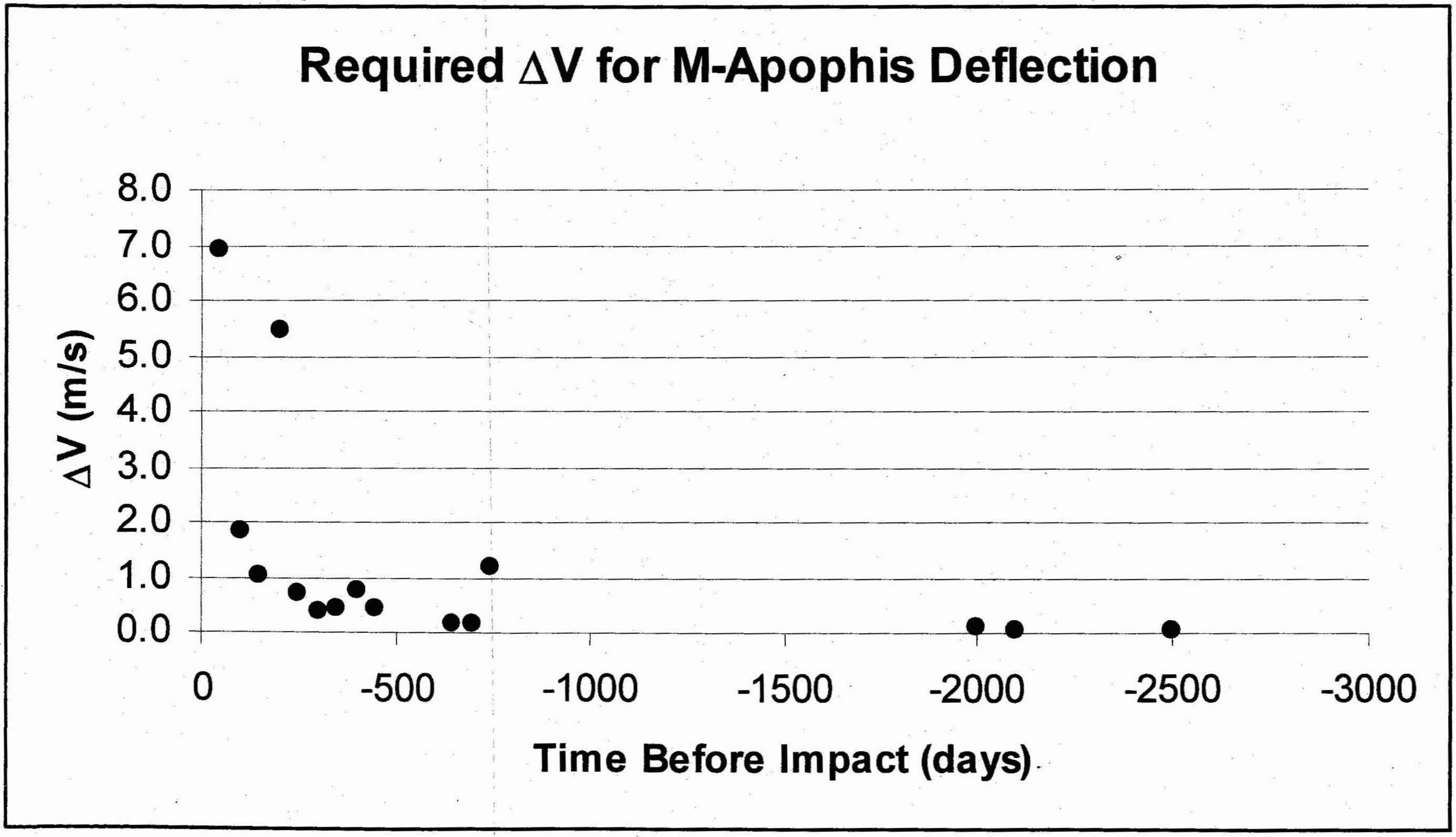
Comparative Analysis

- Required ΔV for impulsive deflection using nuclear interceptors



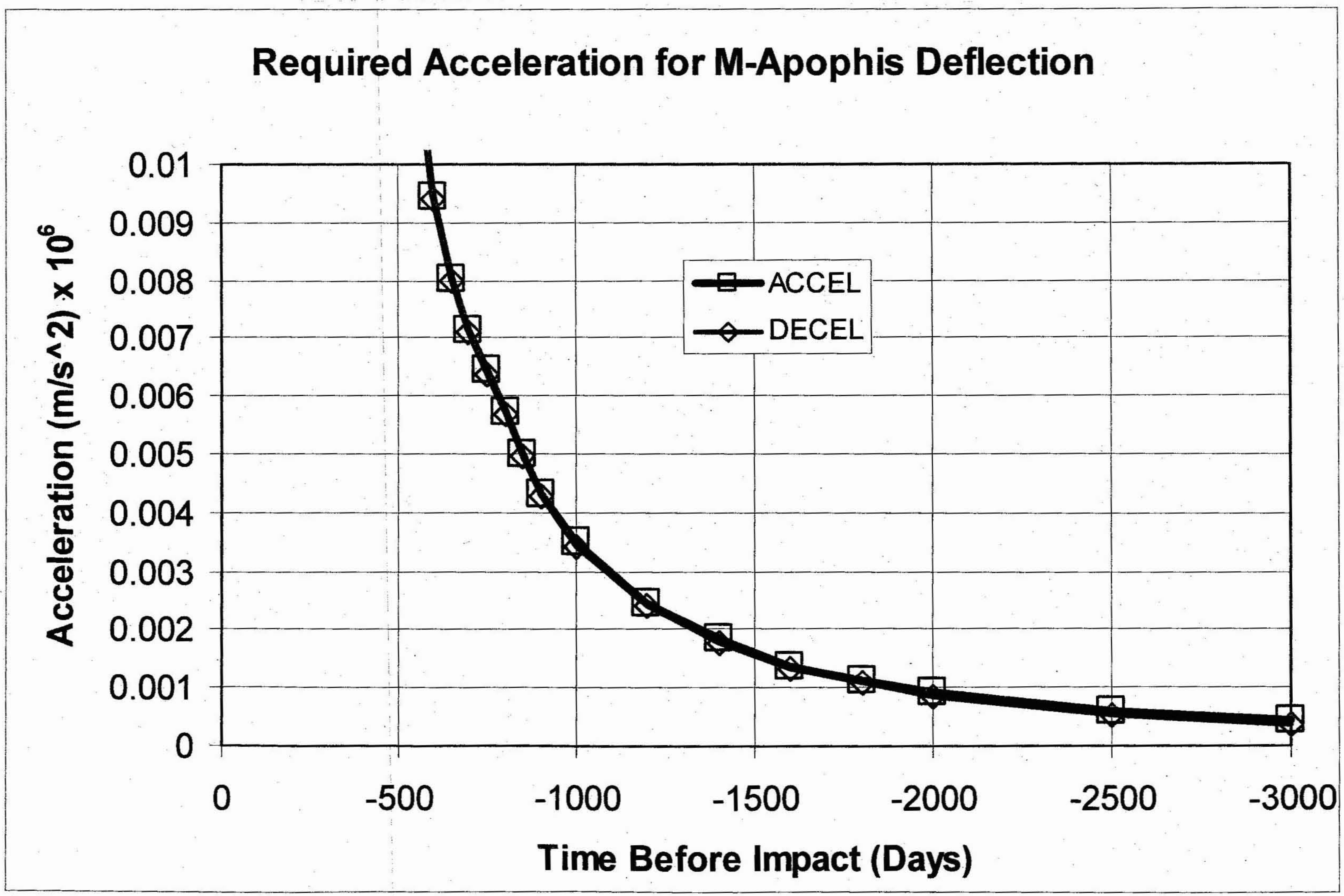
Comparative Analysis

- Required ΔV for impulsive deflection using kinetic interceptor



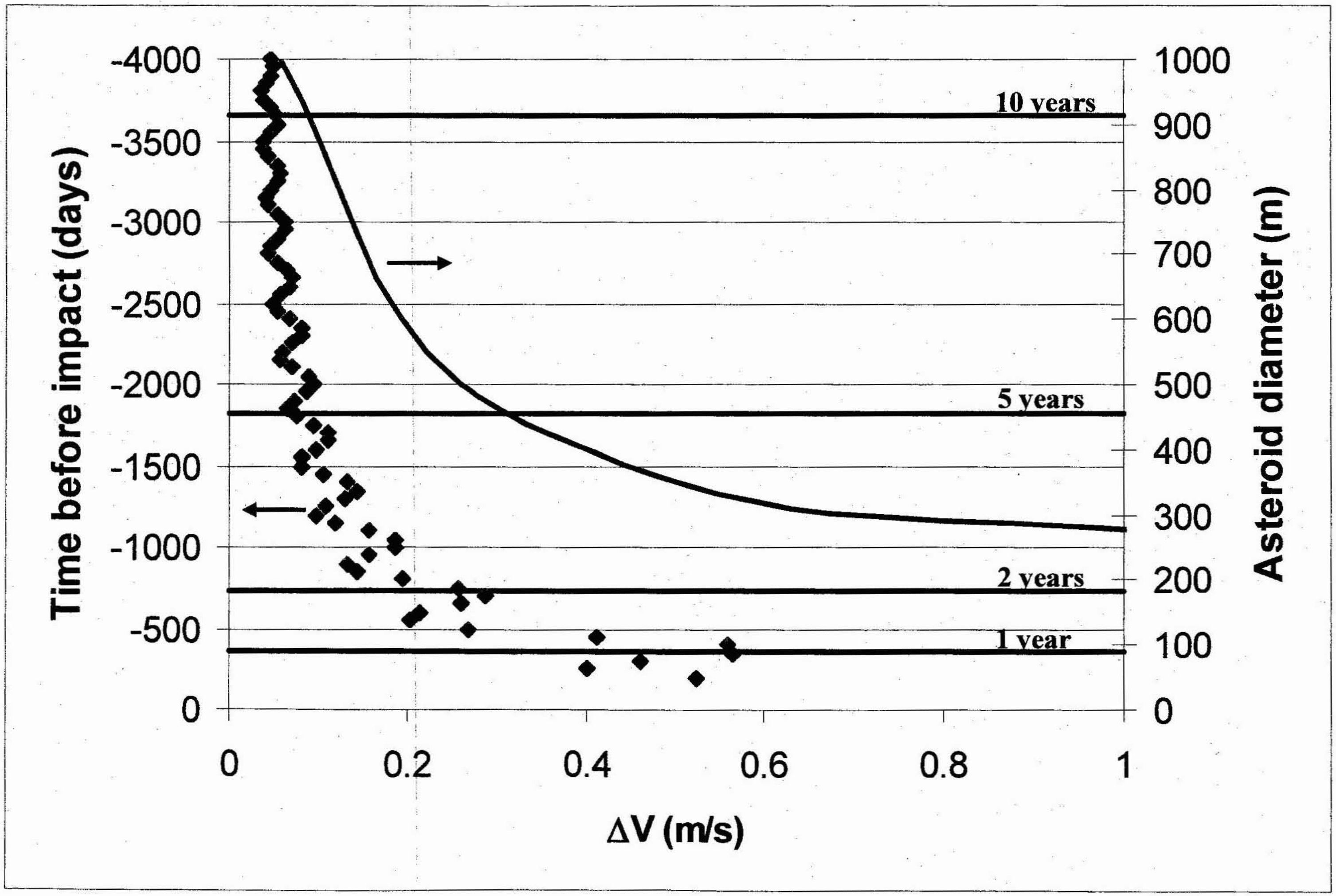
Comparative Analysis

- Required acceleration for continuous deflection



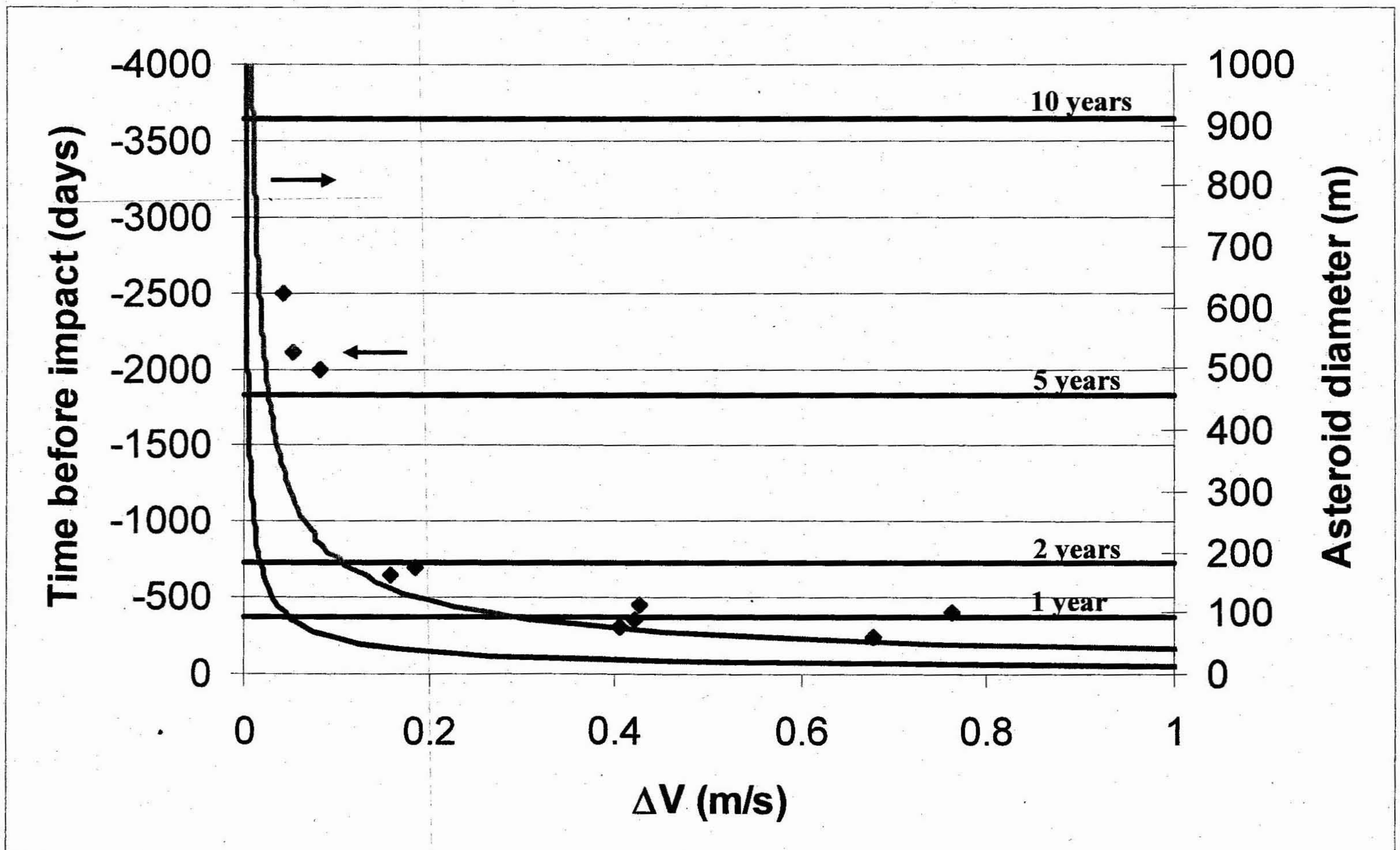
Comparative Analysis

- Combined nuclear interceptor analysis against asteroid diameter



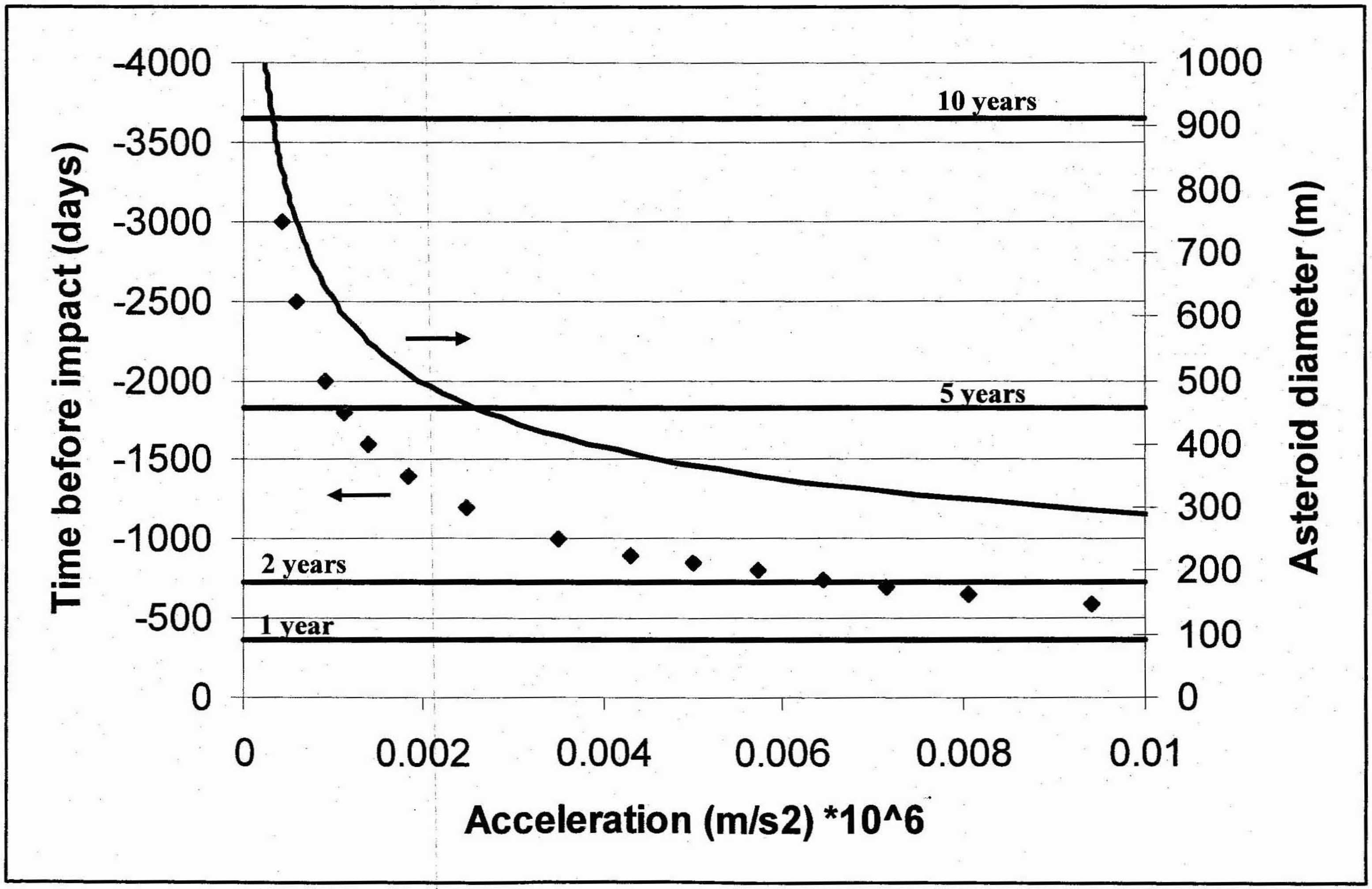
Combined Analysis

- Combined kinetic interceptor analysis against asteroid diameter



Comparative Analysis

- Combined solar collector performance against asteroid diameter



Conclusions

- Nuclear Interceptor option can deflect NEO's of smaller size (100-500 m) with 2 years or more time before impact, and larger NEO's with 5+ years warning.
- Kinetic Interceptors may be effective for deflection of asteroid up to 300-400 m but require 8-10 years warning time.
- Solar collectors show promise for deflection of NEO's up to 1 km if issues pertaining to long operation time can be overcome.
- Ares I and Ares V vehicles show sufficient performance to enable development of a near term categorization and mitigation architecture

Future Work

- Complete more detailed designs for all vehicles
  - Consider reuse of Lox/LH2 stage in both observer and interceptor stacks
  - Consider use of existing kick stages (such as Centaur) in architecture
- Investigate ability of proposed architecture to handle other threats
  - Asteroids with different orbital elements
  - Short and long period comets
- Demonstrate other uses for proposed architecture
  - Resource utilization
  - Support human/robotic missions to NEO's, Mars, etc.

Future Work

- Mitigation technologies
  - Nuclear Interceptor
    - Include neutron flux in asteroid deflection models
    - Extend range of analysis to cover all expected asteroid composition
    - Refine terminal guidance technologies
    - More investigation on optimal stand off distance
    - Some question to effectiveness on rubble piles
  - Kinetic Interceptor
    - Refine trajectory analysis to include low thrust segment to optimize impact velocity and angle
    - Refine penetrator design and modeling of interaction with asteroid. (Our model assumes inelastic coupling, β=1.)
  - Solar Collector
    - Investigate issues surrounding heating of secondary collector
    - Refine estimates of beam divergence, focusing issues
    - Refinement of rendezvous trajectories
    - Consider shorter operation times instead of continuous acceleration from time before impact to reaching Earth

Acknowledgements

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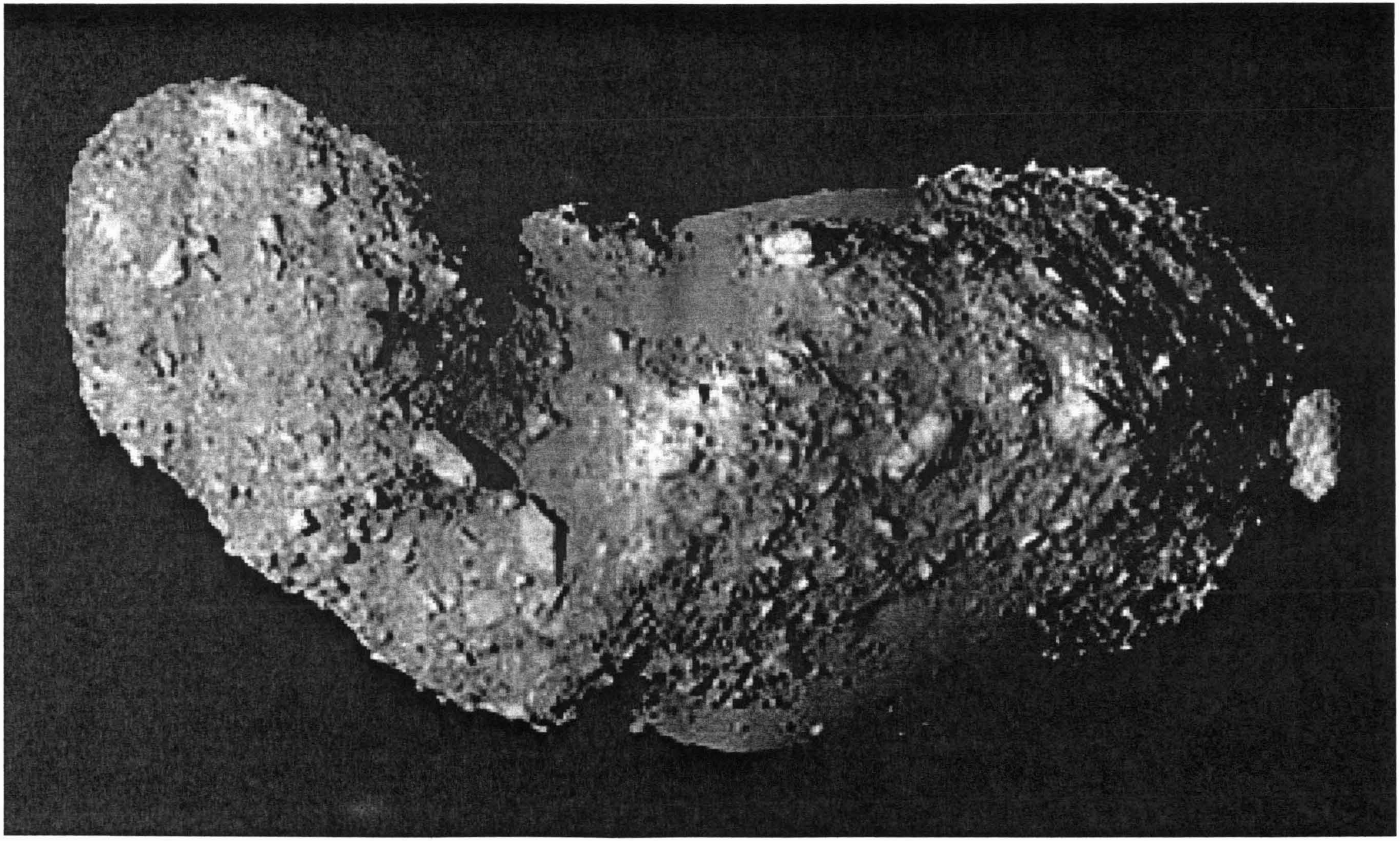
    - Slade White

Backup Charts

Possible Future Activities

- Research
  - The issue of "retiring risk" or is it moving risk from probabilistic to deterministic
  - Biases in current detection systems and consequences for mitigation strategy
  - Targeting resolution for terminal intercept options
  - Number of NEO's that have keyhole events, can be deflected using the gravity tractor concept
  - Dynamics of KE impact on rubble pile, distribution model, time to coalesce, amount of energy delivered to move center of mass.
  - Long term dynamics of gravity tractor concept, stretch out the rubble pile?
  - Bench KI simulations to Deep Impact
- Concepts
