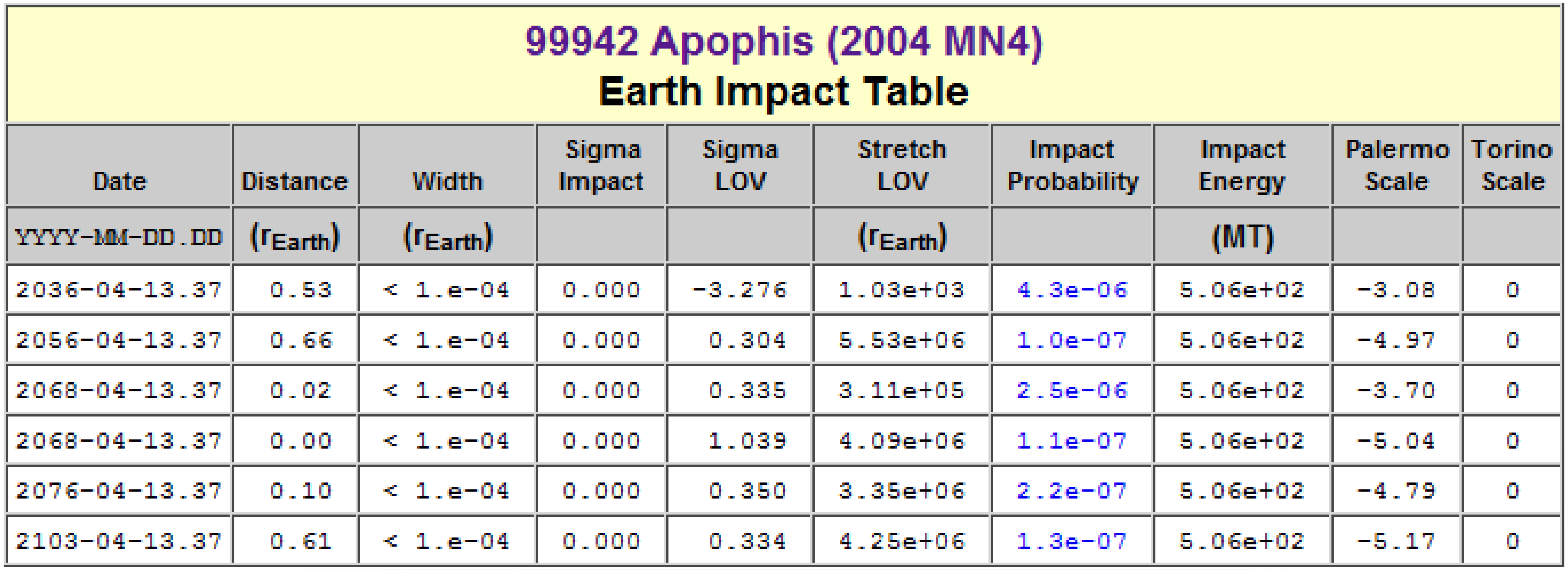
Systems of Systems

NEO – Near Earth Object
Datensammlung: Auftrag – Ziele - Wege

Asteroiden auf erdnahen Umlaufbahnen
Sommersemester 2012

Beispiel: 99942 Apophis (2004 MN4)



99942 Apophis (2004 MN4)
Earth Impact Table

Date	Distance	Width	Sigma Impact	Sigma LOV	Stretch LOV	Impact Probability	Impact Energy	Palermo Scale	Torino Scale
YYYY-MM-DD.DD	(r_{Earth})	(r_{Earth})			(r_{Earth})		(MT)		
2036-04-13.37	0.53	< 1.e-04	0.000	-3.276	1.03e+03	4.3e-06	5.06e+02	-3.08	0
2056-04-13.37	0.66	< 1.e-04	0.000	0.304	5.53e+06	1.0e-07	5.06e+02	-4.97	0
2068-04-13.37	0.02	< 1.e-04	0.000	0.335	3.11e+05	2.5e-06	5.06e+02	-3.70	0
2068-04-13.37	0.00	< 1.e-04	0.000	1.039	4.09e+06	1.1e-07	5.06e+02	-5.04	0
2076-04-13.37	0.10	< 1.e-04	0.000	0.350	3.35e+06	2.2e-07	5.06e+02	-4.79	0
2103-04-13.37	0.61	< 1.e-04	0.000	0.334	4.25e+06	1.3e-07	5.06e+02	-5.17	0

These results were computed on Oct 07, 2009

Summary Table Description

The Summary Table includes basic information about the hazard for this object. The maximum Torino and Palermo Scale values are listed, as well as the number of tabulated potential impacts and their corresponding cumulative Palermo Scale value and cumulative impact probability. The observation set used for the analysis is also listed. Certain parameter values depend upon the specific impact event in question, but they change little among the various table entries. For this reason we tabulate only mean values for these parameters:

$\mathbf{V_{impact}}$	Velocity at atmospheric entry.
$\mathbf{V_{infinity}}$	Relative velocity at atmospheric entry neglecting the acceleration caused by the Earth's gravity field, often called the hyperbolic excess velocity. ($V_{infinity}^2 = V_{impact}^2 - V_{escape}^2$, where V_{escape} = ~11.2 km/s is the Earth escape velocity.)
H	Absolute Magnitude, a measure of the intrinsic brightness of the object.

Summary Table Description

- **Diameter** This is an estimate based on the absolute magnitude, usually assuming a uniform spherical body with visual albedo p_V = 0.154 (in accordance with the Palermo Scale) but sometimes using actual measured values if these are available. Since the albedo is rarely measured, the diameter estimate should be considered only approximate, but in most cases will be accurate to within a factor of two.
- **Mass** This estimate assumes a uniform spherical body with the computed diameter and a mass density of 2.6 g/cm^3. The mass estimate is somewhat more rough than the diameter estimate, but generally will be accurate to within a factor of three.
- **Energy** The kinetic energy at impact: 0.5 * Mass * V_{impact}^2. Measured in Megatons of TNT.

Impact Table Legend

Impact Energy

The kinetic energy at impact, based upon the computed absolute magnitude and impact velocity for the particular case, and computed in accordance with the guidelines stated for the Palermo Technical Scale. Uncertainty in this value is dominated by mass uncertainty and the stated value will generally be good to within a factor of three.

Palermo Scale

The hazard rating according to the Palermo Technical Impact Hazard Scale, based on the tabulated impact date, impact probability and impact energy.

Impact Table Legend

Torino Scale

The hazard rating according to the Torino Impact Hazard Scale, based on the tabulated impact probability and impact energy. The Torino Scale is defined only for potential impacts less than 100 years in the future.

