Near Earth Object Study

Deflection Aspects

Vern Weyers

March 6, 2007

Chances of Dying from Selected Causes (USA)
(From C.R. Chapman & D. Morrison, 1994, Nature 367)

Cause of death	Chances
Motor vehicle accident	1 in 100
Homicide	1 in 300
Fire	1 in 800
Firearms accident	1 in 2,500
Electrocution	1 in 5,000
Asteroid/comet impact	**1 in 20,000**
Passenger aircraft crash	1 in 20,000
Flood	1 in 30,000
Tornado	1 in 60,000
Venomous bite or sting	1 in 100,000
Fireworks accident	1 in 1 million
Food poisoning by botulism	1 in 3 million

Impact Frequencies and Typical Consequences

The purpose of deflection is to mitigate these threats

Type of Event	Diameter of Object	Fatalities per Impact	Typical Impact Interval (years)
High altitude break-up	< 50 m	~0	annual
Tunguska-like event	> 50 m	~5,000	250 - 500
Regional event	> 140 m	~50,000	5,000
Large sub-global event	> 300 m	~500,000	25,000
Low global effect	> 600 m	> 5 M	70,000
Nominal global effect	> 1 km	> 1 B	1 million
High global effect	> 5 km	> 2 B	6 million
Extinction-class Event	> 10 km	6+ B	100 million

The probability of a 140m impact over the next 50 years is about 1%

Organization through the Working Group Level

Study Lead
B. Claybaugh

Study Coordinator
D. Mulville

Study Executive
M. Shaw

Core Team

Coonce	Tom	NASA PA&E
Puhek	Jim	USAF
Liesveld	Rod	NASA PA&E
Johnson	Lindley	NASA SMD
Morgan	Tom	NASA SMD
Dastoor	Minoo	NASA ESMD
Wegeng	Robert	NASA ESMD
Avery	Don	NASA LaRC
Barker	Ed	NASA JSC

Consultants to Core Team

Ailor	Bill	Aerospace
Derleth	Jason	JPL
Gold	Rob	JHU/APL
Weyers	Vern	NASA (Ret)
Ross	Larry	NASA (Ret)
Spurlock	Frank	NASA (Ret)
Yeomans	Don	JPL

Detection / Tracking Working Group

Barker	Ed	NASA JSC
Yeomans	Don	JPL
Stuart	Scott	MIT/LL
Chesley	Steve	JPL
Chodas	Paul	JPL
Spahr	Tim	SAO CfA MPC
Harris	Al	SSI
Heimerdinger	Dan	Consultant
Lawrie	Dave	Aerospace

Characterization Working Group

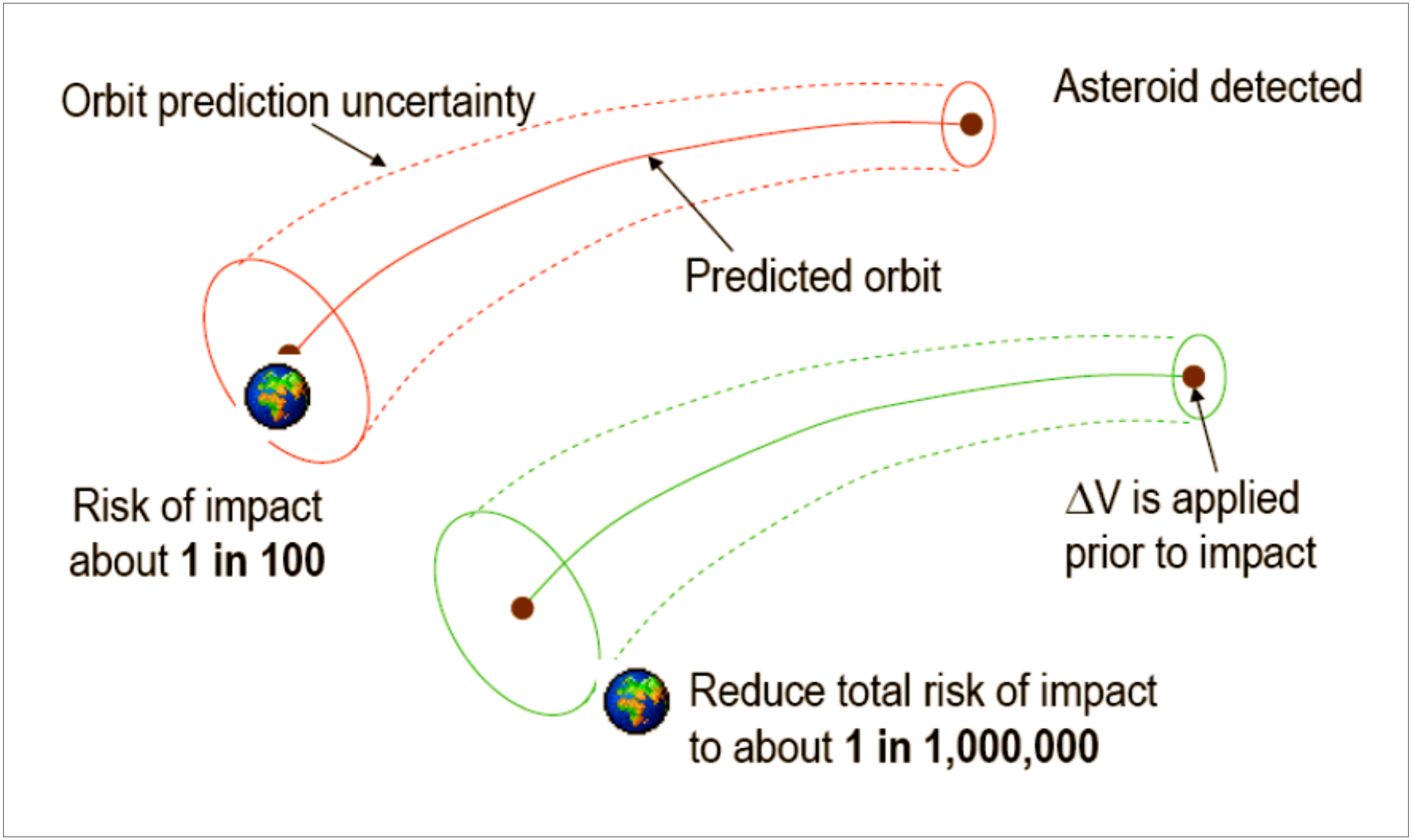
Morgan	Tom	NASA SMD
Gold	Rob	JHU/APL
Binzel	Richard	MIT/LL
Rivkin	Andy	JHU/APL
Lemke	Larry	NASA ARC
Lu	Ed	NASA JSC
Jones	Tom	LM/NASA (ret)
Lynch	Dave	Aerospace
Tokunaga	Alan	U of Hawaii