  - Investigate a combination solar collector/gravity tractor concept
  - Characterization mission using multiple solar sails
  - Estimate of error measurement of position, velocity vector using observer satellite
- Outreach
  - Chair AIAA Joint Propulsion Conference session on PD
  - Present at Natural Hazards Conference
- Synergy with Science/Exploration
  - In Situ Resource Utilization using PD technologies
  - Common architecture for Exploration, PD, Resource Utilization

Itokawa



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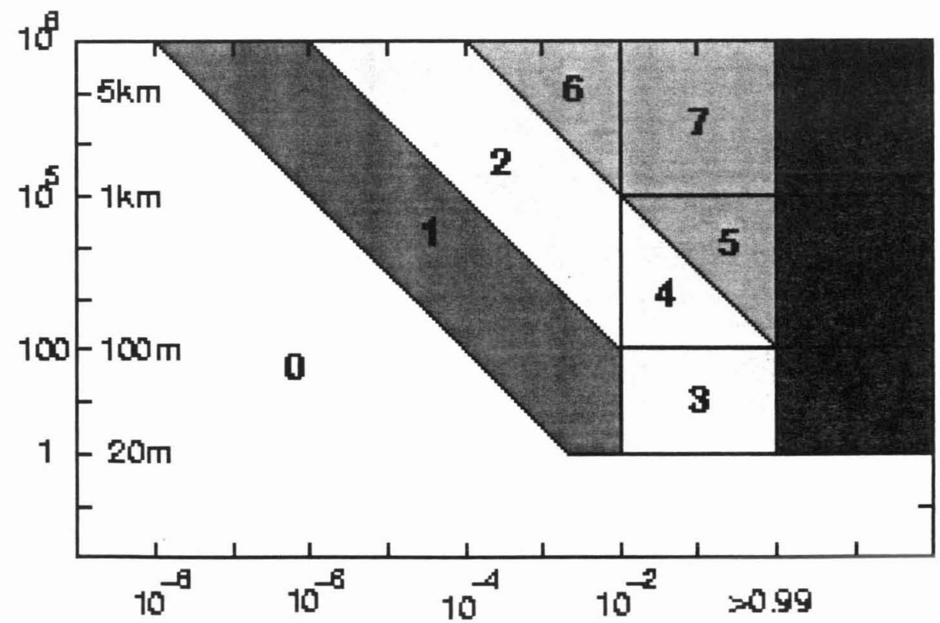
THE TORINO SCALE

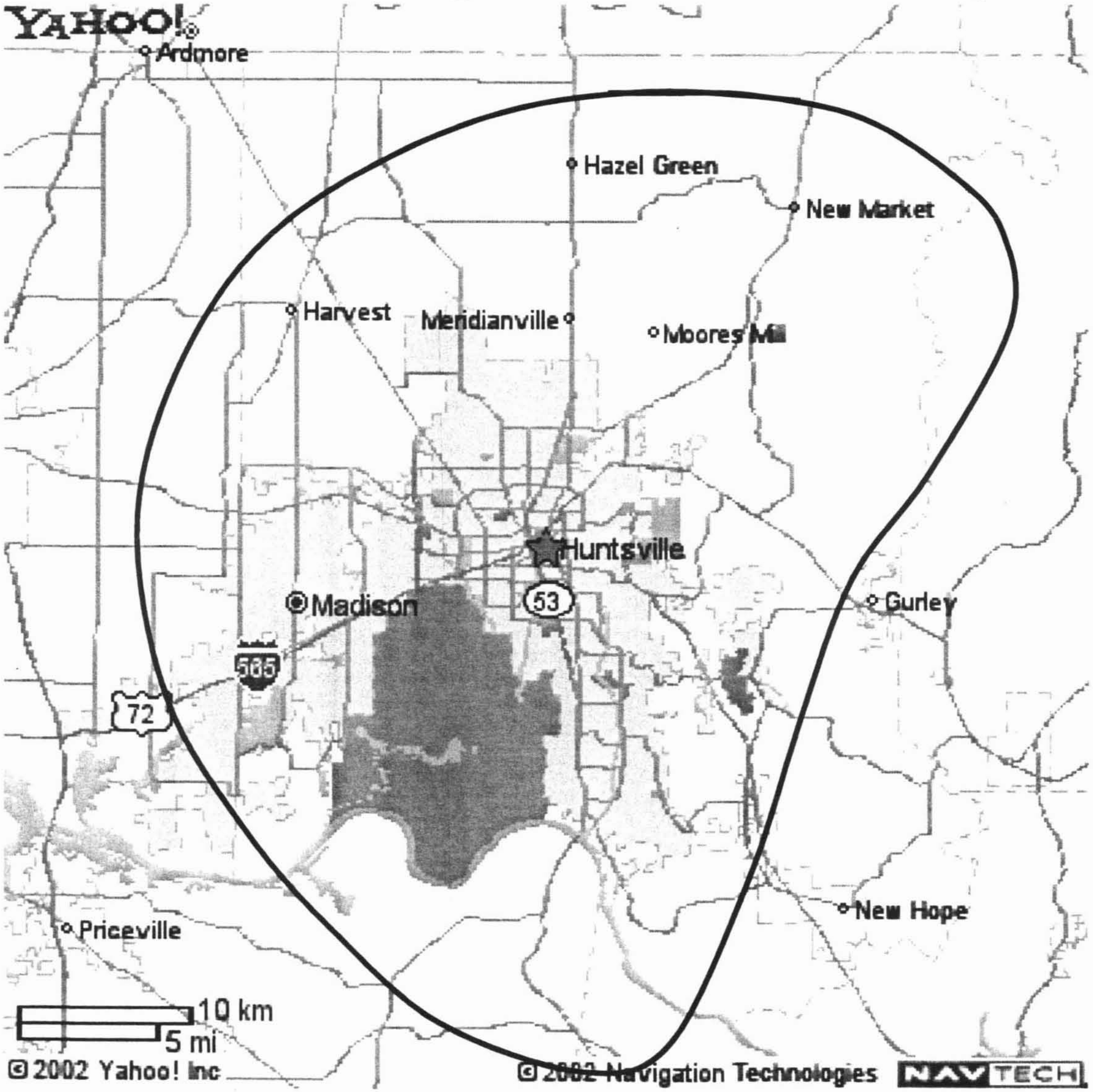
Assessing Asteroid/Comet Impact Predictions

No Hazard	0	The likelihood of collision is zero, or is so low as to be effectively zero. Also applies to small objects such as meteors and bolides that burn up in the atmosphere as well as infrequent meteorite falls that rarely cause damage.
Normal	1	A routine discovery in which a pass near the Earth is predicted that poses no unusual level of danger. Current calculations show the chance of collision is extremely unlikely with no cause for public attention or public concern. New telescopic observations very likely will lead to re-assignment to Level 0.
Meriting Attention by Astronomers	2	A discovery, which may become routine with expanded searches, of an object making a somewhat close but not highly unusual pass near the Earth. While meriting attention by astronomers, there is no cause for public attention or public concern as an actual collision is very unlikely. New telescopic observations very likely will lead to re-assignment to Level 0.
	3	A close encounter, meriting attention by astronomers. Current calculations give a 1% or greater chance of collision capable of localized destruction. Most likely, new telescopic observations will lead to re-assignment to Level 0. Attention by the public and by public officials is merited if the encounter is less than a decade away.
	4	A close encounter, meriting attention by astronomers. Current calculations give a 1% or greater chance of collision capable of regional devastation. Most likely, new telescopic observations will lead to re-assignment to Level 0. Attention by the public and by public officials is merited if the encounter is less than a decade away.
Threatening	5	A close encounter posing a serious, but still uncertain threat of regional devastation. Critical attention by astronomers is needed to determine conclusively whether or not a collision will occur. If the encounter is less than a decade away, governmental contingency planning may be warranted.
	6	A close encounter by a large object posing a serious, but still uncertain threat of a global catastrophe. Critical attention by astronomers is needed to determine conclusively whether or not a collision will occur. If the encounter is less than three decades away, governmental contingency planning may be warranted.
	7	A very close encounter by a large object, which if occurring this century, poses an unprecedented but still uncertain threat of a global catastrophe. For such a threat in this century, international contingency planning is warranted, especially to determine urgently and conclusively whether or not a collision will occur.
[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]
	[illegible]	[illegible]

Fig. 2. Public description for the Torino Scale, revised from Binzel (2000) to better describe the attention or response that is merited for each category.