Analysis of Deflection Alternatives

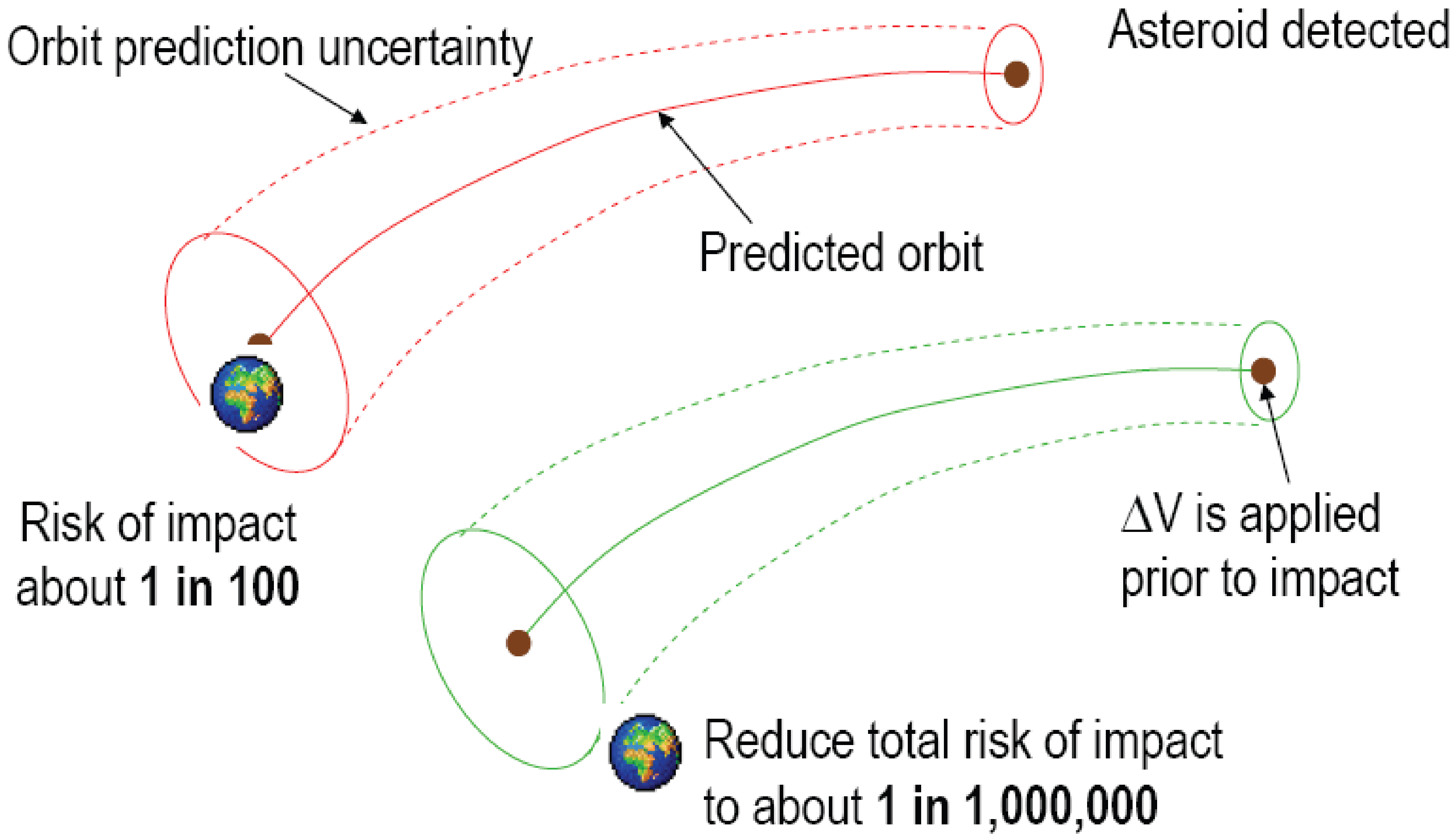
This study differentiates between mitigation in general and the congressional direction to study methods of diverting (or deflecting) an object.

1. Deflection Campaigns
2. Launch Energy and C3
3. Momentum Exchange Efficiency (beta, β)
4. Specific Impulse (Isp)

Derived Requirements

1. Derived Deflection Distance Requirement
2. Derived Reliability Requirement
3. Derived Characterization Requirements
    - To provide “warning“
    - To inform “mitigation“