Deflection Working Group

Weyers	Vern	NASA (Ret)
Ross	Larry	NASA (Ret)
Spurlock	Frank	NASA (Ret)
Winkler	Marty	Retired Ind.
Ailor	Bill	Aerospace
Wegeng	Robert	NASA ESMD
Asphaug	Eric	UC Santa Cruz
Hahrahan	Robert	NNSA

Analysis Team: Aerospace Corporation, JPL, NASA Langley, MIT / Lincoln Labs

What is Mitigation / Deflection?



Deflection Alternatives Considered

	Concept	Description
Impulsive	**Conventional Explosive – Surface**	Detonate on impact
	Conventional Explosive – Subsurface	Drive explosive device into PHO, detonate
	Kinetic Impact	Impact PHO at high velocity
	Nuclear Surface Contact	Impact, detonate via contact fuse
	Nuclear Surface – Delayed Action	Land on surface, detonate at optimal time
	Nuclear – Standoff	Flyby, detonate using proximity fuse
	Nuclear – Subsurface	Drive explosive device into PHO, detonate
Slow Push	**Focused solar**	Use large mirror to focus solar energy on a spot, heat surface, “boil off” material
	Pulsed Laser	Rendezvous, position spacecraft near PHO, focus laser on surface, material “boiled off” surface provides force
	Mass Driver	Rendezvous, land, attach, mine material, eject material from PHO at high velocity
	Gravity Tractor	Rendezvous with PHO, fly in close proximity for extended period, gravitational attraction provides small force
	Asteroid Tug	Rendezvous with PHO, attach, push
	Enhanced Yarkovsky Effect	Change albedo of a rotating PHO; radiation from sun-heated material provides small force as body rotates