Background and History



Map of Madison County, Alabama with the damage template from the 1908 Tunguska event superimposed

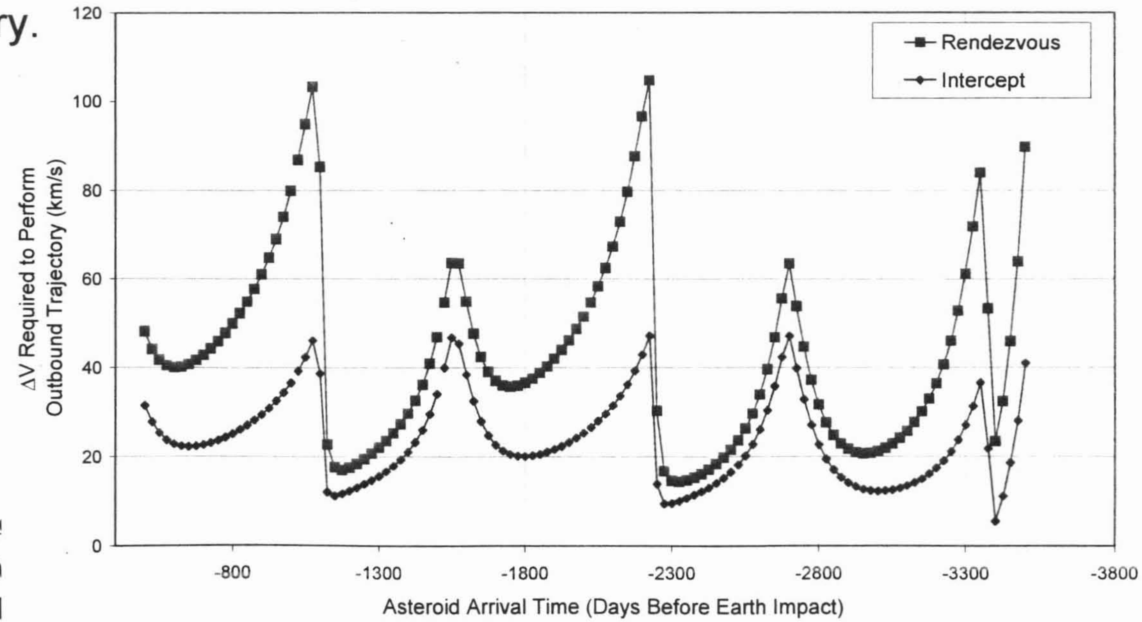
Total population within damage area ~ 350,000

Pertinent Websites

- NASA Near-Earth Object Program
  http://neo.jpl.nasa.gov/
- Asteroid/Comet Impact Hazards
  http://impact.arc.nasa.gov/
- NEO Information Centre
  http://www.nearearthobjects.co.uk/
- NASA HQ Library on NEO's
  http://www.hq.nasa.gov/office/hqlibrary/pathfinders/aster.htm
- Spaceguard Foundation Home Page
  http://spaceguard.iasf-roma.inaf.it/
- B612 Foundation Home Page
  http://www.b612foundation.org/

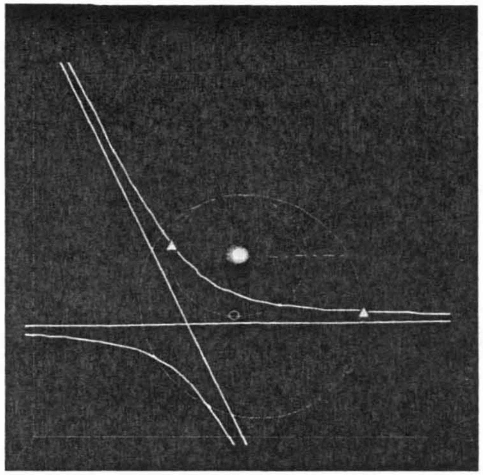
Trajectory Analysis

- Outbound Trajectory
  - Given an asteroid's orbital elements, a departure date, and the desired outbound time of flight, ΔV's for both rendezvous and ballistic interception trajectories are generated.
  - The departure date defines Earth's position at departure and therefore the vehicle's initial position.
  - Similarly, the asteroid's initial position is calculated and using the time of flight, it's final position can be calculated. The asteroid's final position is the same as the vehicle's final position.
  - Using Gauss' method, the 2 positions of the vehicle and a time of flight between them defines the vehicle's trajectory.

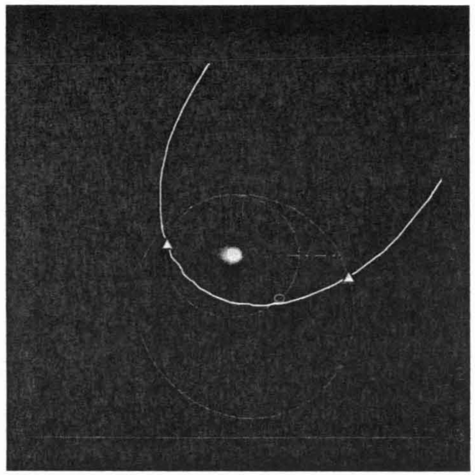


Outbound Trajectory

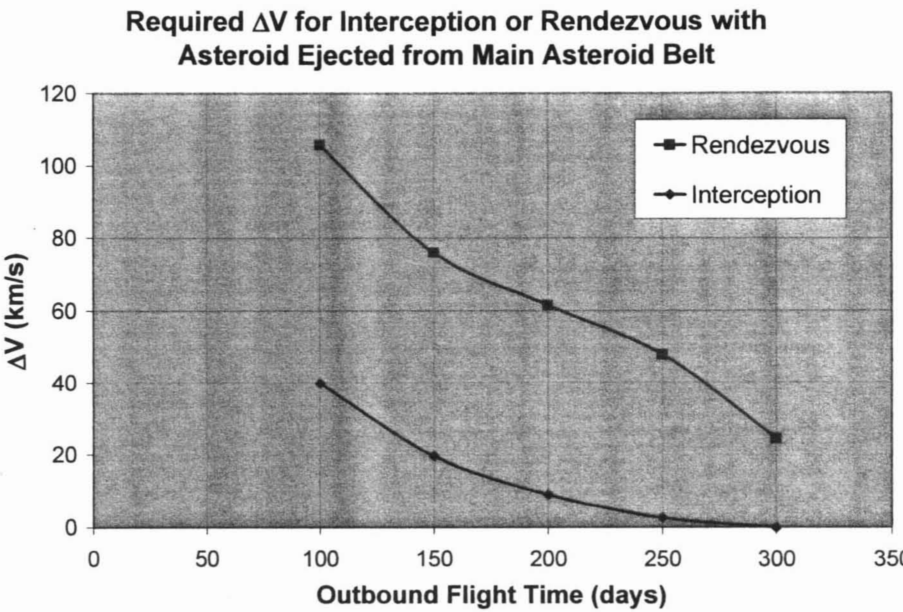
Sample Results – Changing Flight Time

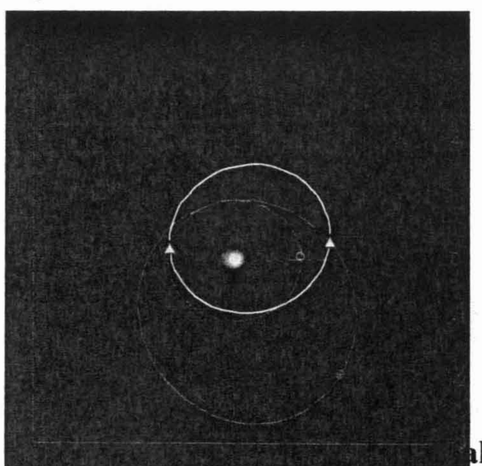


100 days

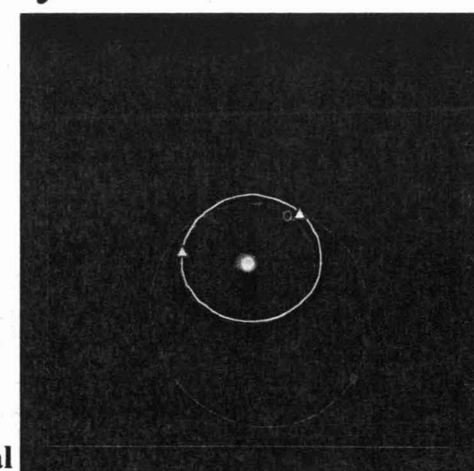


150 days

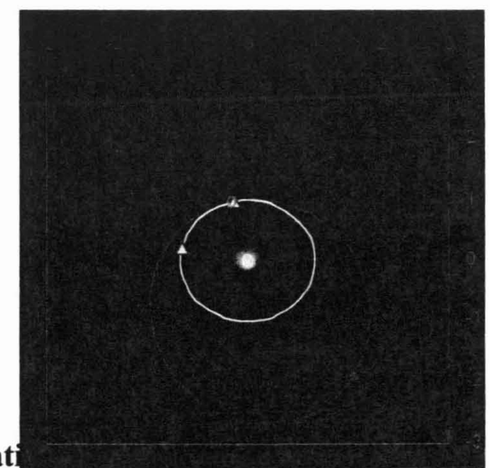




200 days



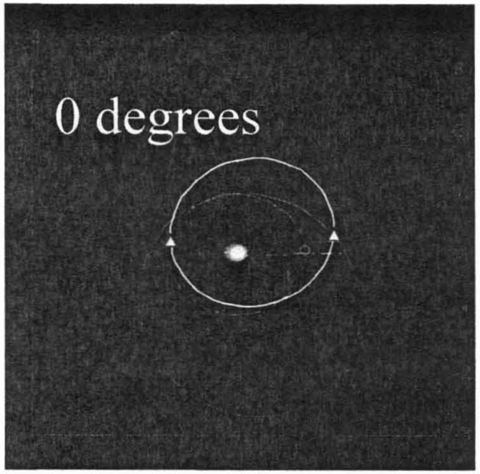
250 days

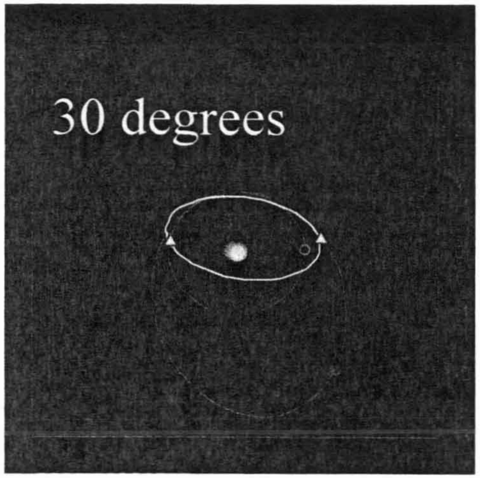


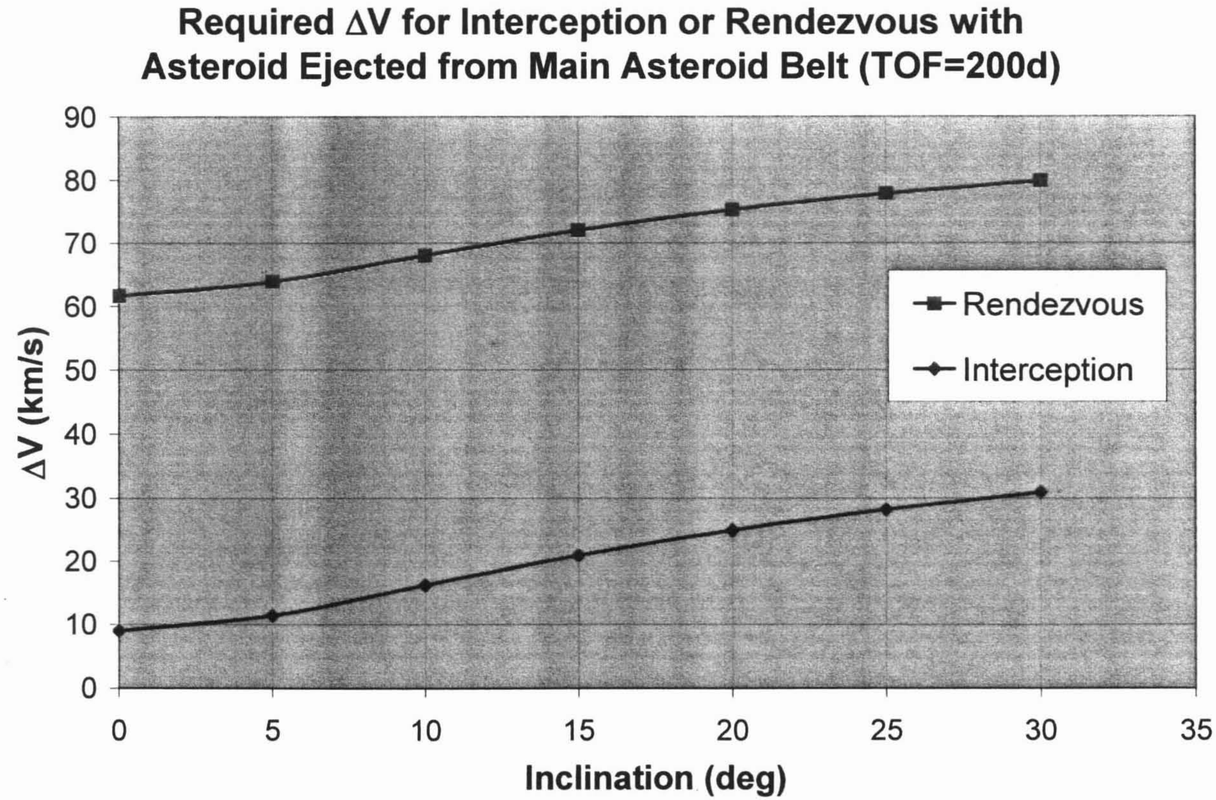
300 days

Outbound Trajectory

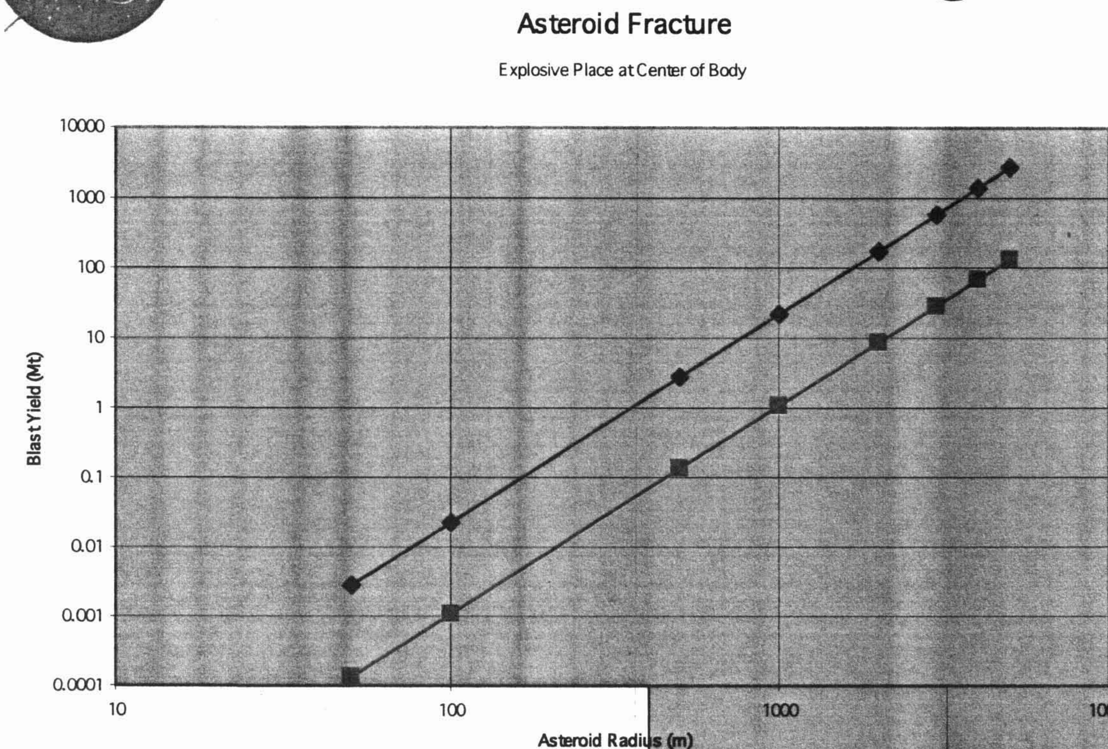
- Sample Results – Changing Inclination
  - In this example, the asteroid's inclination was varied. An outbound time of flight of 200 days was held constant