Deflecting a Potentially Hazardous Object



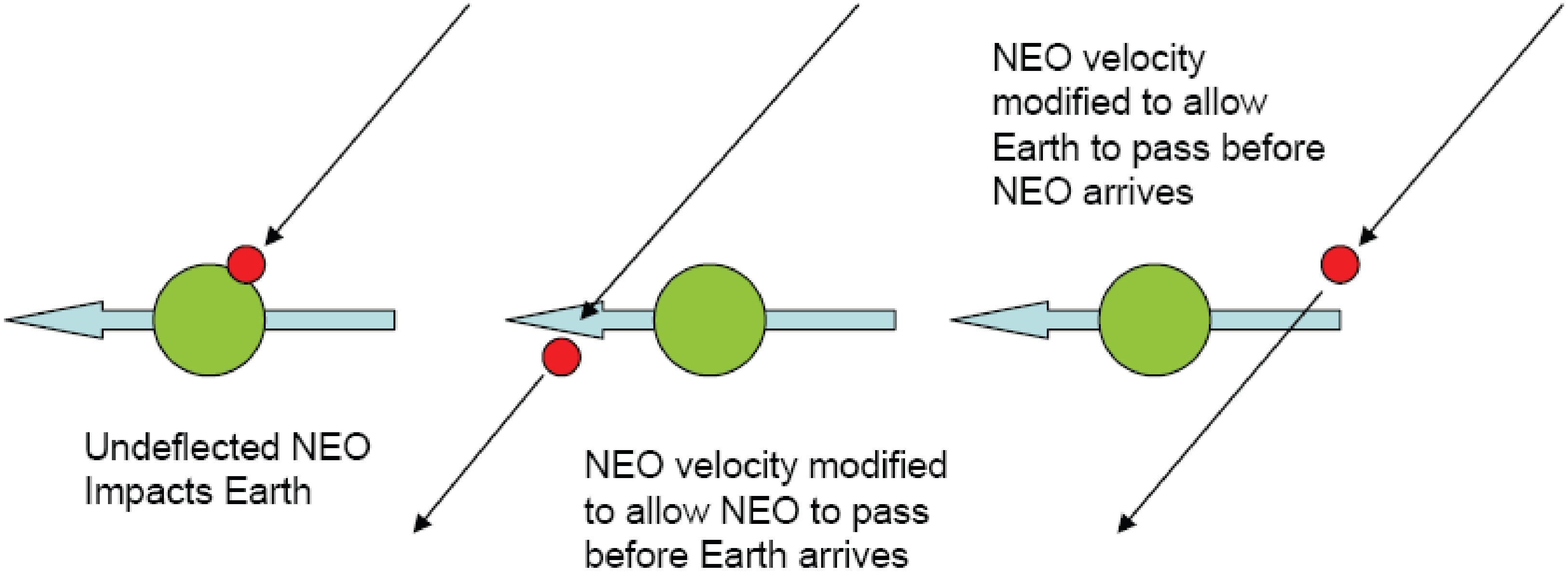


Figure 2. Illustration of PHO Deflection

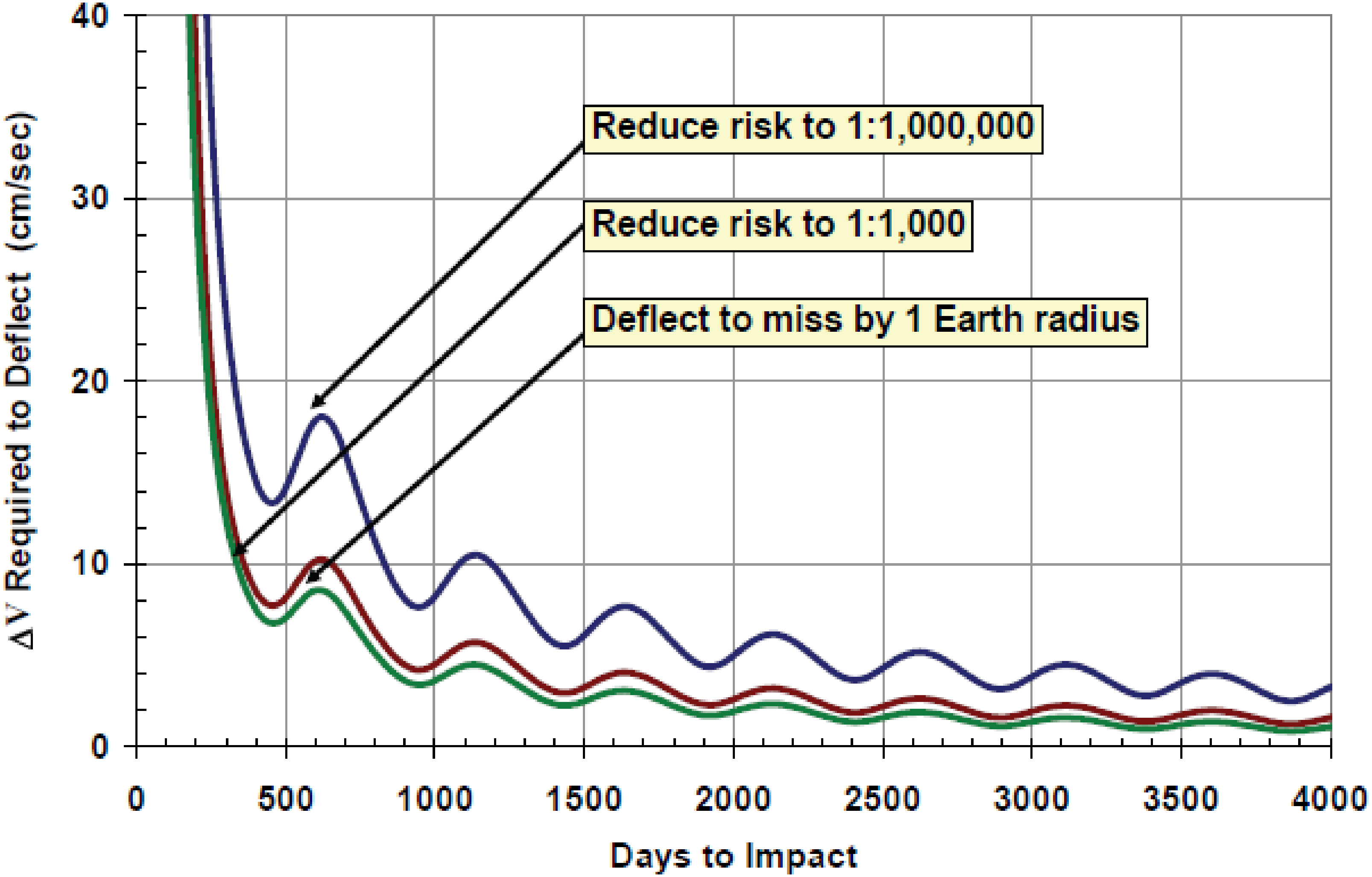
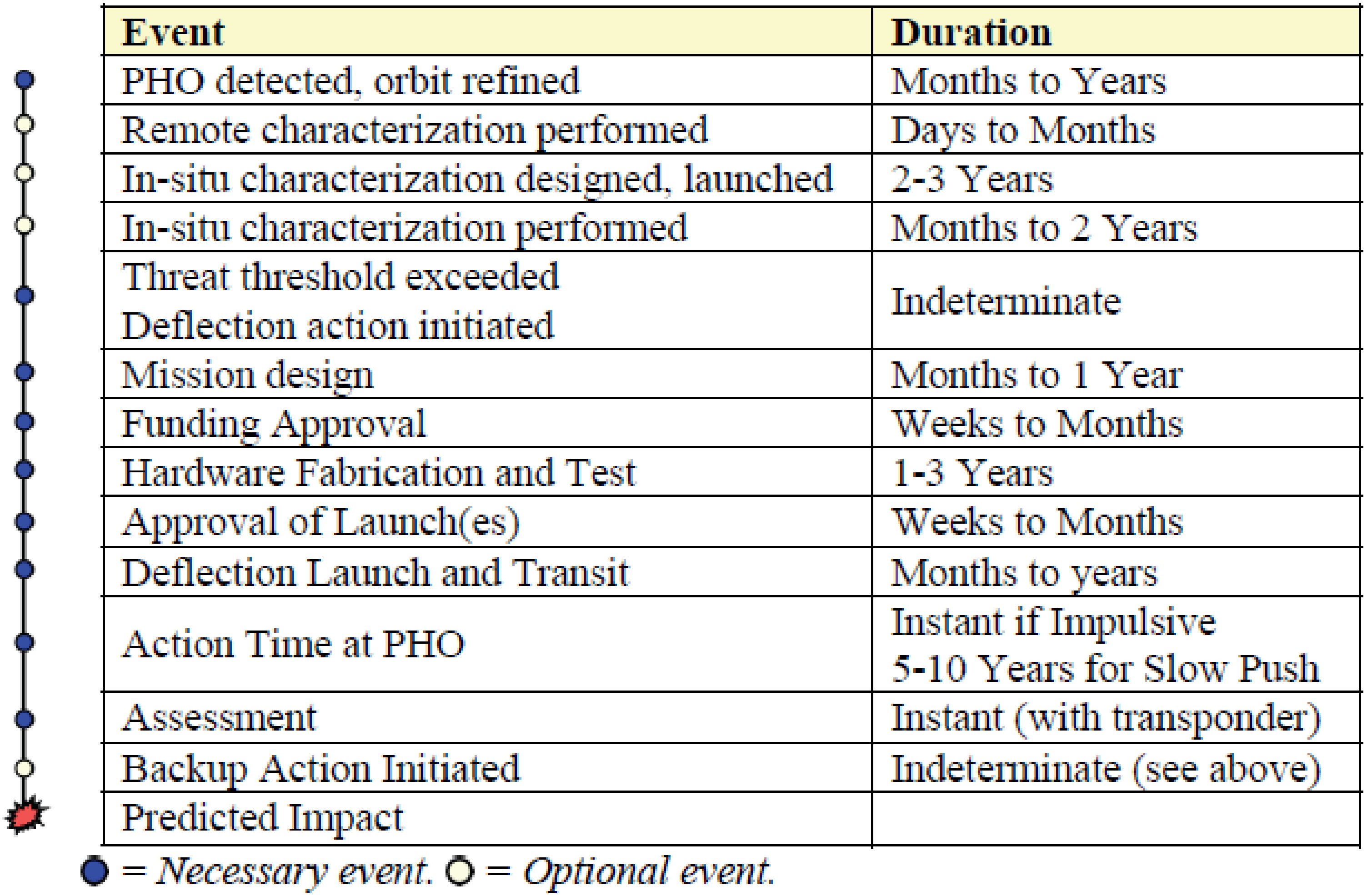