Technology Readiness and Effectiveness of Deflection Alternatives

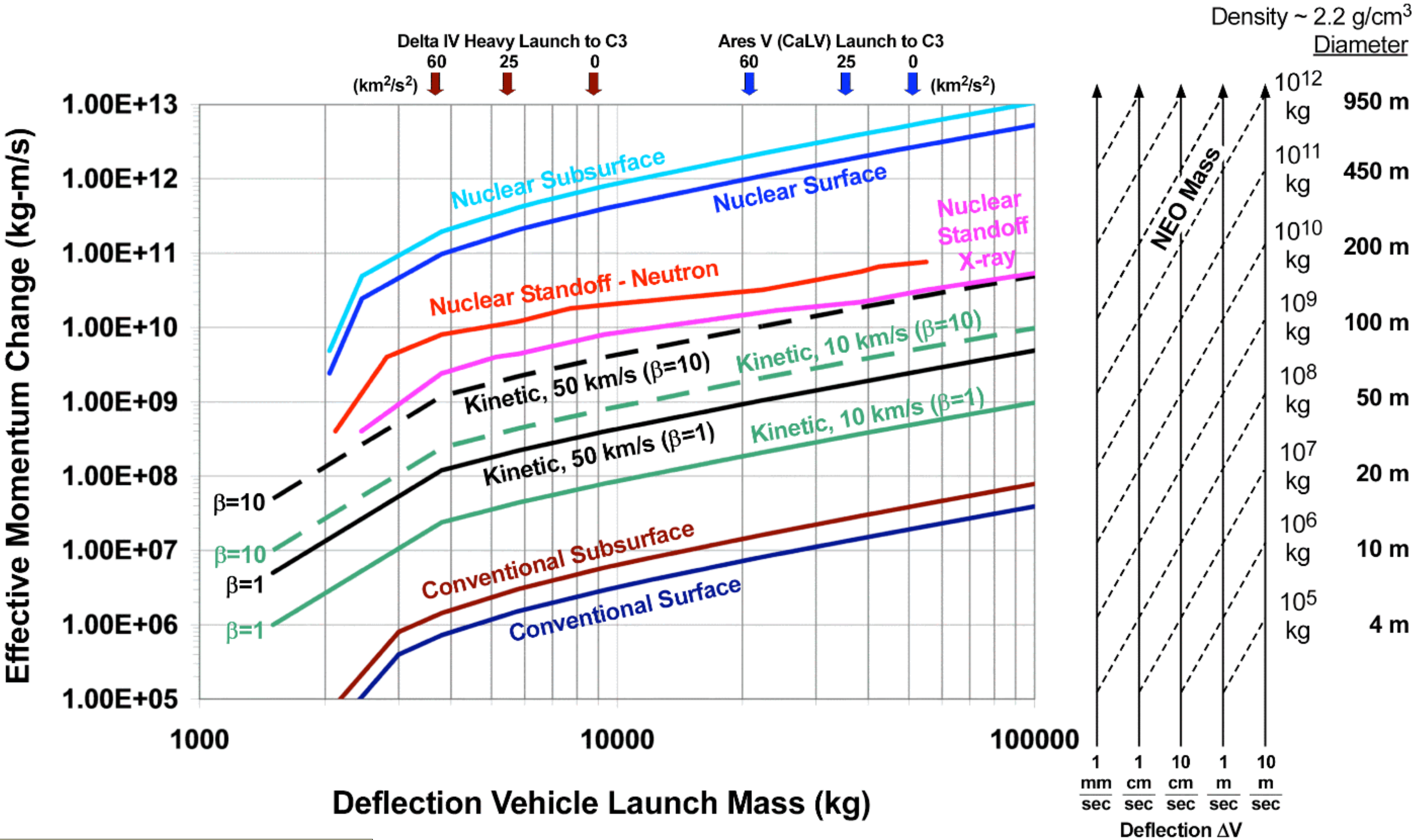
	Concept	Readiness	Effectiveness
Impulsive	Conventional Explosive – Surface	High	Medium
Impulsive	Conventional Explosive - Subsurface	Medium	Medium
Impulsive	Kinetic Impact	High	Very High
Impulsive	Nuclear Surface Contact	High	Very High
Impulsive	Nuclear Surface – Delayed Action	Medium	High
Impulsive	Nuclear Standoff	High	Very High
Impulsive	Nuclear Subsurface	Medium	Medium
Slow Push	Enhanced Yarkovsky	Low	Low
Slow Push	Focused Solar	Low	Medium
Slow Push	Gravity Tractor	Medium	Medium
Slow Push	Mass Driver	Low	Medium
Slow Push	Pulsed Laser	Low	Medium
Slow Push	Space Tug	Low	Medium

Technology Readiness
High = We know how to do it
Medium = Some development needed
Low = Conceptual, needs research

Effectiveness Against Range of Threats
Very High = Effective against most threats
High = Effective against many threats
Medium = Effective against some threats
Low = Effective against few threats

Momentum Change Performance of Impulsive Alternatives

BUILD SLIDE – POWERPOINT SHOW



β=ejecta efficiency factor

Deflection Scenarios Analyzed

- The 320 m asteroid Apophis with two deflection options
  - Prior to close approach to Earth in 2029 (keyhole pass)
  - After the close approach and prior to the 2036 Earth encounter
- The 580 m asteroid VD17 that could be a threat in the year 2102
- A hypothetical 200-m asteroid named Athos*
  - Representative of 100 m class
- A hypothetical asteroid named Aramis larger than 1 km*
- A hypothetical long-period comet named Porthos*
  - Short warning typical of long-period comets
  - 9-24 warning times assumed (difficult to extend with today's technology)
  - Comet analyzed is 200x smaller than any found to date
  - Comets represent a tiny fraction of the yearly risk (< 1%)

* *D. Lynch and G. Peterson. Athos, Porthos, Aramis, & D'Artagnon, Four Planning Scenarios for Planetary Protection. AIAA 2004-1417.*