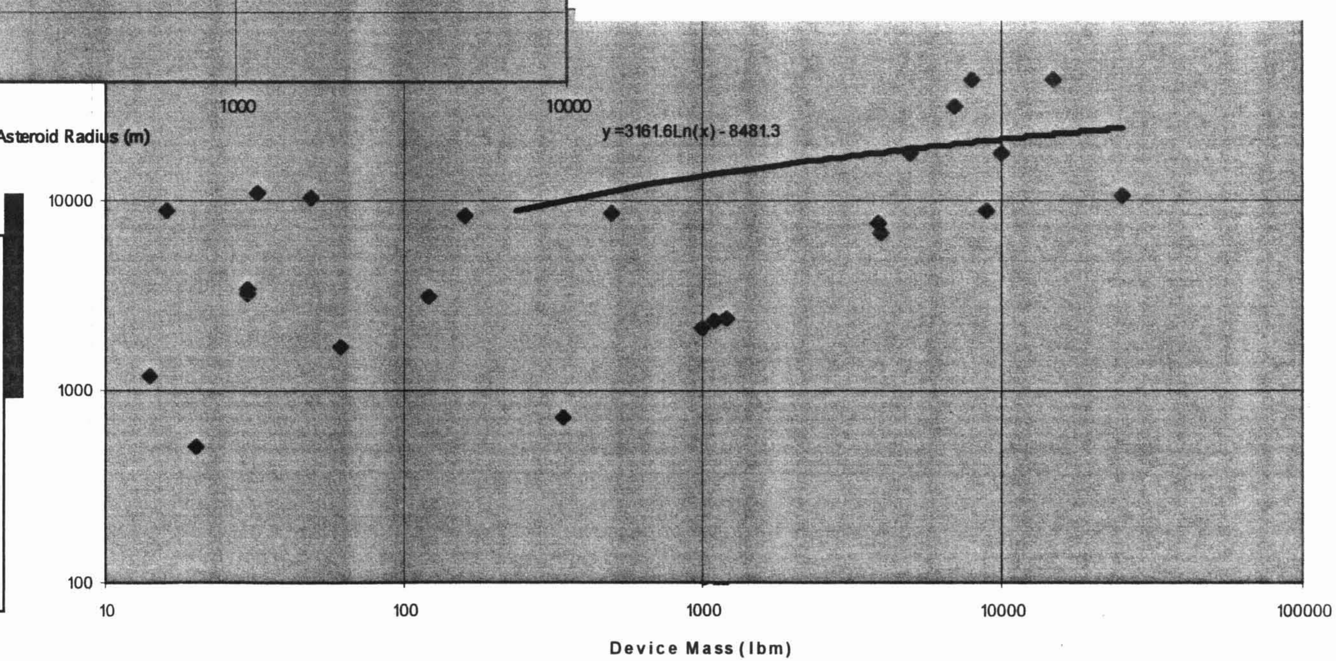




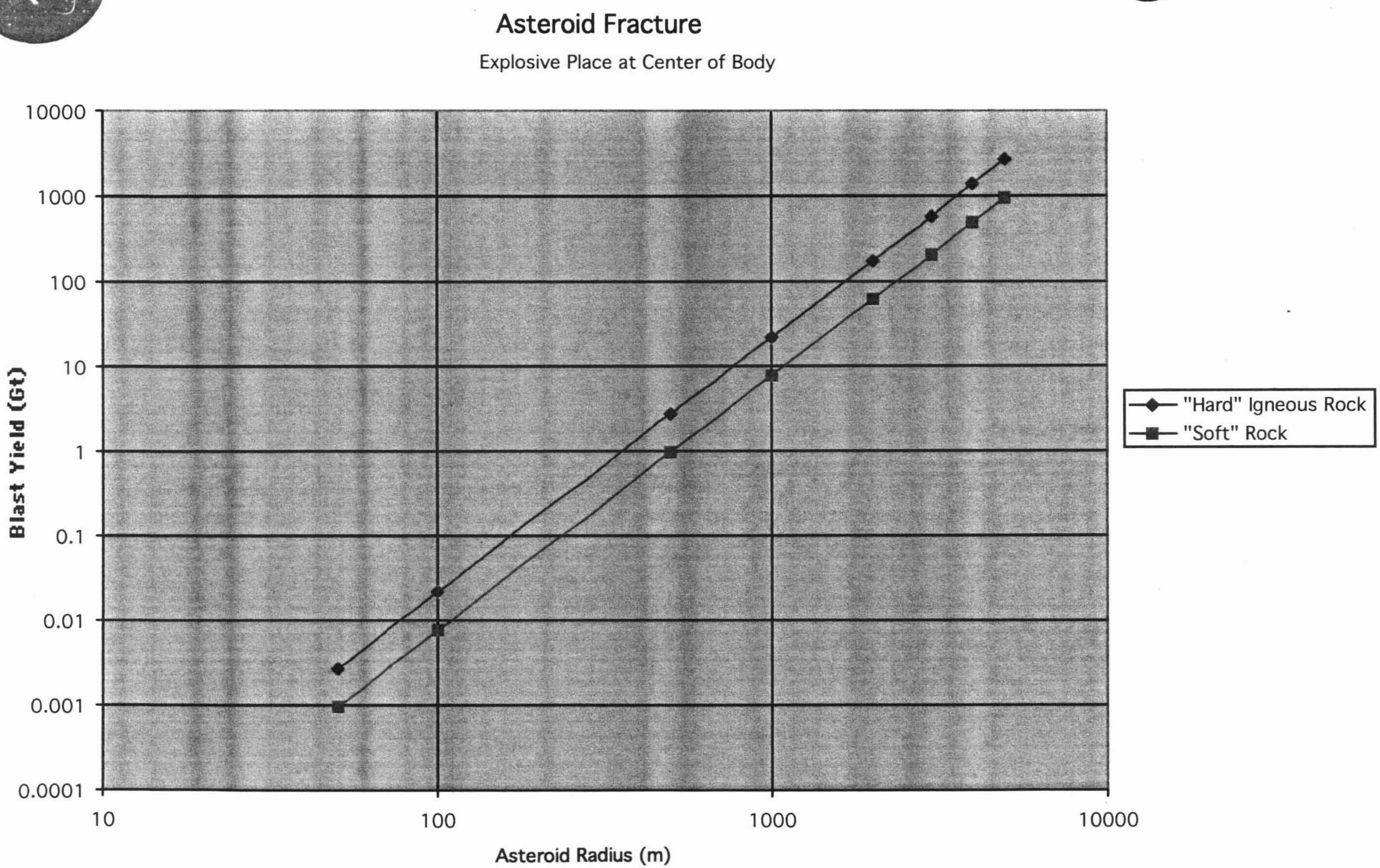
Threat Mitigation



- Nuclear Fragmentation
  - Simple, robust concept using largely established technology
  - May require landing on target
  - Detailed knowledge of target composition is desirable – otherwise uncertainty over fragmentation dynamics



•Ahrens, Thomas J., and Harris, Alan W., "Deflection and Fragmentation of Near-Earth Asteroids ", *Hazards Due to Comets and Asteroids*, p897-924, The University of Arizona Press, Tucson, 1994
•http://www.danshistory.com/nuke.shtml)
•http://danshistory.com/lgb.shtml
•Nelson, Robert A., "Low-Yield Earth Penetrating Nuclear Weapons," *FSA Public Interest Report*, January/February 2001, p 4.



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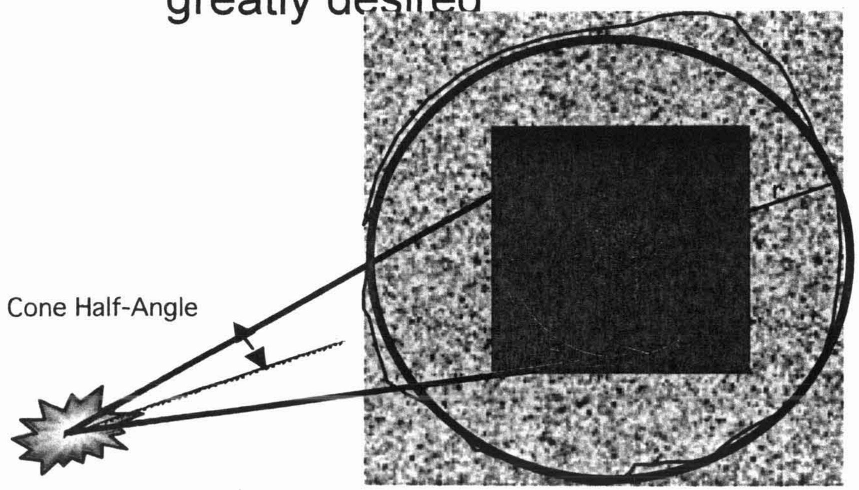
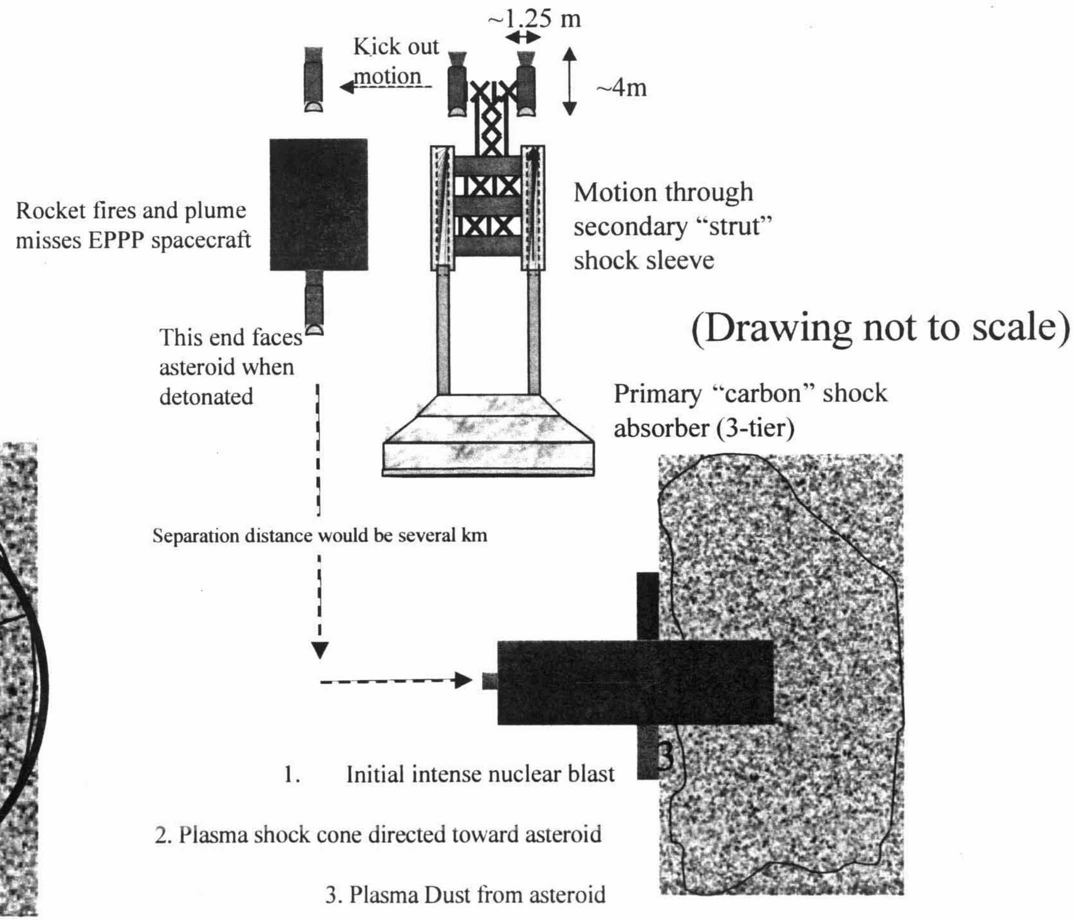
"Catastrophic disruption" is generally defined as fragmentation where the largest fragment is less than or approximately one-half the total mass. The energy density to accomplish this decreases with increasing size of the body, and becomes uncertain when extrapolated to 1 to 10 km size bodies. However, for the present purpose, we are interested in the energy density necessary to break up a NEO so that all fragments are less than or approximately 10 m in size. This is obviously a higher energy density than required to "just break it in two," and we suggest that it should be of the order of the energy density needed to "break in two" a 10 m object $E_{fracture} \sim 10^7$ erg/g. - Ahren, Thomas J. and Harris, Alan W., "Deflection and Fragmentation of Near-Earth Asteroids" pg 919-920.