Figure 3. ΔV Required to Deflect a Hypothetical Asteroid



	Event	Duration
●	PHO detected, orbit refined	Months to Years
○	Remote characterization performed	Days to Months
○	In-situ characterization designed, launched	2-3 Years
○	In-situ characterization performed	Months to 2 Years
●	Threat threshold exceeded Deflection action initiated	Indeterminate
●	Mission design	Months to 1 Year
●	Funding Approval	Weeks to Months
●	Hardware Fabrication and Test	1-3 Years
●	Approval of Launch(es)	Weeks to Months
●	Deflection Launch and Transit	Months to years
●	Action Time at PHO	Instant if Impulsive 5-10 Years for Slow Push
●	Assessment	Instant (with transponder)
○	Backup Action Initiated	Indeterminate (see above)
✸	Predicted Impact	

● = *Necessary event.* ○ = *Optional event.*

Table 1. Potentially Hazardous Object Mission Timeline

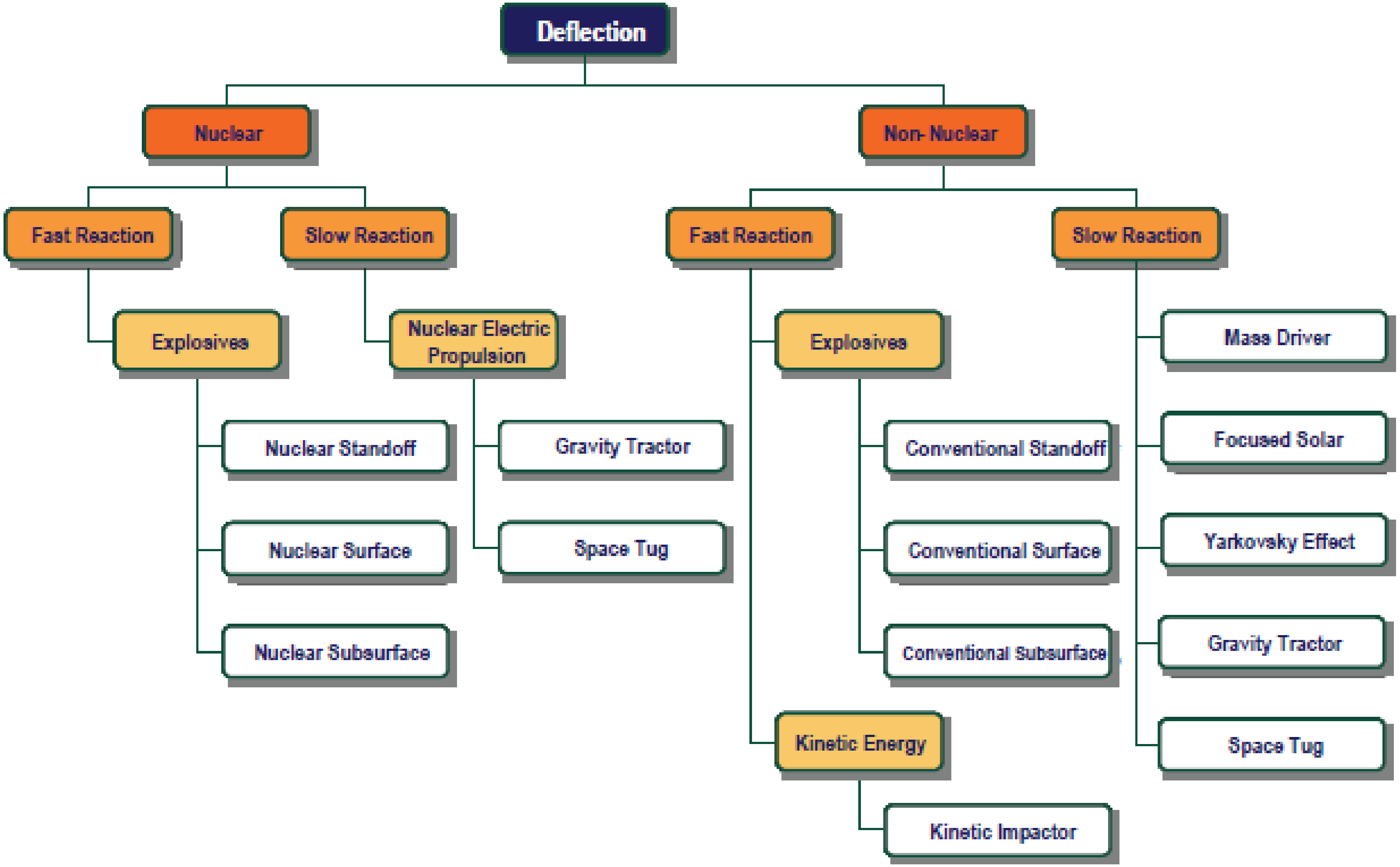
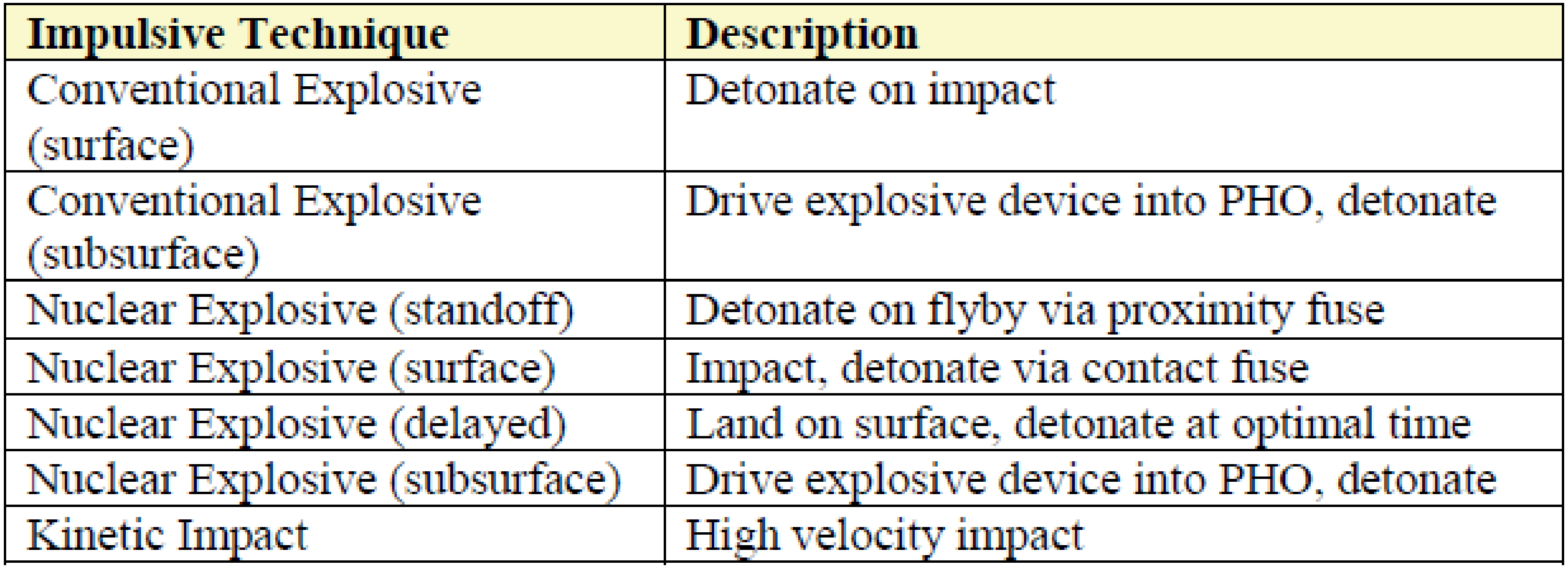