Deflection Scenarios Analyzed

Case:	A_1 Apophis	A_2 Apophis	B Apophis	C VD-17	D Athos	E Aramis	F Porthos
Diameter, m	320	320	320	580	200	1,000	1,000
Feature	Keyhole	Keyhole	Direct	Direct	Moon	Rubble	Comet
Date of Impact	2029	2029	2036	2102	Hypothetical		
Time to act, yrs	22	22	7	>90	20	17	2
Lead Time*	10	6	2	15	10	6	1
Mass, Kg	4.6×10^{10}	4.6×10^{10}	4.6×10^{10}	2.6×10^{11}	1.1×10^{10}	1.2×10^{12}	1.0×10^{12}
ΔV required	5 mm/s	0.026 mm/s	4 cm/s	1 cm/s	4 cm/s	2 cm/s	5 m/s
ΔM^+, kg m/s	2.3×10^8	1.2×10^6	1.8×10^9	2.6×10^9	4.4×10^8	2.4×10^{10}	5.0×10^{12}
Miss Distance	5000 m	$P_i=10^{-6}$	$P_i=10^{-6}$	$P_i=10^{-6}$	$P_i=10^{-6}$	$P_i=10^{-6}$	$P_i=10^{-6}$
Rate of impacts**	~10,000	~10,000	~10,000	~100,000	~5,000	~1M	>> 1 M
Feasible to deflect	✓	✓	✓	✓	✓	✓	X

* Action time ahead of impact in (years)

** Average impact frequency for objects this size (years)

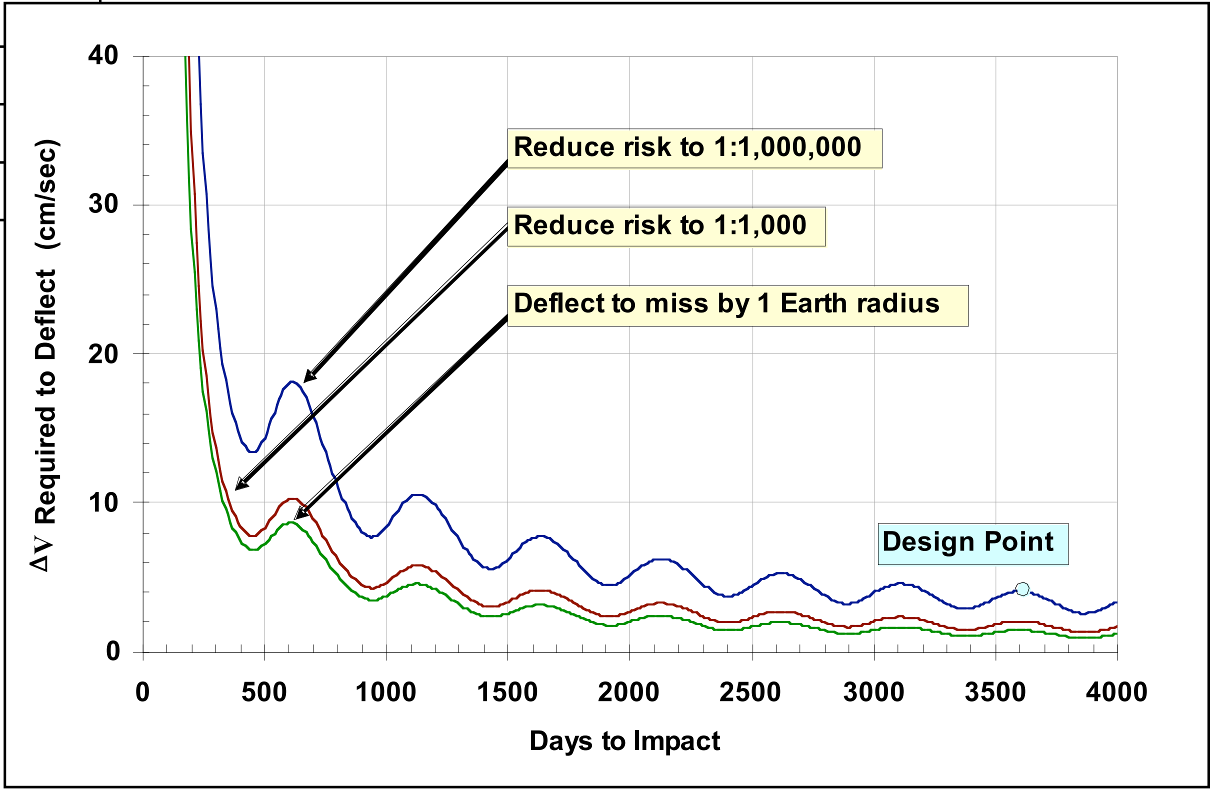
+ Momentum change required at design point

200 m Asteroid Athos

Scenario	200 m class Asteroid
Impact Frequency	~5,000 years
Time to Act	20 years
Action Begins	10 years prior to impact
Diameter of Threat	200 m
Mass of Threat	1.1×10^{10} kg
ΔV	4 cm/s
Δ Momentum	4.4×10^{8} kg m/s

Unique Features

- Most likely size of threat detected
- Moderate warning
- Companion (moon)
- Launch constraints