Threat Mitigation

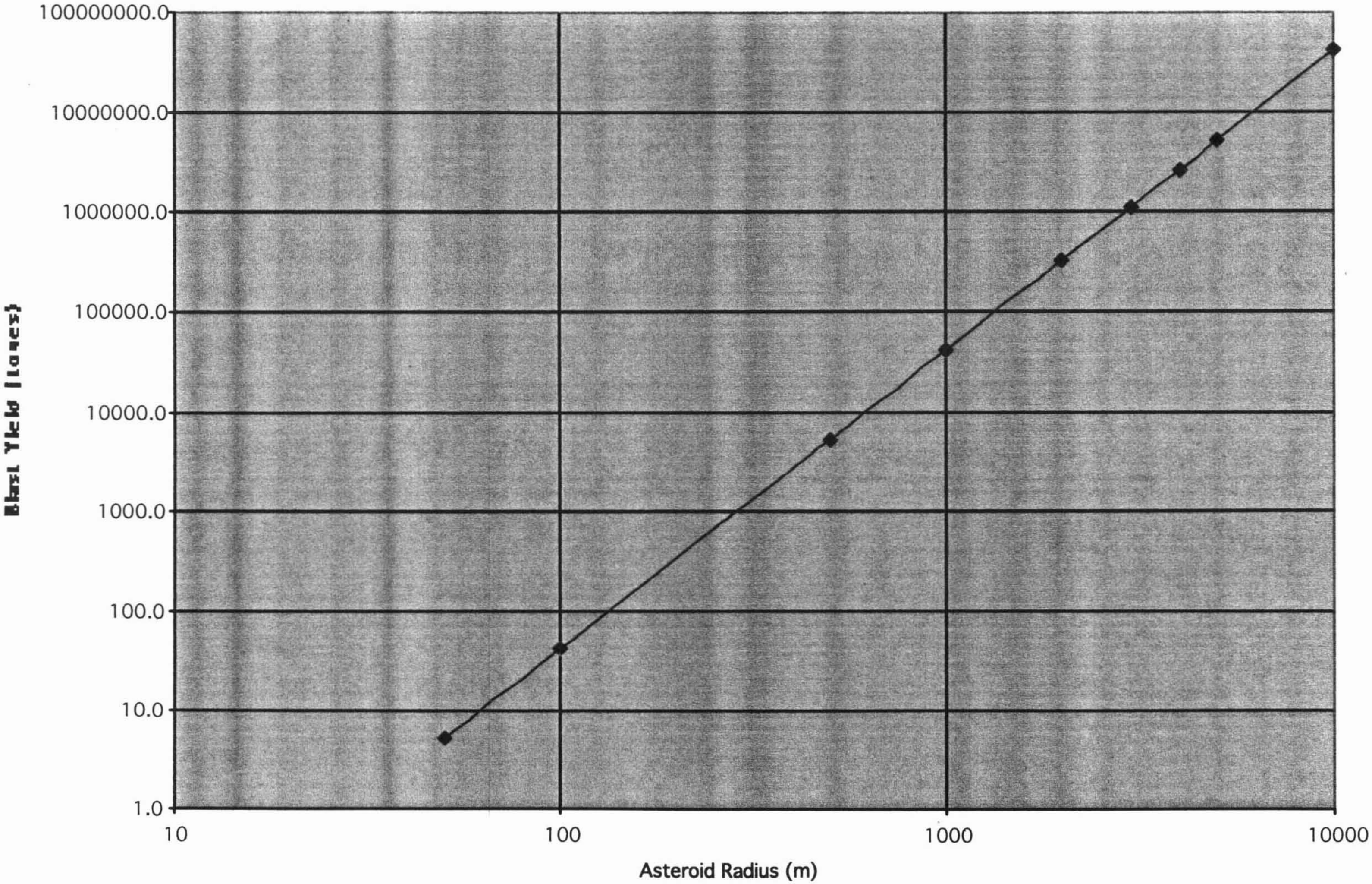
- Nuclear Deflection
  - Shaped charge emits blast in largely conical configuration
  - Standoff distance insures that cone is tangent to "spherical" object
  - Thermal and electromagnetic energy evaporates object, producing thrust
  - Again prior knowledge of composition of object is greatly desired





Surface Blast Deflection

Yield Required to Impart 1 cm/sec Delta V



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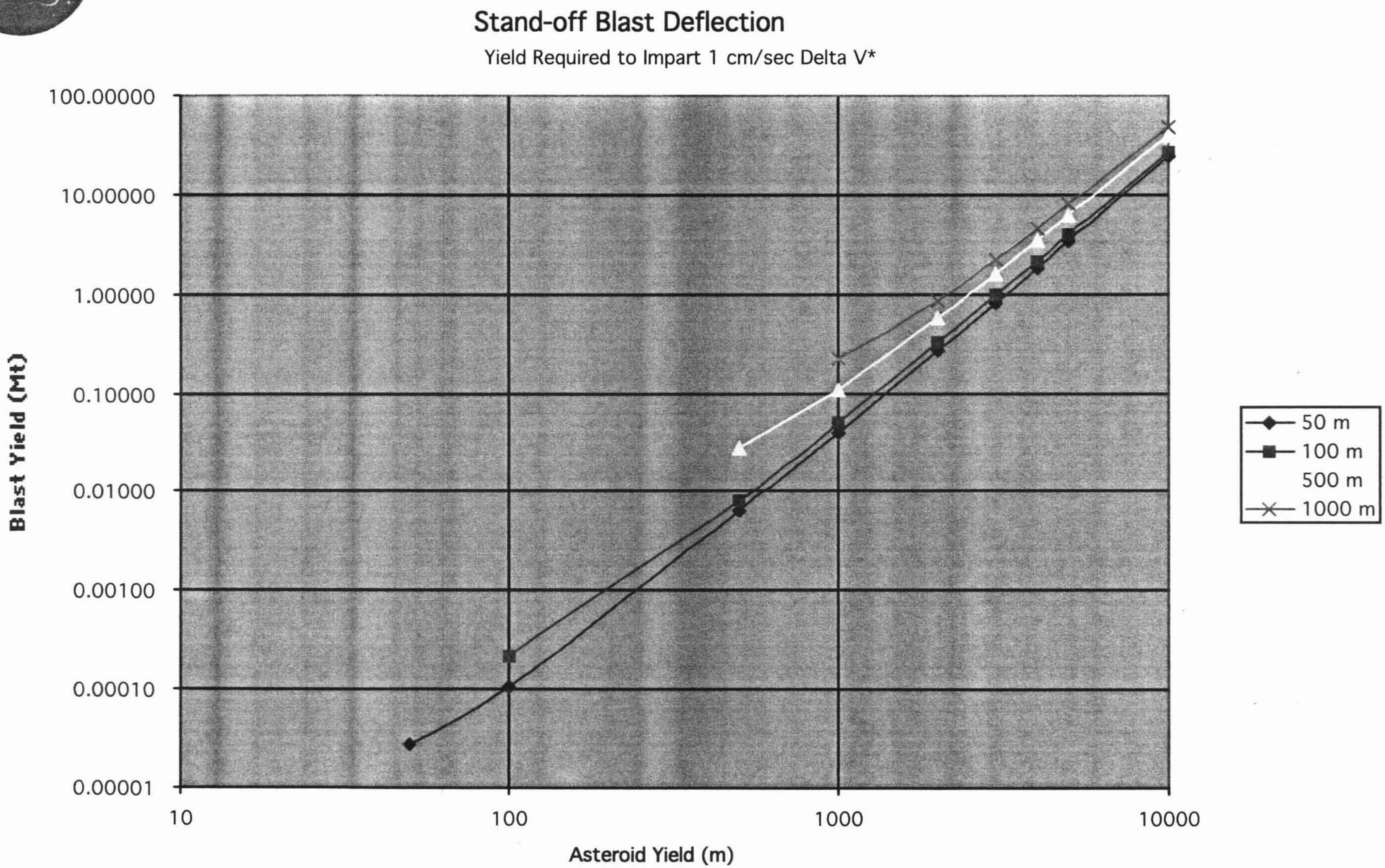
Maximum Delta V Achievable in a Single Impulse

"… it appears that for NEO's greater than or equal to 100 m diameter, the maximum single impulse delta V that can be applied without danger of dispersing the NEO into large fragments is of the order of its surface escape velocity. This is ~ 1 m/s for a 1 km diameter NEO, and is directly proportional to diameter, ie., ~10 cm/s for a 100 m NEO and ~10 m/s for a 10 km NEO. One can imagine that it would be desirable, indeed probably necessary, to apply several small velocity impulses to an object in order to divert it accurately. However there are limits to the number of impulses that could be economically employed, perhaps on the order of ten." - Ahren, Thomas J. and Harris, Alan W., "Deflection and Fragmentation of Near-Earth Asteroids" pg 921-922.



* neutron production efficiency (n) = 0.3

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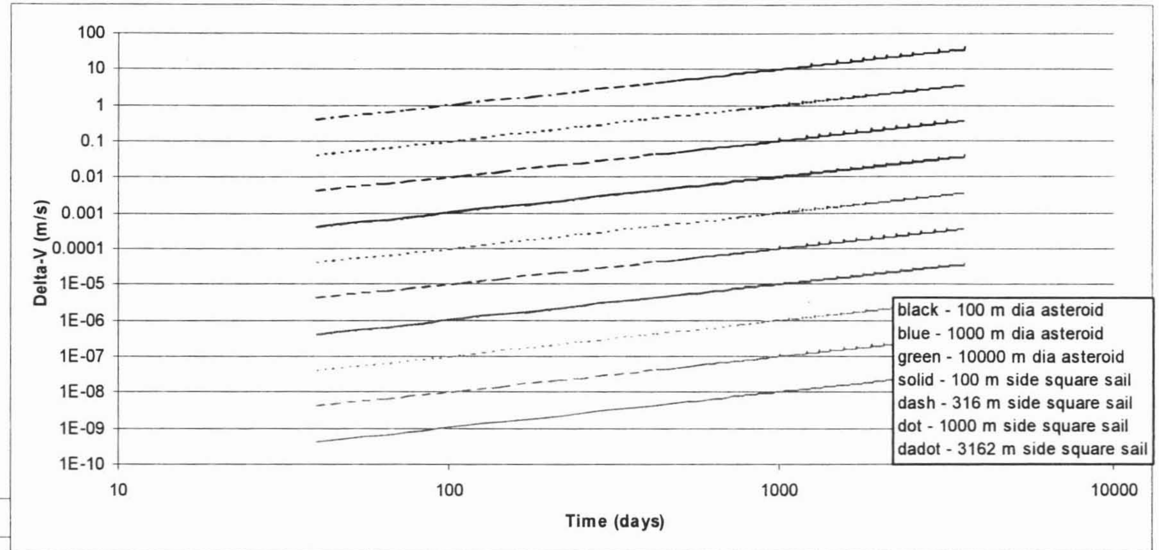
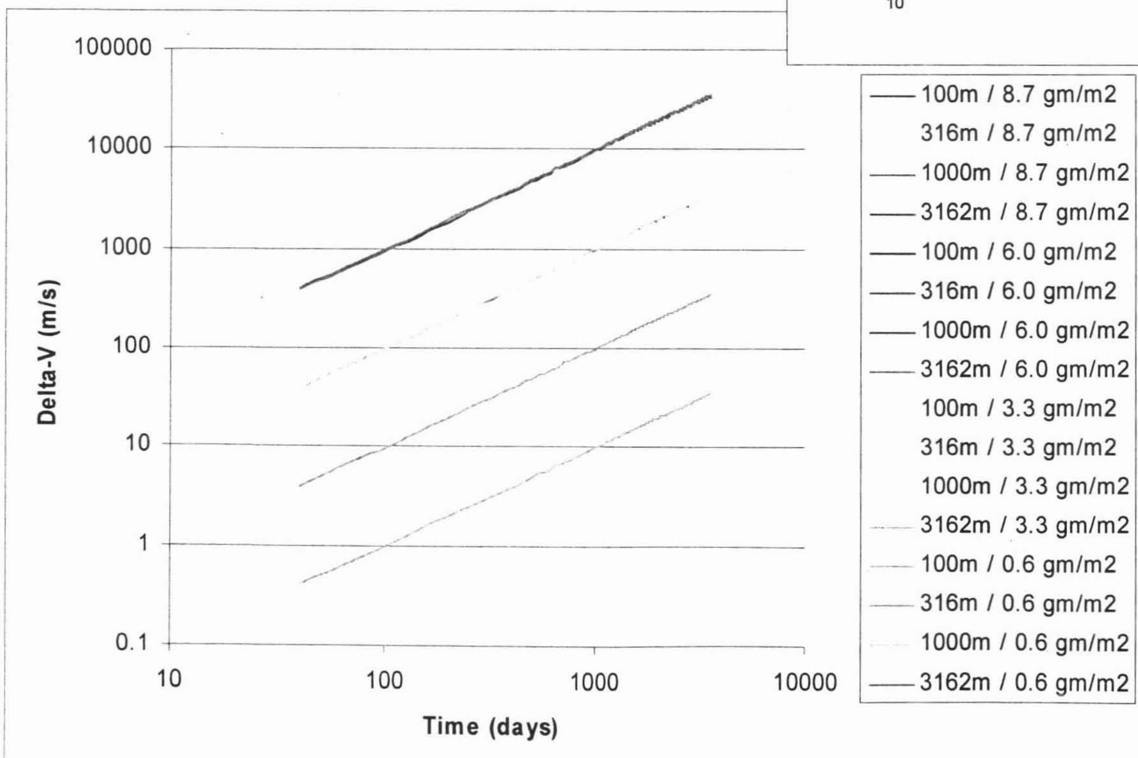
Threat Mitigation

- Solar Sail
  - Concept simplicity offset by operational difficulties for: rotating bodies, debris-rich environments, fragmented bodies





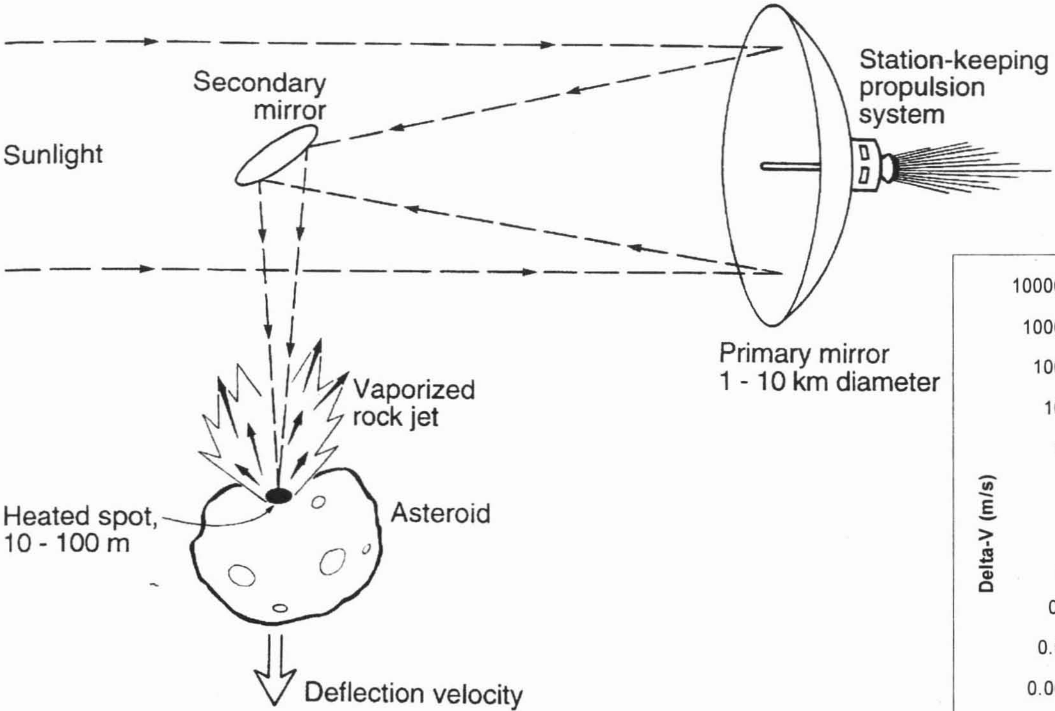
–Thrust simply not sufficient for any but the smallest objects