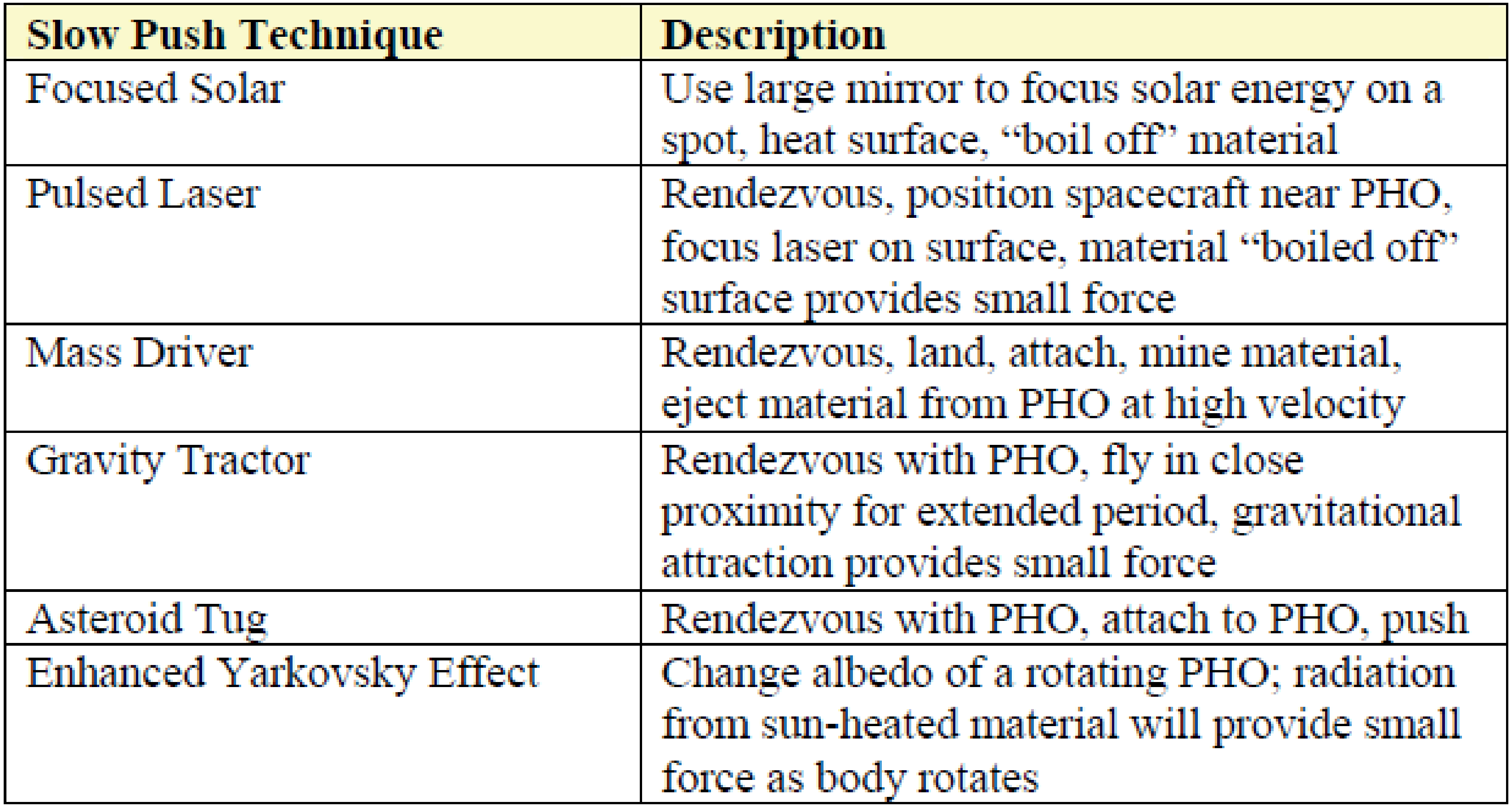
Figure 5. Deflection Alternatives Trade Tree