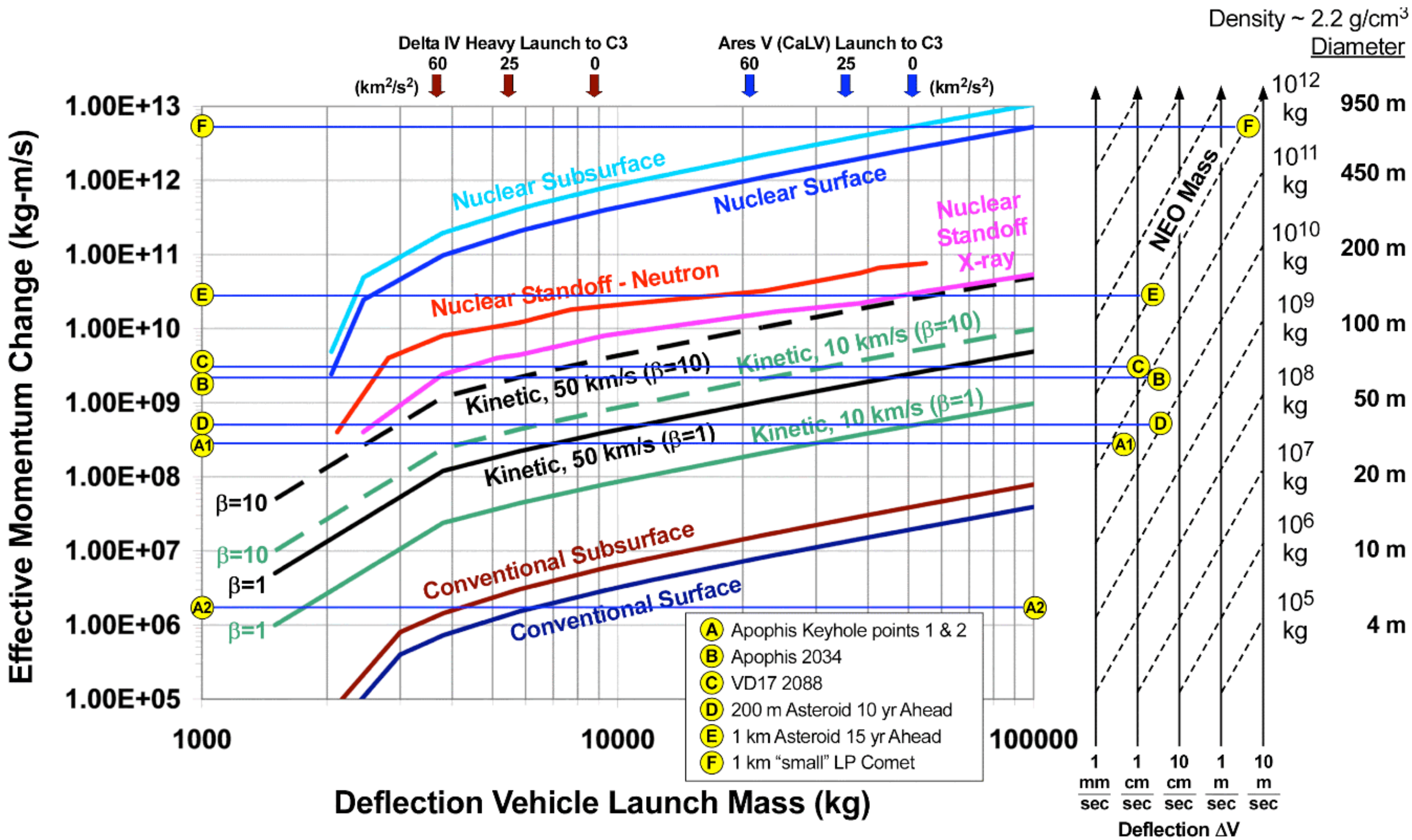
200 m Asteroid with Companion Moon Performance and Summary

[illegible]