Melosh, H. J., Nemchinov, I. V., Zetzer, Yu. I., "Non-Nuclear Strategies for Deflecting Comets and Asteroids", *Hazards Due to Comets and Asteroids*, p1111-1132, The University of Arizona Press, Tucson, 1994

ice

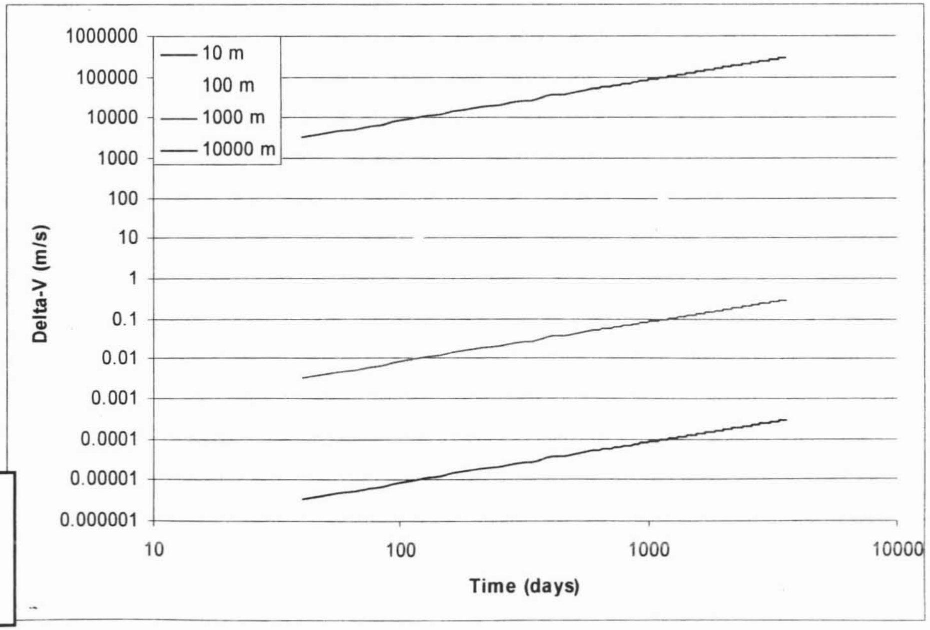
Threat Mitigation

- Solar Collector
  - Concept simplicity makes this an attractive option provided operational issues can be resolved
  - Could work well with rotating and fragmented bodies – even in a debris-rich environment



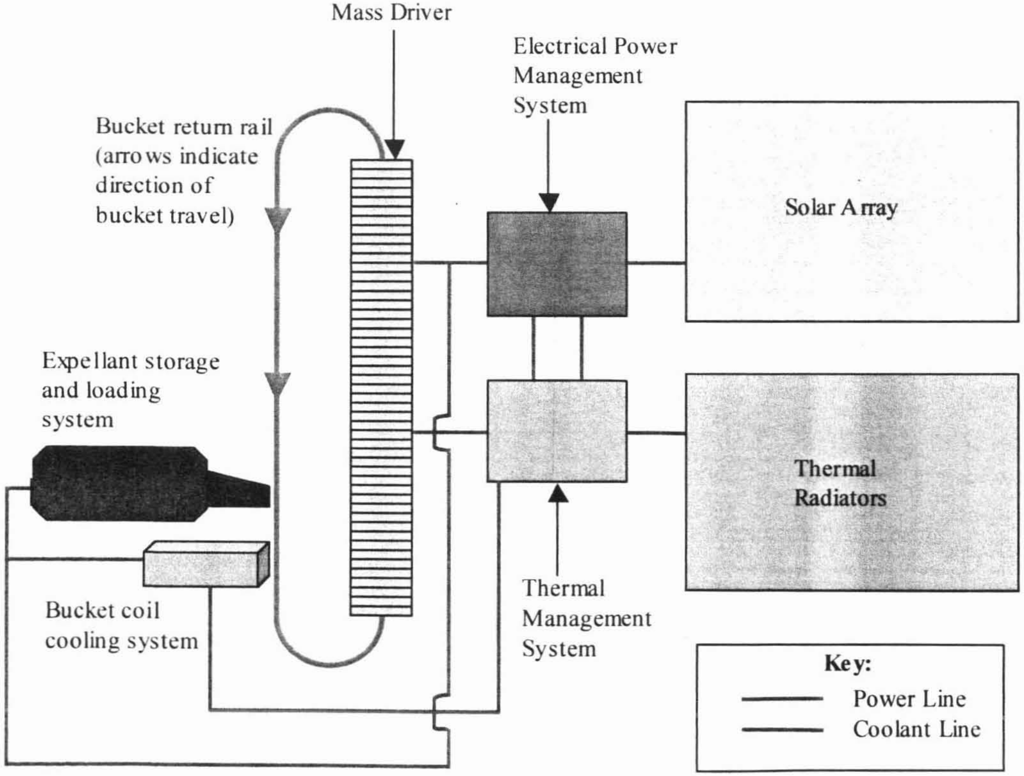
-100 m collector could concentrate enough energy to move up to 1 km objects

Melosh, H. J., Nemchinov, I. V., Zetzer, Yu. I., "Non-Nuclear Strategies for Deflecting Comets and Asteroids", *Hazards Due to Comets and Asteroids*, p1111-1132, The University of Arizona Press, Tucson, 1994



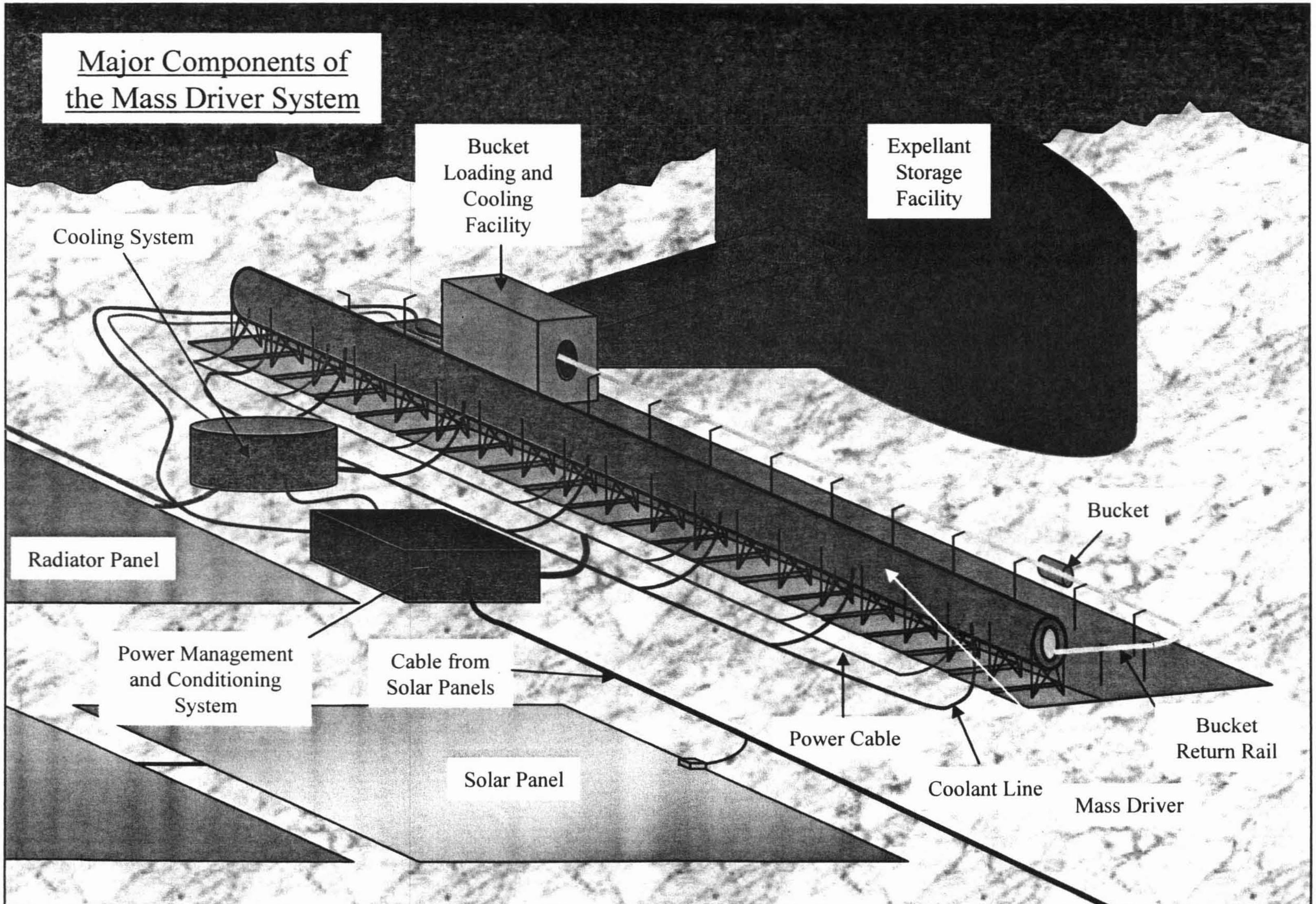
Threat Mitigation

- Mass Driver
  - Mechanically complex and massive system – requires extensive assembly and preparation work on target
  - Could work well as part of a long-term deflection campaign (i.e. with years before Earth-impact) provided mechanical reliability problems can be overcome



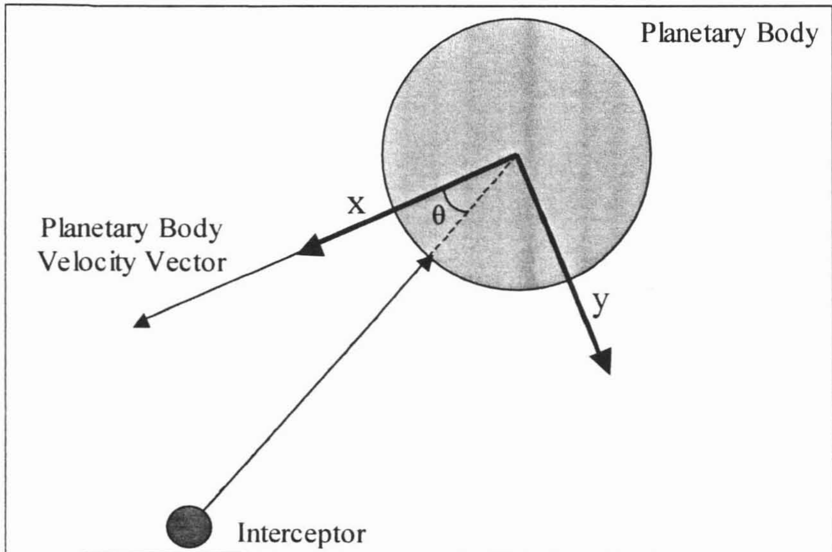
•O'Neill, G.K. and O'Leary, B, "Space-Based Manufacturing from Nonterrestrial Materials", Progress in Astronautics and Aeronautics, Volume 57, published by the American Institute of Aeronautics and Astronautics, 1977.

Mass Driver Design – Main Components



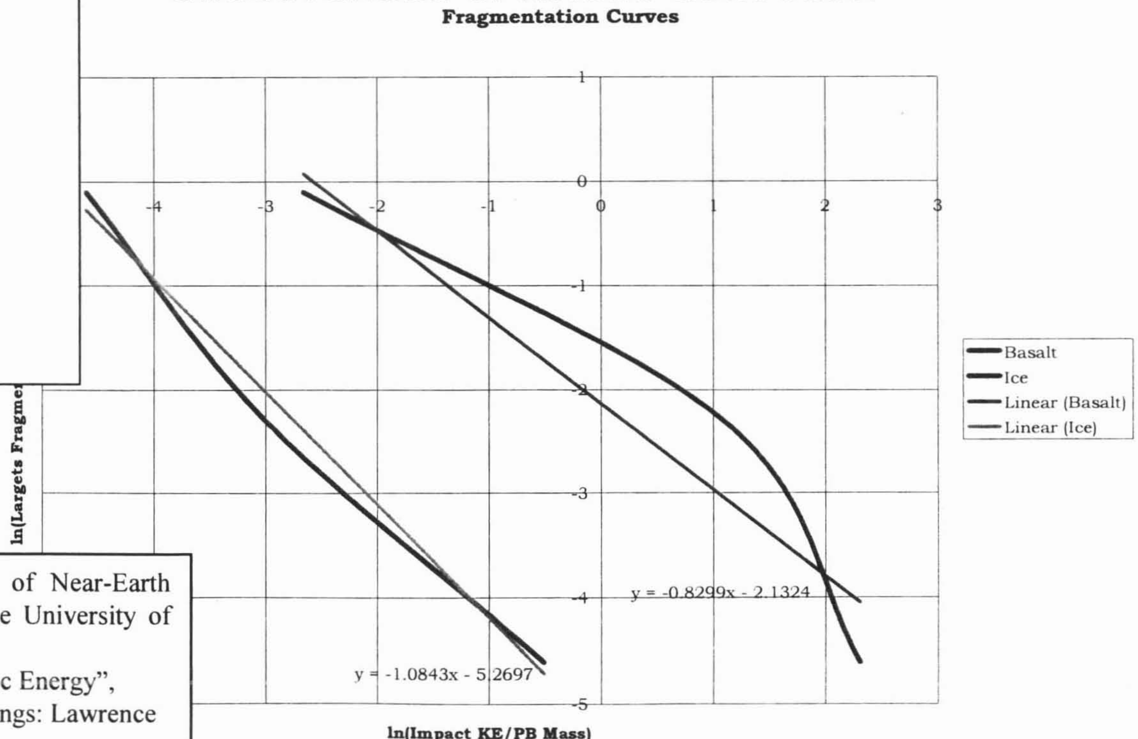
Threat Mitigation

- Kinetic Deflection/Fragmentation
  - Simple and robust system, but poses challenges in targeting
  - Long response time



–Mass of spent stage adds to kinetic mass

–Current models may underestimate effectiveness of kinetic deflection



Ahrens, T.J and Harris, A.W., "Deflection and Fragmentation of Near-Earth Asteroids", *Hazards Due to Comets and Asteroids*, p897-927, The University of Arizona Press, Tucson, 1994.

Tedeschi, W.J., "Mitigation of the NEO Impact Hazard Using Kinetic Energy", Planetary Defense Workshop. May 22-26, 1995, p313-323. Proceedings: Lawrence Livermore National Laboratory, Livermore, CA.

Threat Mitigation

- Interceptors with sufficiently high mass and/or speed will cause the planetary body to fragment. Depending upon the circumstances, this may or may not be desirable
- A simple, semi-empirical model has been used to determine the approximate criteria for fragmentation:
- Reference:
  - Tedeschi, W.J., "Mitigation of the NEO Impact Hazard Using Kinetic Energy", Planetary Defense Workshop. May 22-26, 1995, p313-323. Proceedings: Lawrence Livermore National Laboratory, Livermore, CA..