Deflection Alternatives Analyzed



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

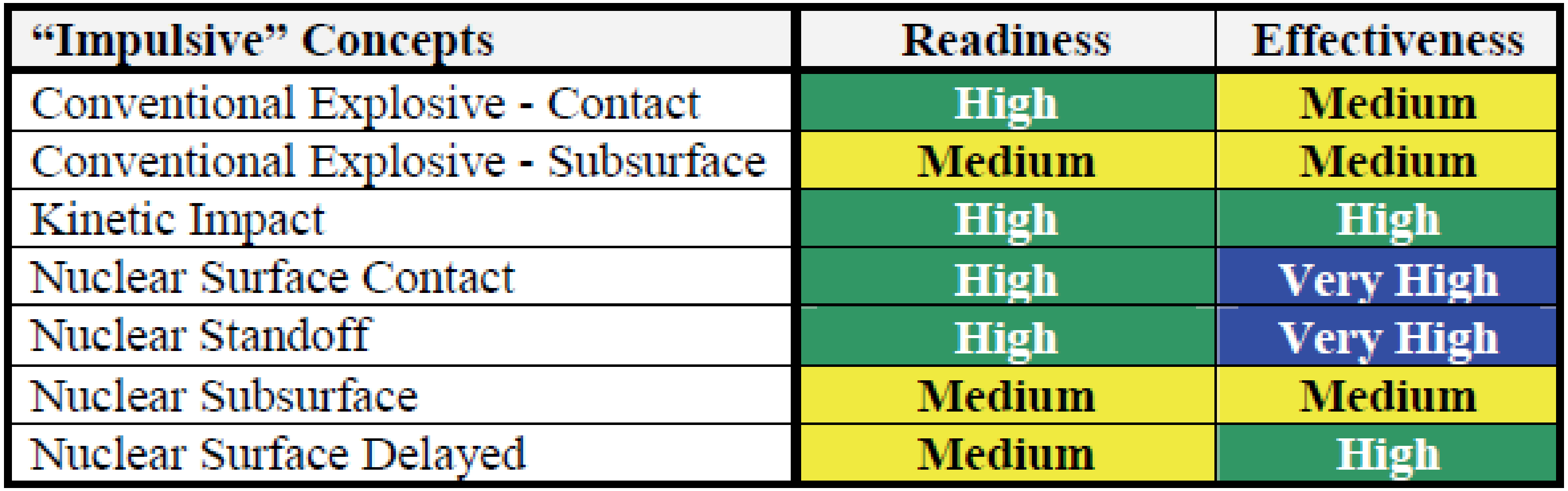
Table 2. Impulsive Deflection Alternatives Considered



Slow Push Technique	Description
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 small 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 to PHO, push
Enhanced Yarkovsky Effect	Change albedo of a rotating PHO; radiation from sun-heated material will provide small force as body rotates

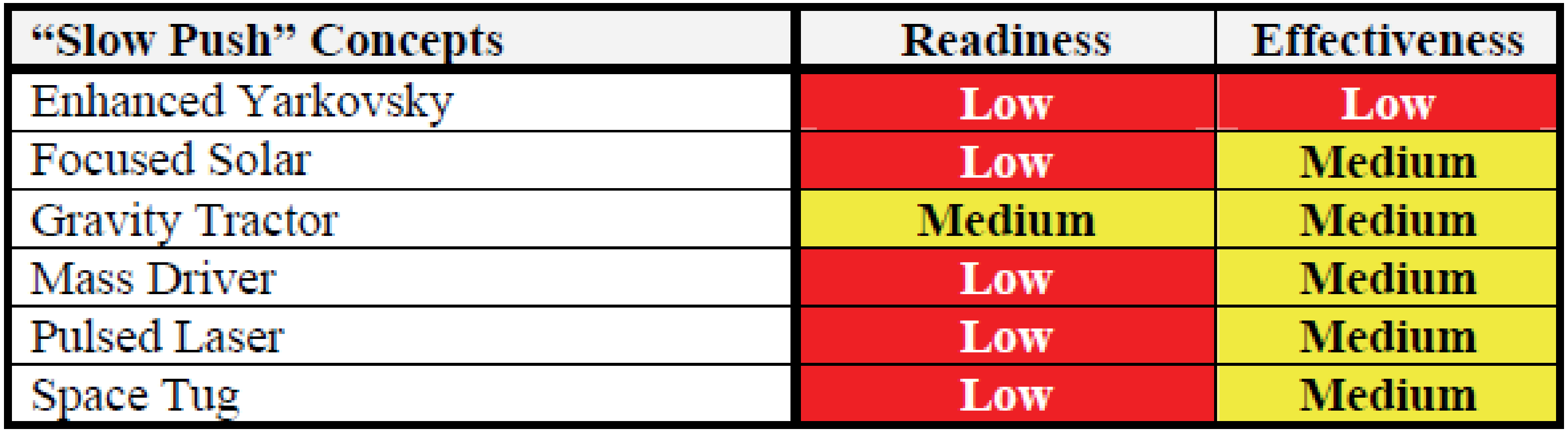
Table 3. Slow Push Deflection Alternatives Considered

Readiness and Effectiveness Summaries



“Impulsive” Concepts	Readiness	Effectiveness
Conventional Explosive - Contact	High	Medium
Conventional Explosive - Subsurface	Medium	Medium
Kinetic Impact	High	High
Nuclear Surface Contact	High	Very High
Nuclear Standoff	High	Very High
Nuclear Subsurface	Medium	Medium
Nuclear Surface Delayed	Medium	High