P_{index}>1 indicates feasibility

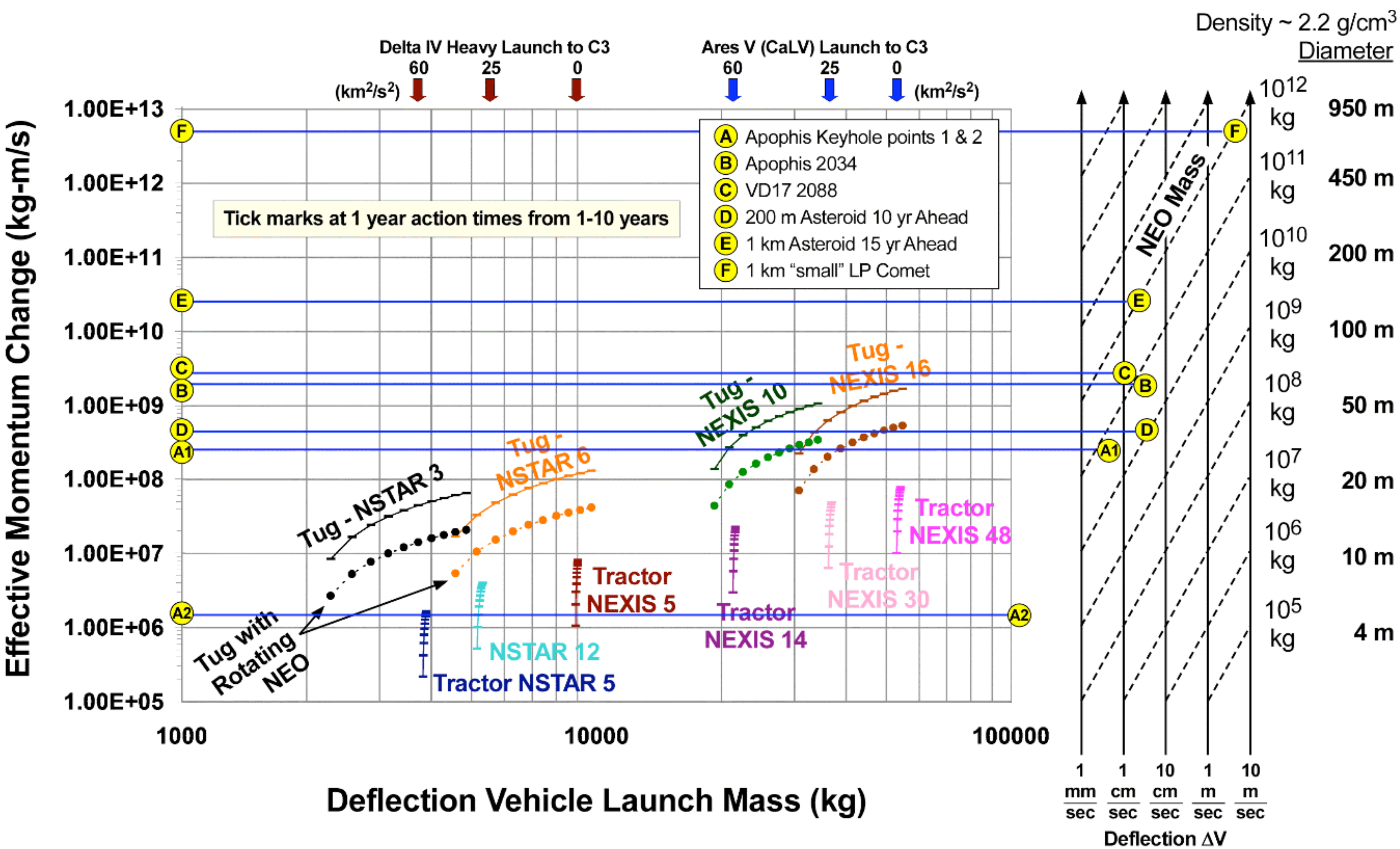
Launch Vehicle → / Concept	Performance Index (P)		Launches Required	
	Delta IV H	Ares V	Delta IV H	Ares V
Nuclear Subsurface	937	8926	1	1
Nuclear Surface	469	4463	1	1
Standoff - Neutron	27	127	1	1
Standoff - Standard	7.3	36	1	1
Kinetic, 50 km/s, β=10	5.0	42	1	1
Kinetic, 10 km/s, β=1	0.1	0.8	**10**	**2**
Space Tug - Rotating	0.3	3.9	**4**	1
Gravity Tractor	0.0	0.2	**55**	**6**
Conventional Explosive	0.0	0.1	**145**	**16**