Threat Mitigation

If

M_T = Planetary Body (i.e. target) mass

M_L = Mass of largest post-impact fragment

E_P = Kinetic energy of collision

then

$$\ln\left(\frac{M_L}{M_T}\right) = A\ln\left(\frac{E_P}{M_T}\right) + B$$

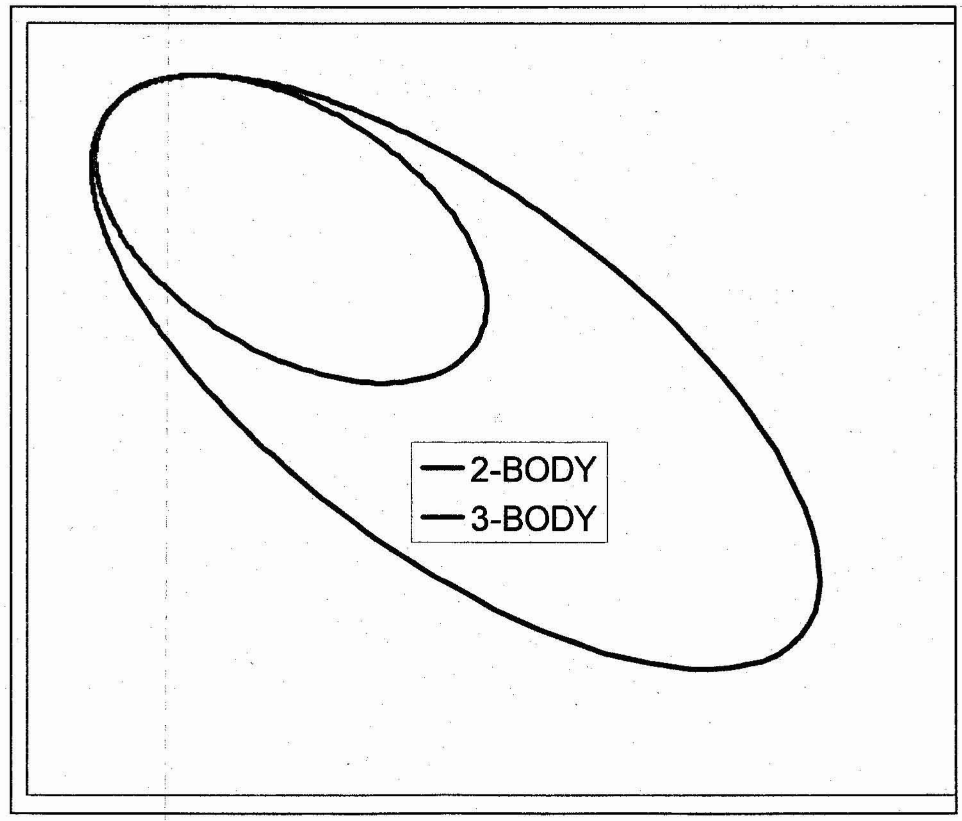
Where:

A = -0.8299 for Basalt and –1.0843 for ice

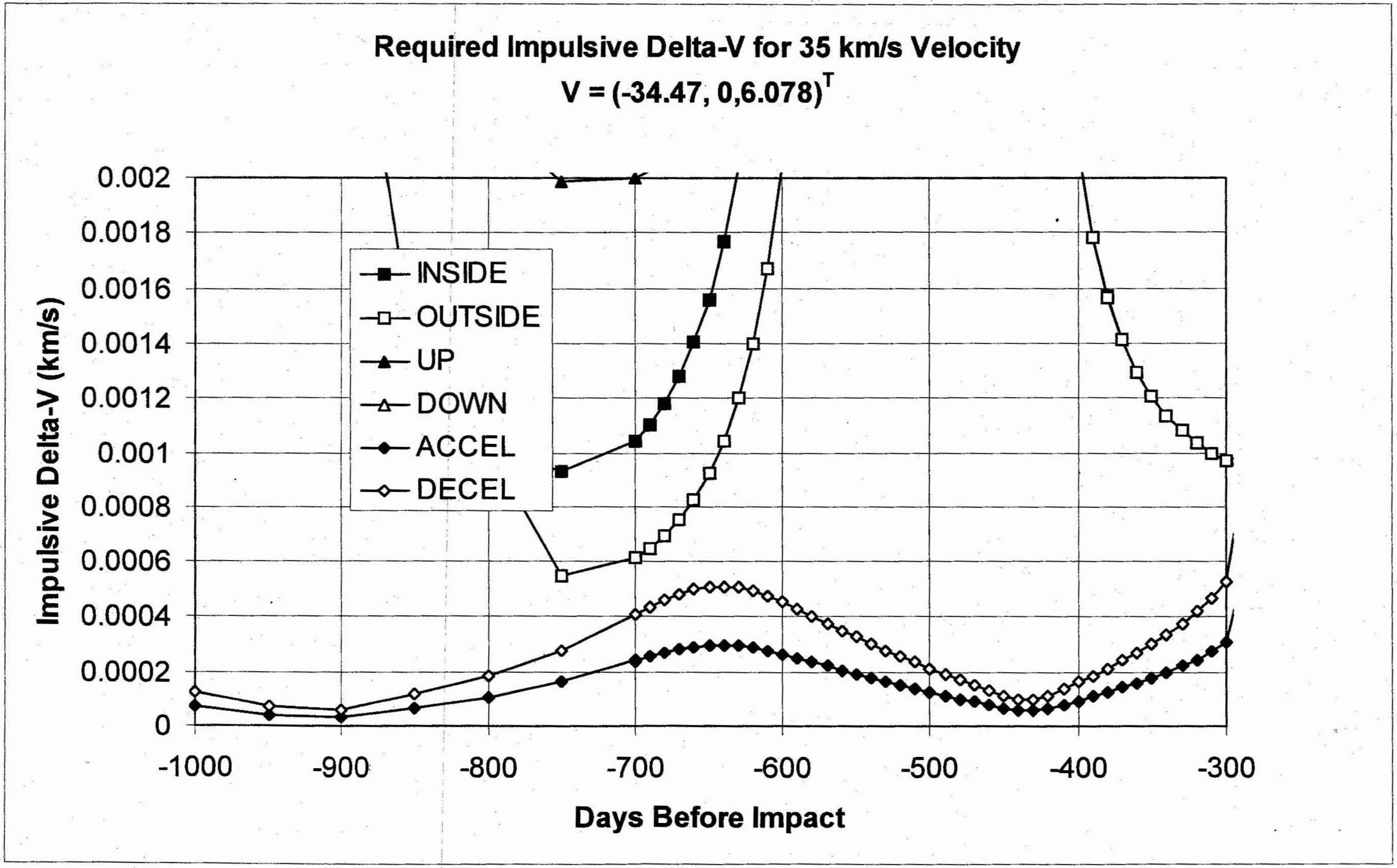
B = -2.1324 for Basalt and –5.2697 for ice

Inbound Trajectory

Given the velocity vector of the planetary body at impact to be $(-40, 0, 0)^T$, what do the two-body and three-body orbits look like that will give this velocity at impact? ANS: 2.5 versus 5.0 AU!



Inbound Trajectory



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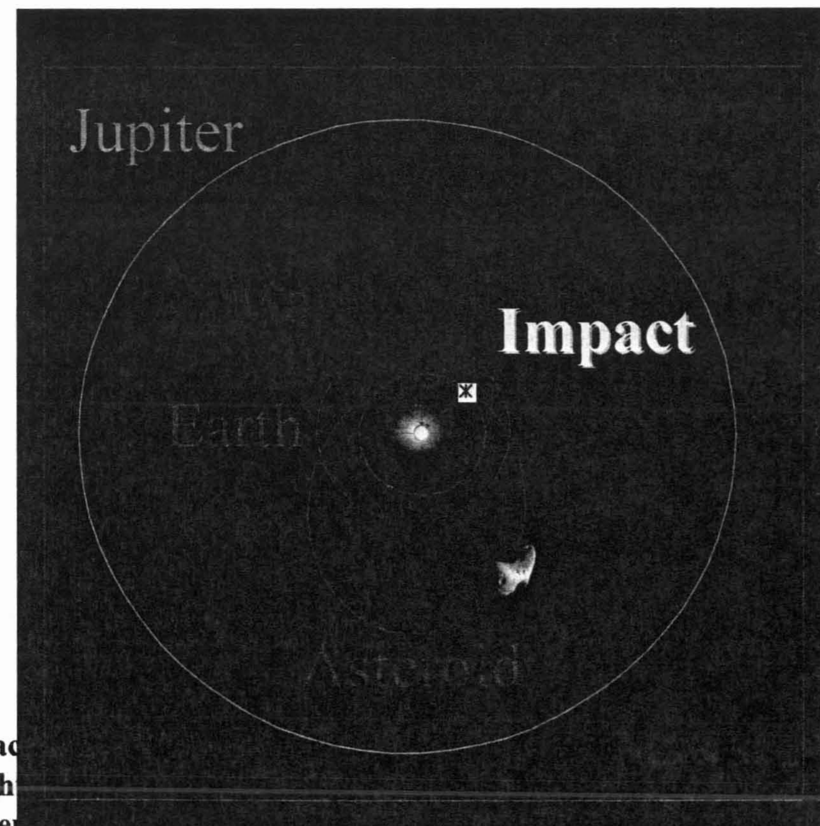
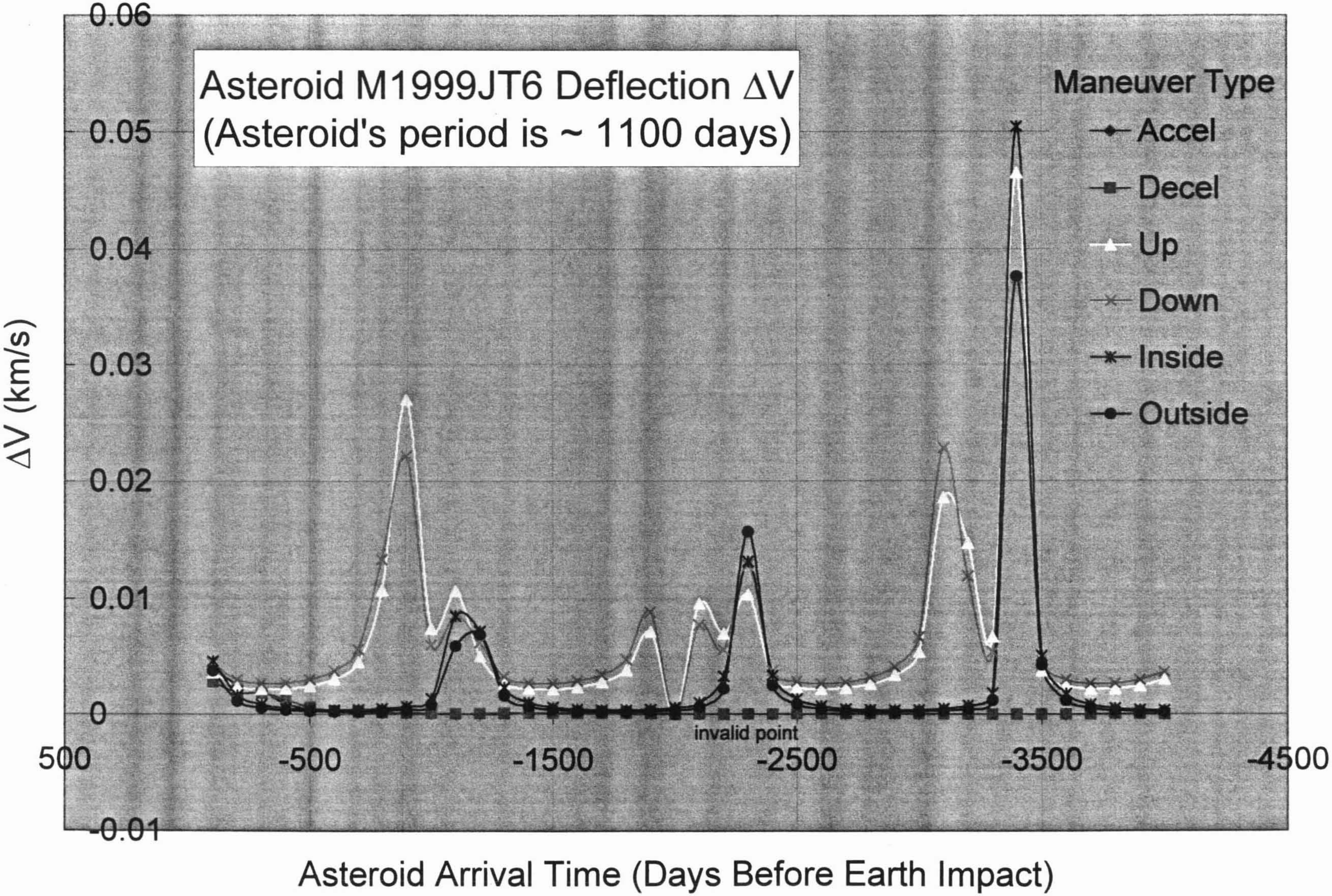
Inbound Trajectory

- Modified Asteroid 1999JT6
  - 1999JT6 orbit was modified slightly to force Earth collision. It is this modified (hypothetical) asteroid that is being defended against in this study.

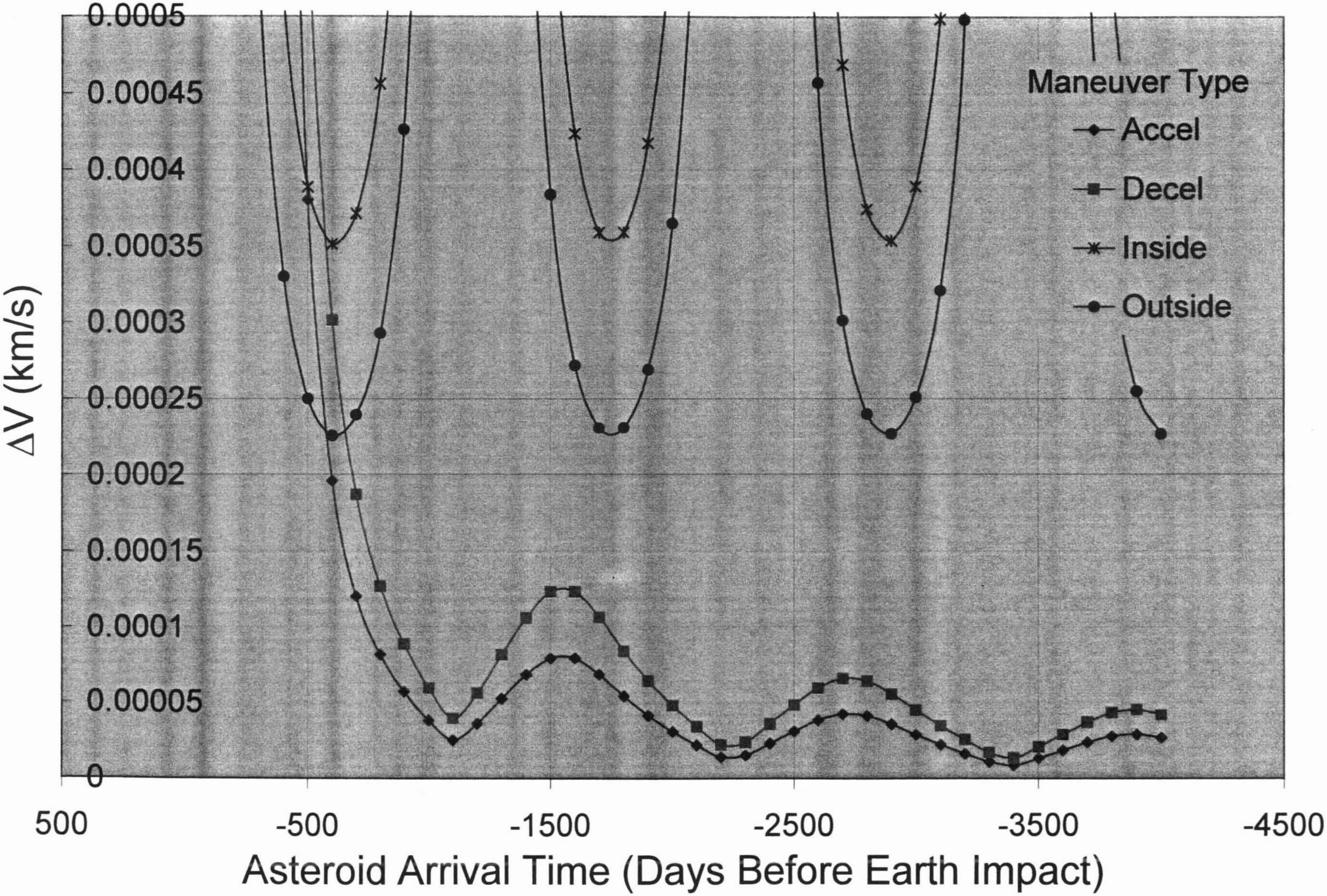
Semimajor Axis (AU)	2.13
Eccentricity	0.578
Inclination	11.46
Ascending Node (deg)	45.02
Argument of Periapsis (deg)	41.83