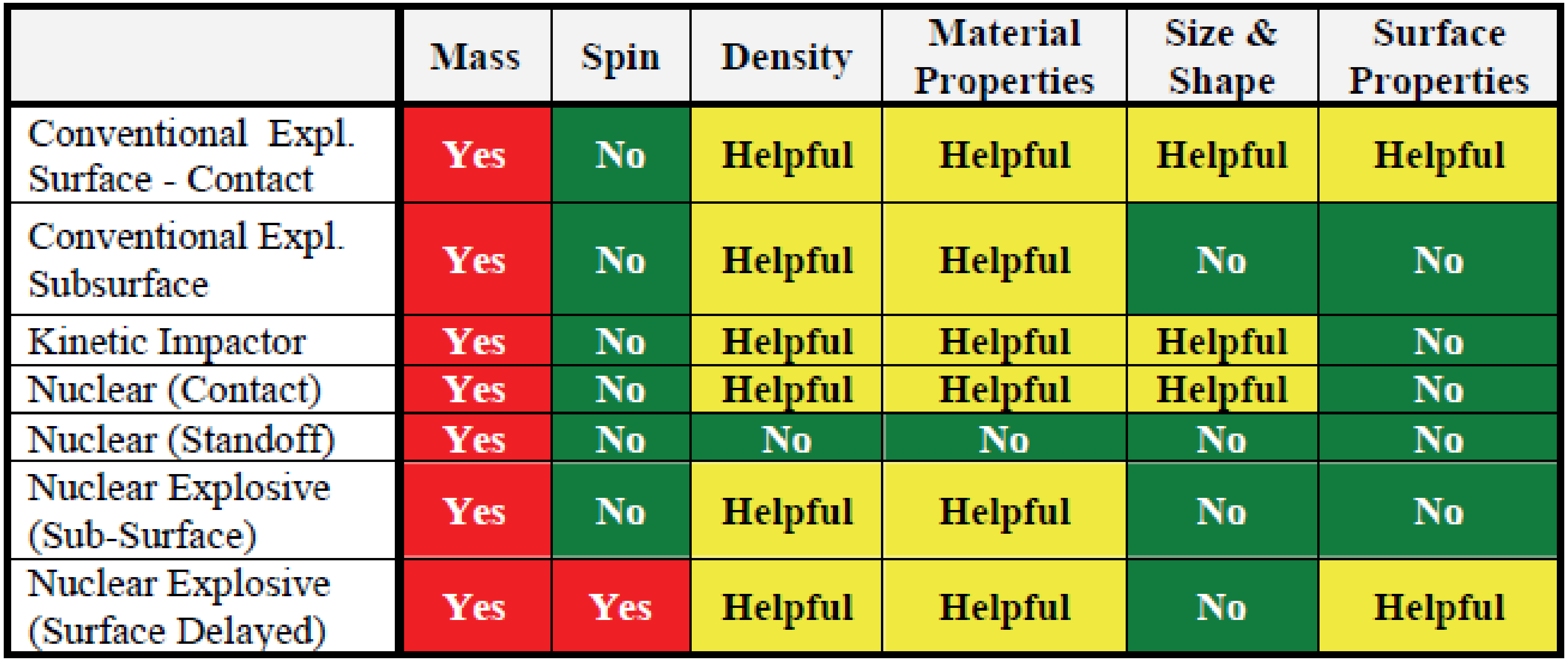
Table 4. Impulsive Alternatives Readiness and Effectiveness Summary



“Slow Push” Concepts	Readiness	Effectiveness
Enhanced Yarkovsky	Low	Low
Focused Solar	Low	Medium
Gravity Tractor	Medium	Medium
Mass Driver	Low	Medium
Pulsed Laser	Low	Medium
Space Tug	Low	Medium

Table 5. “Slow Push” Alternatives Readiness and Effectiveness Summary

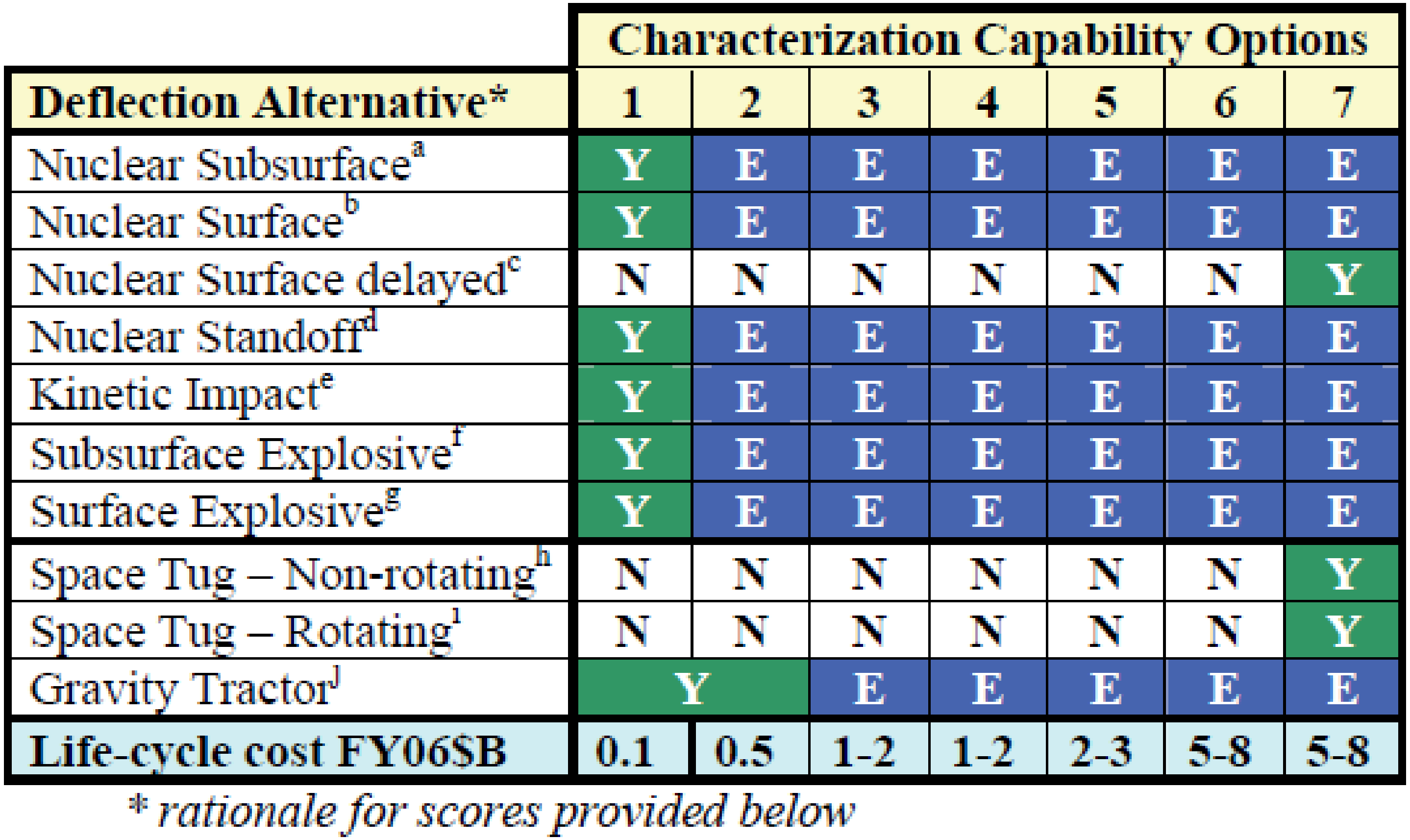
Linkage of Characterization and Mitigation



	Mass	Spin	Density	Material Properties	Size & Shape	Surface Properties
Conventional Expl. Surface - Contact	Yes	No	Helpful	Helpful	Helpful	Helpful
Conventional Expl. Subsurface	Yes	No	Helpful	Helpful	No	No
Kinetic Impactor	Yes	No	Helpful	Helpful	Helpful	No
Nuclear (Contact)	Yes	No	Helpful	Helpful	Helpful	No
Nuclear (Standoff)	Yes	No	No	No	No	No
Nuclear Explosive (Sub-Surface)	Yes	No	Helpful	Helpful	No	No
Nuclear Explosive (Surface Delayed)	Yes	Yes	Helpful	Helpful	No	Helpful