Performance Summary for Scenarios
Impulsive Techniques

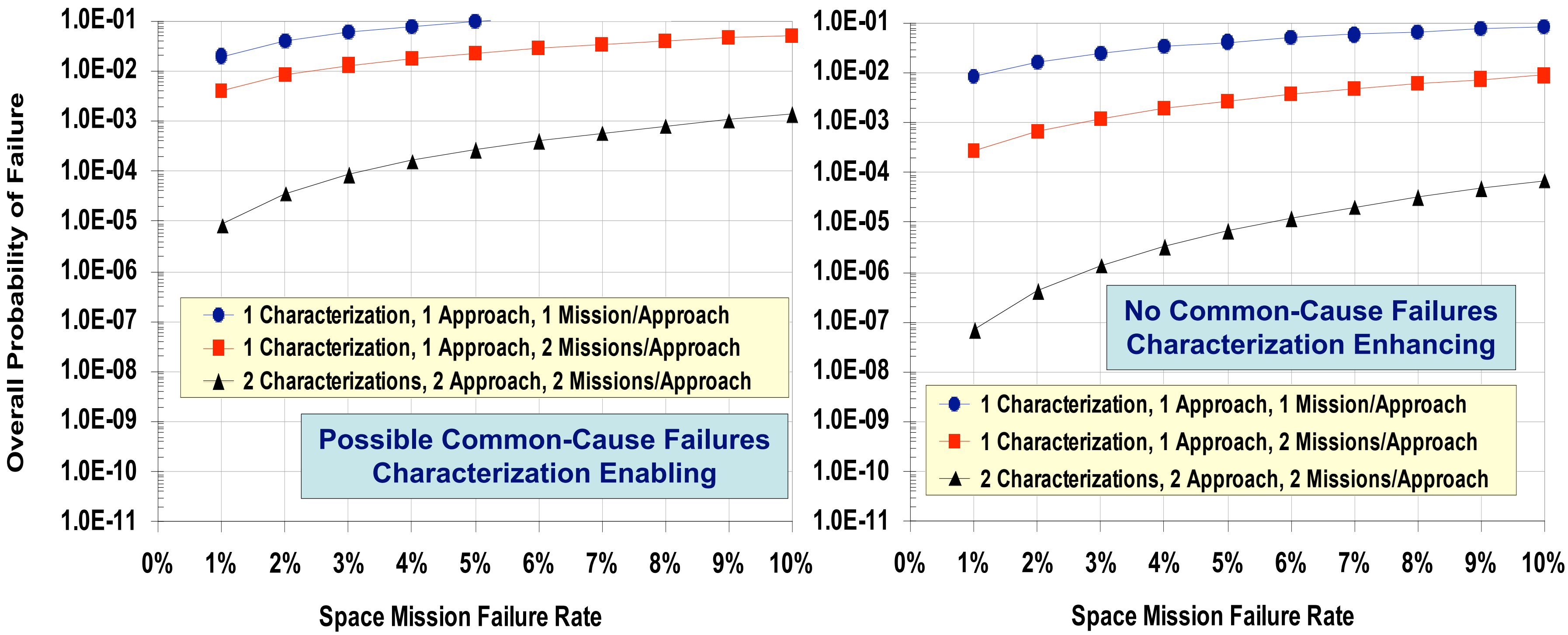


β=ejecta efficiency factor

Performance Summary for Scenarios
Slow Push Techniques

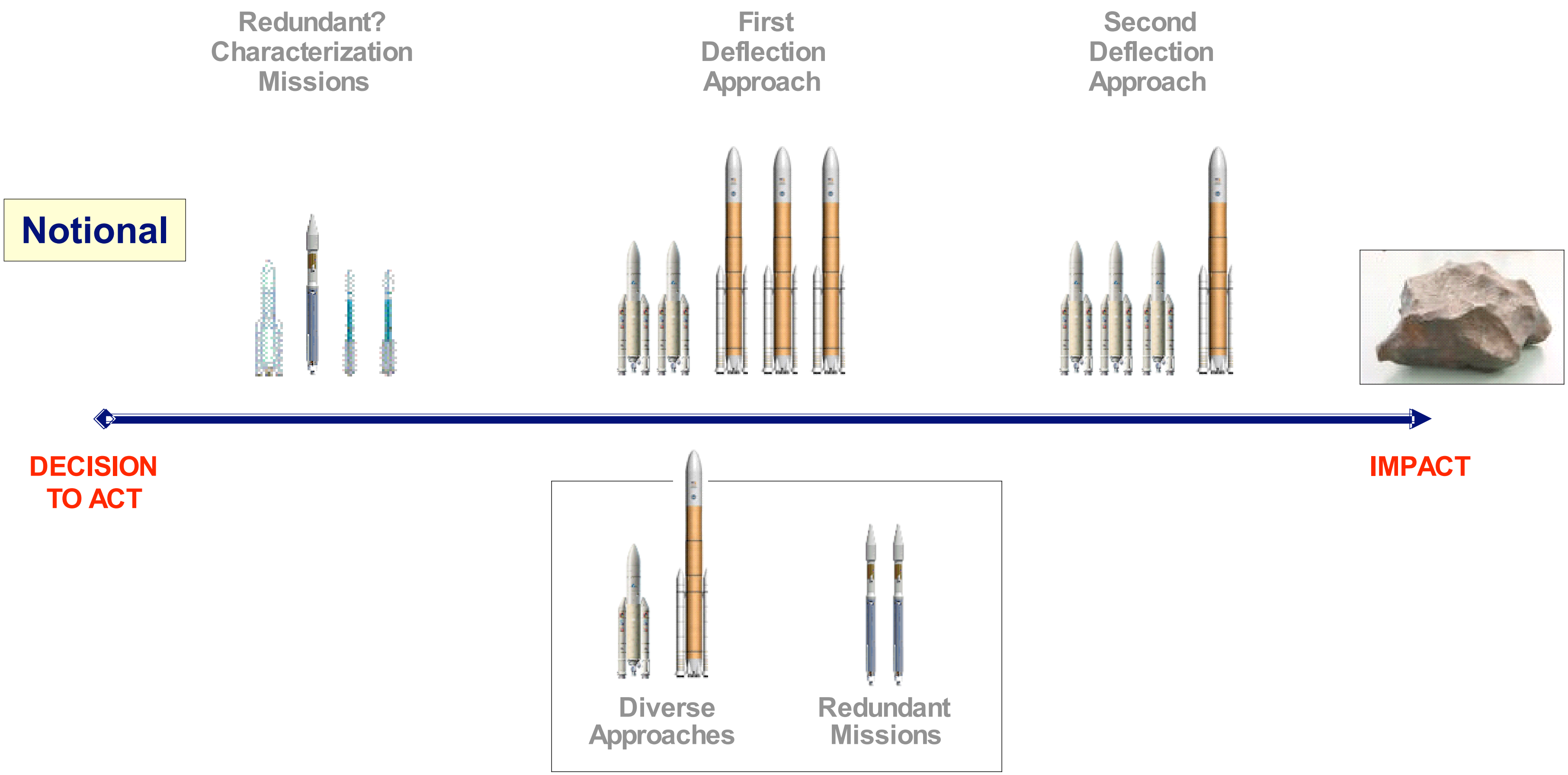


High Reliability of Deflection Campaigns are Difficult to Achieve



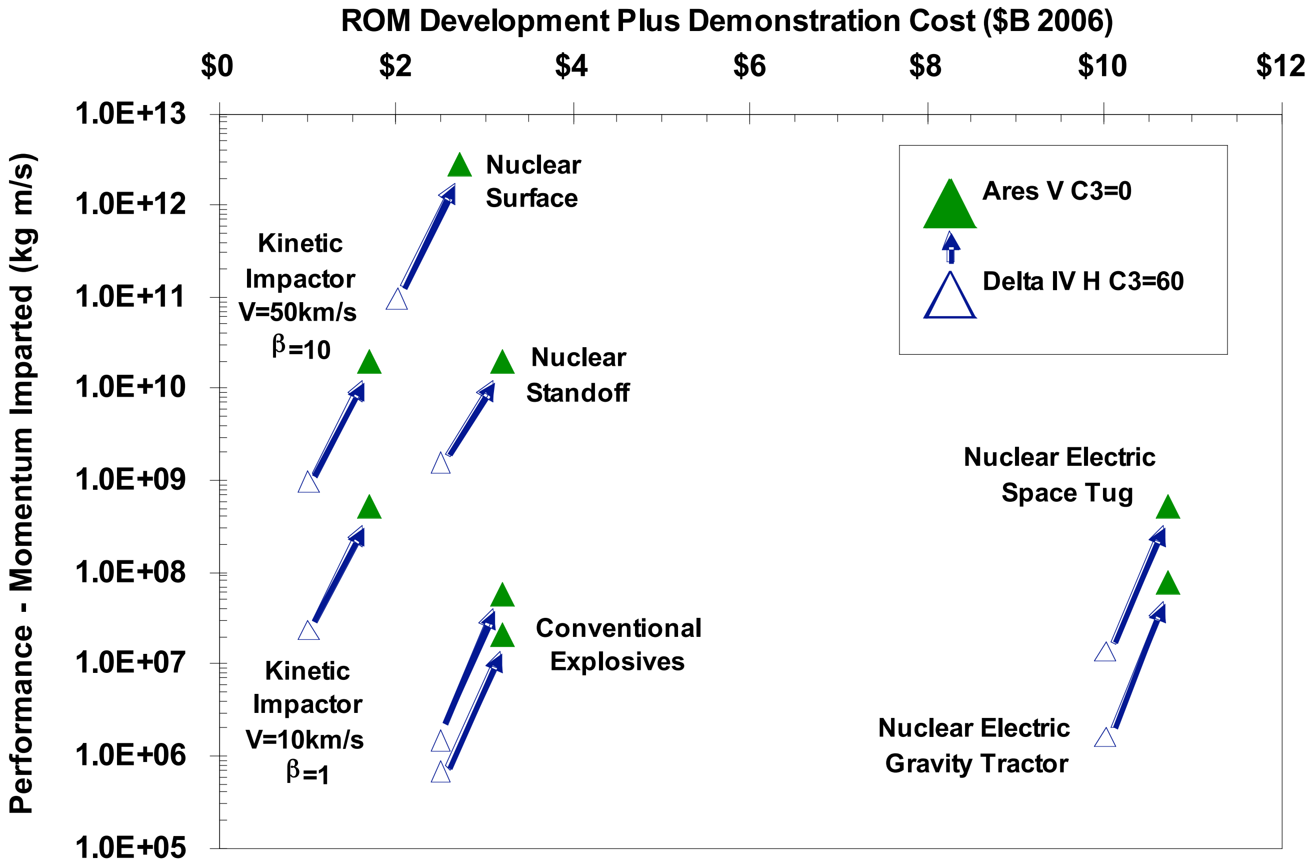
- Campaign reliability is directly tied to reducing impact probability
- Figures show campaign reliability of 1 failure in 1000
- If reducing the impact probability to 1-in-1 million is required, deflection alternatives may be more complicated and limited

Deflection Reliability Requires Diverse Approaches and Redundant Attempts



Mission Failures = Random Failures + Common Failures

Deflection Performance vs. Rough Order of Magnitude (ROM) Development Costs



- ROM Costs per mission are about half of the development costs
- Deflection campaigns may require multiple missions and approaches

Findings of the Deflection Analysis of Alternatives

- Nuclear standoff explosives are an effective mitigation option for many threat scenarios
- Kinetic impactors are the most mature approach and could be used in some scenarios
  - Especially for a single, small, solid mass
- Slow push techniques are the most expensive
  - Their ability to divert an object is very limited unless very long action times are assumed
- It is likely that several spacecraft, launch vehicles, launch sites, and design approaches will be required to ensure that the campaign is accomplished
- Long period comets are likely beyond the ability of launch systems to launch deflection missions in the time available