Inbound Trajectory



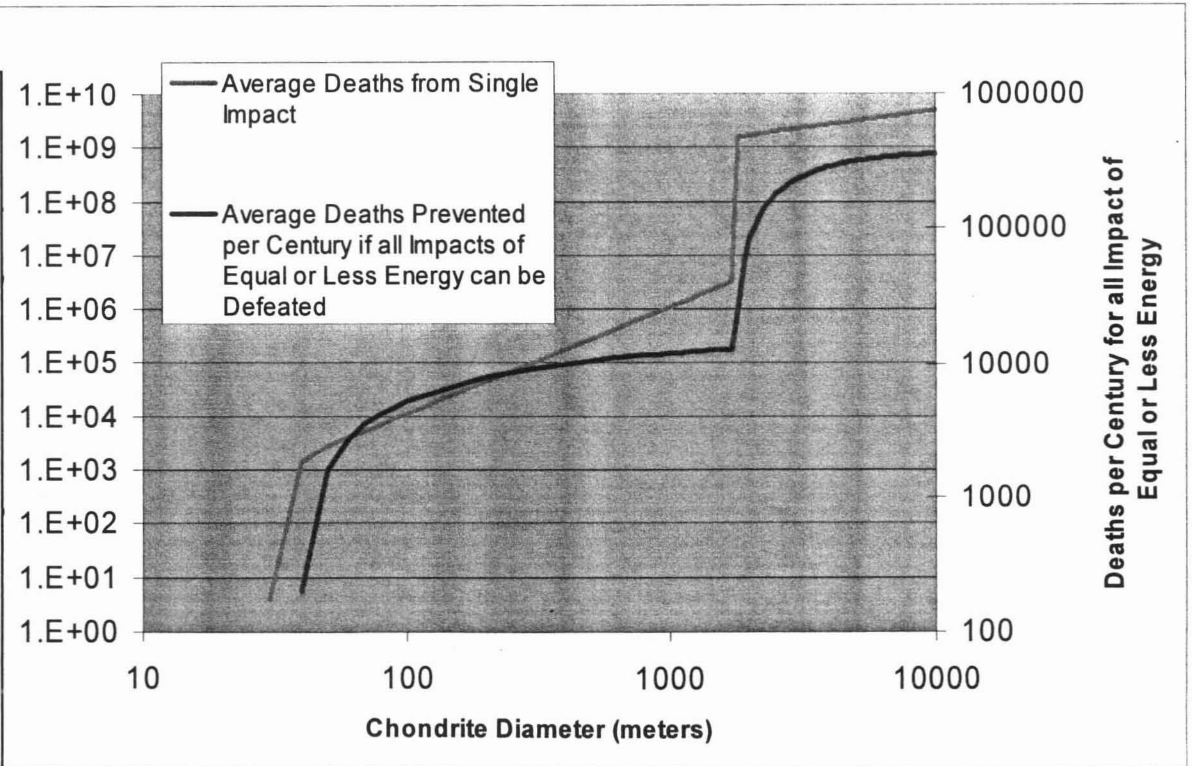
Inbound Trajectory



Threat Assessment

- Modified version of existing Monte Carlo code used to estimate number of deaths caused by asteroid impact
- Given maximum size and energy of deflectable NEO's calculates number of deaths prevented per century

•Chapman, C. R, and Morrison, D., "Impacts on the Earth by Asteroids and Comets: Assessing the Hazard," *Nature*, 6 January 1994.
•Gold, R. E., "SHIELD – A Comprehensive Earth Protection System: A Phase I Report to the NASA Institute for Advanced Concepts," 28 May 1999.
•Lewis, John S., *Comet and Asteroid Impact Hazards on a Populated Earth*, Academic Press, 1999.
•Jeffers, S. V., Manley, S. P., Bailey, M. E., and Asher, D. J., "Near-Earth Object Velocity Distributions and Consequences for the Chicxulub Impactor," *Mon. Not. R. Astron. Soc.*, 327 (2001).
•Chesley, S, Chodas, P, Milani,, A., Valsecchi, G., Yeomans. D., "Quantifying the risk posed by Potential Earth impacts," *Icarus Asteroids*, 2001.
•Ivezic, Zeljko, *et al*, "Solar System Objects Observed in the Sloan Digital Sky Survey Commissioning Data," *The Astronomical Journal*, November 2001.
•Shoemaker, E. M., "Asteroid and Comet Bombardment of the Earth," *Annual Review of Earth and Planetary Sciences*, 11: 461-494.
•Chapman, C.R. & Morrison, D., 1994, Nature 367, 33-40



Integrated Analysis

- An architecture designed to address this threat will incorporate several of the components above
- For each architecture the pertinent components are wrapped and brought into ModelCenter™
- A parametric analysis of the percentage of the total threat defeated, weighted by probability of occurrence, vs. total mission time can be calculated for several total mission masses.
- These parametrics, combined with the qualitative data collected for each propulsion system allows for a comparison of all the envisioned architectures

Conclusions

System	Maneuver	Time Before Impact (days)#/ Outbound Travel Time (days)	Total System Mass at SOI (mT) for Different Asteroid Diameters (meters)			Maximum Diameter of Asteroid (meters)/Total System Mass at Earth SOI (mT)
			100	1000	10000	
Staged Chemical + Mass Driver	Rendezvous	2900/2400	n/a	n/a	n/a	50/6,849 80/6,918
Staged Chemical + Nuclear Deflection	Intercept	1509/599	0.847	8.27	1300	9000/1000
	Rendezvous	1075/943	5.62	568	87,800	1000/1000
Staged Chemical + Kinetic Deflection	Intercept	1025/800	73.8	n/a	n/a	260/1,000
Nuclear Pulse	Rendezvous	2170/970	29.7	41.8	1240	9000/1000
Solar Collector	Rendezvous (~3 yr)	1076/1011**	0.637	1.07	167	§
	Rendezvous (~10 yr)	3635/3520**	0.550	0.636	34.6	§

*maximum was constrained to a total system mass at Earth SOI of 1000 metric tons.

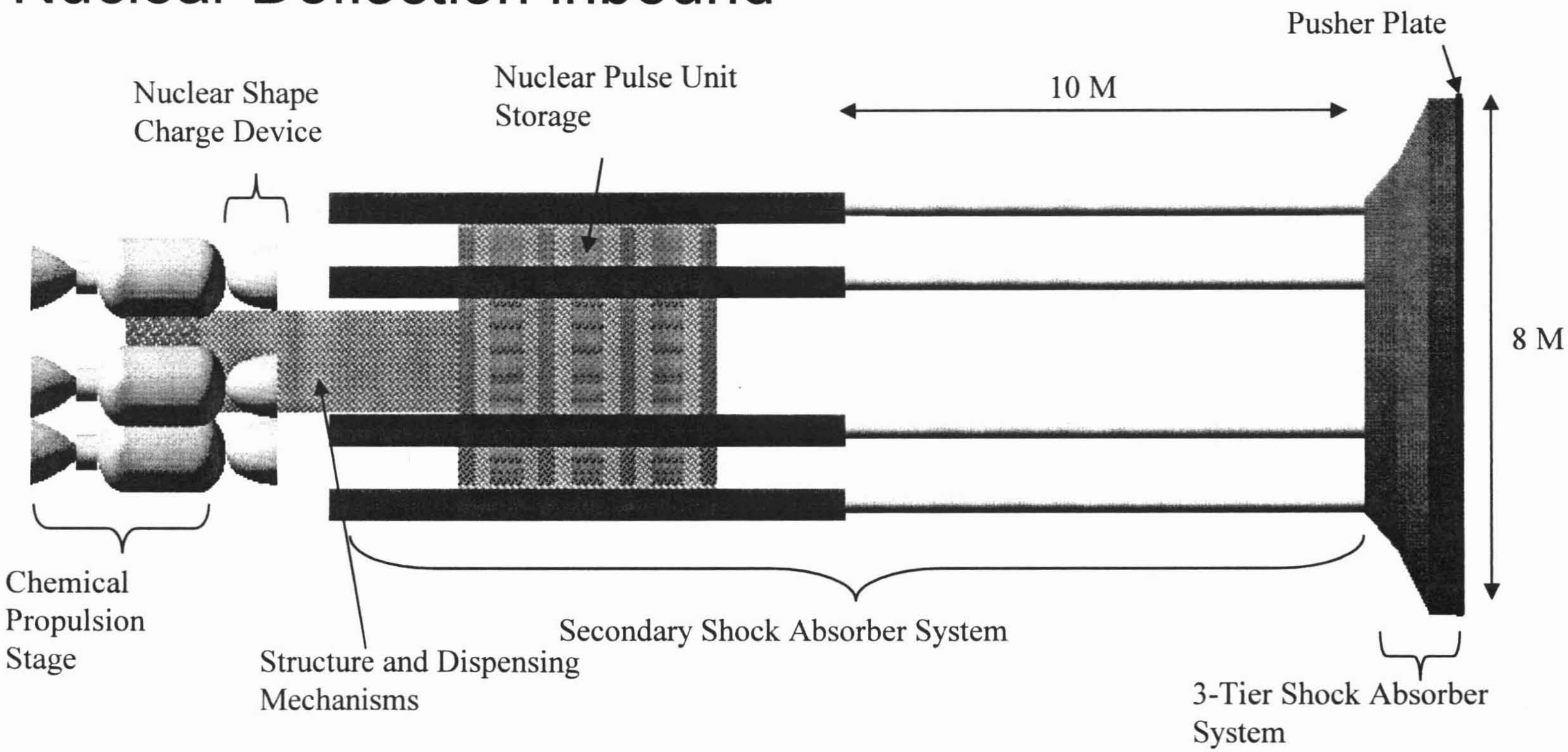
** times are for 100m chondrite. Outbound times must be shorter for larger asteroids, although total mission times change little.

§ the solar collector system is limited more by solar collector size than by total system mass.

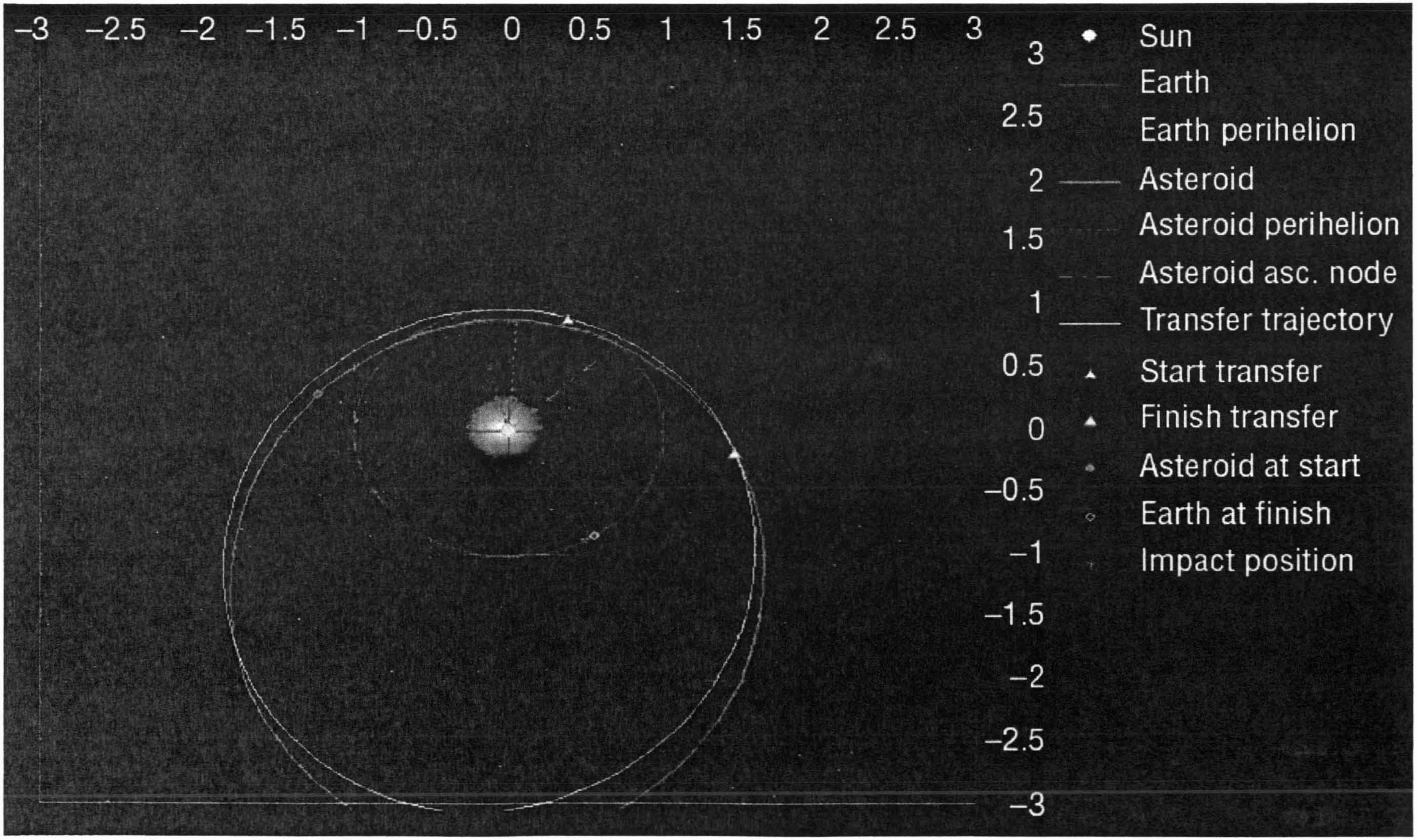
the time from launch of the vehicle to the expected date of impact of the unperturbed NEO

Conclusions

- Baseline case is Nuclear Pulse outbound with Nuclear Deflection inbound



- Mission Profile for Baseline case



Outline

- Introduction
- Background and History – relegated to backup charts
- Mission Classification
- Outbound Propulsion Options
- Outbound Trajectory Modeling
- Threat Mitigation Options
- Inbound Trajectory Modeling
- Threat Assessment
- Integrated Analysis
- Results
- ***Conclusions***

Conclusions

- The results from this analysis are preliminary only.
  - Corollary 1 - Uncertainties arising from the nature of the threat, the approximations made in the propulsion and threat mitigation sections, and the impulsive assumption for the trajectory analysis should all be addressed before reaching final conclusions.
  - Corollary 2 – The recommendation of the nuclear pulse option should be taken with a large grain of salt.
  - Corollary 3 – Funding is needed to expand the tools developed as part of this study and to refine the study methodology proposed herein.
- NEO's pose a roughly near equal threat compared to other natural disasters. And opposed to earthquakes, tsunamis, tornados and hurricanes there is a clear engineering path to handle the threat of NEO's.
  - Corollary - Investment in NEO research and mitigation should be comparable to that for other natural disasters, and perhaps more given the probability for greater effectiveness.

Conclusions

- The NEO threat is very poorly understood. Research is needed in population distribution both in orbital elements and composition, geometry and spin and structural mechanics of NEO's.
  - Corollary 1- Consideration must be given to debris belts, threat from long period comets, burnt out comets (stealth bombers), etc.
  - Corollary 2 - Substantial conceptual and preliminary design efforts on threat mitigation options are needed to prioritize asteroid and comet research, especially to define scientific requirements for deep space probes.
- Mitigation of any NEO threat above the most minor will require advanced propulsion systems and technologies not currently flight mature.
  - Corollary 1 - Very long development times from start of funding (10 – 20 years) can be expected for any mitigation system.
  - Corollary 2 - Advanced propulsion technology research should be funded immediately to reduce development time.

Conclusions

- Nuclear options show much promise in NEO deflection.
  - Corollary – Issues with space nuclear proliferation treaties will have to be addressed if these promising options are to be carried forward.
- The scale of a threat mitigation system can be expected to be somewhere on the order of constructing the International Space Station or a crewed Mars mission.
  - Corollary 1 - It is fortuitous that the CaLV is projected to be built. A heavy lift launch vehicle is almost imperative in deploying most threat mitigation systems
  - Corollary 2 - Substantial funding will be required for engineering and construction of any threat mitigation system.

Conclusions

- There is the potential for strong synergy between propulsive technology requirements for some threat mitigators and crewed deep space exploration.
  - Corollary - Consideration should be given to inserting the threat mitigation project as a "stepping stone" between the crewed lunar base project and crewed Mars exploration.
- Mission times for threat mitigation can be substantial, running to decades.
  - Corollary 1 – a substantial effort will have to be made to catalog and identify potential threats.
  - Corollary 2 – some effort will have to be given to how to address long period comets, and other NEO threats that may collide with the Earth on the first pass.
  - Corollary 3 – We're out of time, let's get on with it, already!

Acknowledgements

- My Co-Authors on NASA TP-2004-213-089
  - Reginald Alexander, Joseph Bonometti, Jack Chapman, Matthew Devine, Sharon Fincher, Randall Hopkins, Tara Polsgrove; NASA-MSFC
  - Geoffrey Statham, Slade White; ERC, Inc.
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  - Jonathan Campbell, Roy Young; NASA-MSFC
- Our Colleagues from the RASC program
  - Pat Troutman, Dan Mazanek; NASA-LaRC