Table 6. Characterization Required for Impulsive Alternatives

Characterization Options Capabilities Matrix



	Characterization Capability Options						
Deflection Alternative*	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Nuclear Subsurface[a]	Y	E	E	E	E	E	E
Nuclear Surface[b]	Y	E	E	E	E	E	E
Nuclear Surface delayed[c]	N	N	N	N	N	N	Y
Nuclear Standoff[d]	Y	E	E	E	E	E	E
Kinetic Impact[e]	Y	E	E	E	E	E	E
Subsurface Explosive[f]	Y	E	E	E	E	E	E
Surface Explosive[g]	Y	E	E	E	E	E	E
Space Tug – Non-rotating[h]	N	N	N	N	N	N	Y
Space Tug – Rotating[i]	N	N	N	N	N	N	Y
Gravity Tractor[j]	Y		E	E	E	E	E
Life-cycle cost FY06$B	**0.1**	**0.5**	**1-2**	**1-2**	**2-3**	**5-8**	**5-8**

* *rationale for scores provided below*

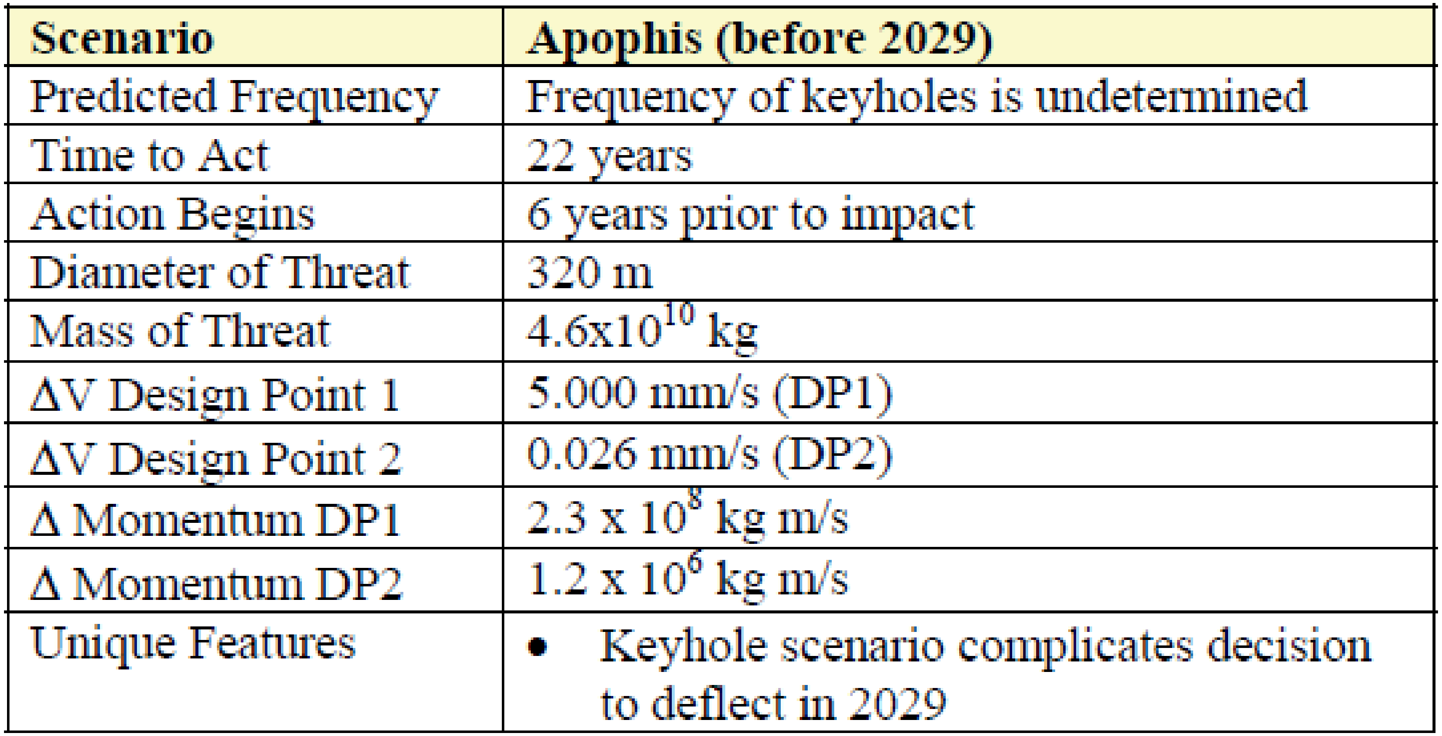
Table 8. Deflection Alternatives Enabled by Characterization Options

Scenario – Apophis (Deflect before 2029)

Asteroid 99942, also known as Apophis (2004 MN4), is estimated to be about 320 meters in diameter, with a mass of 4.6x1010 kg.

Uncertainty about its diameter is currently a factor of two, which means that the mass could vary by a factor of 16 (5.8x109 - 3.7x1011 kg). The equivalent impact energy is proportional to the mass.

Specific information on its shape and rotation are currently not available. Table 26 describes this scenario further.



Scenario	Apophis (before 2029)
Predicted Frequency	Frequency of keyholes is undetermined
Time to Act	22 years
Action Begins	6 years prior to impact
Diameter of Threat	320 m
Mass of Threat	4.6×10^{10} kg
ΔV Design Point 1	5.000 mm/s (DP1)
ΔV Design Point 2	0.026 mm/s (DP2)
Δ Momentum DP1	2.3×10^{8} kg m/s
Δ Momentum DP2	1.2×10^{6} kg m/s
Unique Features	• Keyhole scenario complicates decision to deflect in 2029

Table 10. Apophis before 2029 Scenario Description

Apophis is currently predicted to have a close approach to Earth in 2029, passing within 30,000 km, with a subsequent 2.2x10-5 probability of impact on April 13, 2036. The probability of impact in 2036 will be strongly influenced by the precise location of the close approach in 2029. If it should pass within a 600-meter-wide “keyhole” in 2029 (see Section 5.2.3), the likelihood of impact in 2036 will be much higher. [32]

One approach for avoiding a threat in 2036 is to deflect Apophis so that it is guaranteed to miss the keyhole in 2029. An advantage of this approach is that the asteroid requires only a very relatively small change in the velocity to miss the keyhole, as shown in Figure 45. Assuming optical and radar observations are taken in 2013, 2020, and 2021, it is anticipated that one could achieve a tracking accuracy of 5 km. [16]

To take advantage of either opportunity, acquisition of a deflection system must be started years in advance to account for vehicle development and transit time to the asteroid. Consequently, such a program may need to begin with incomplete information.

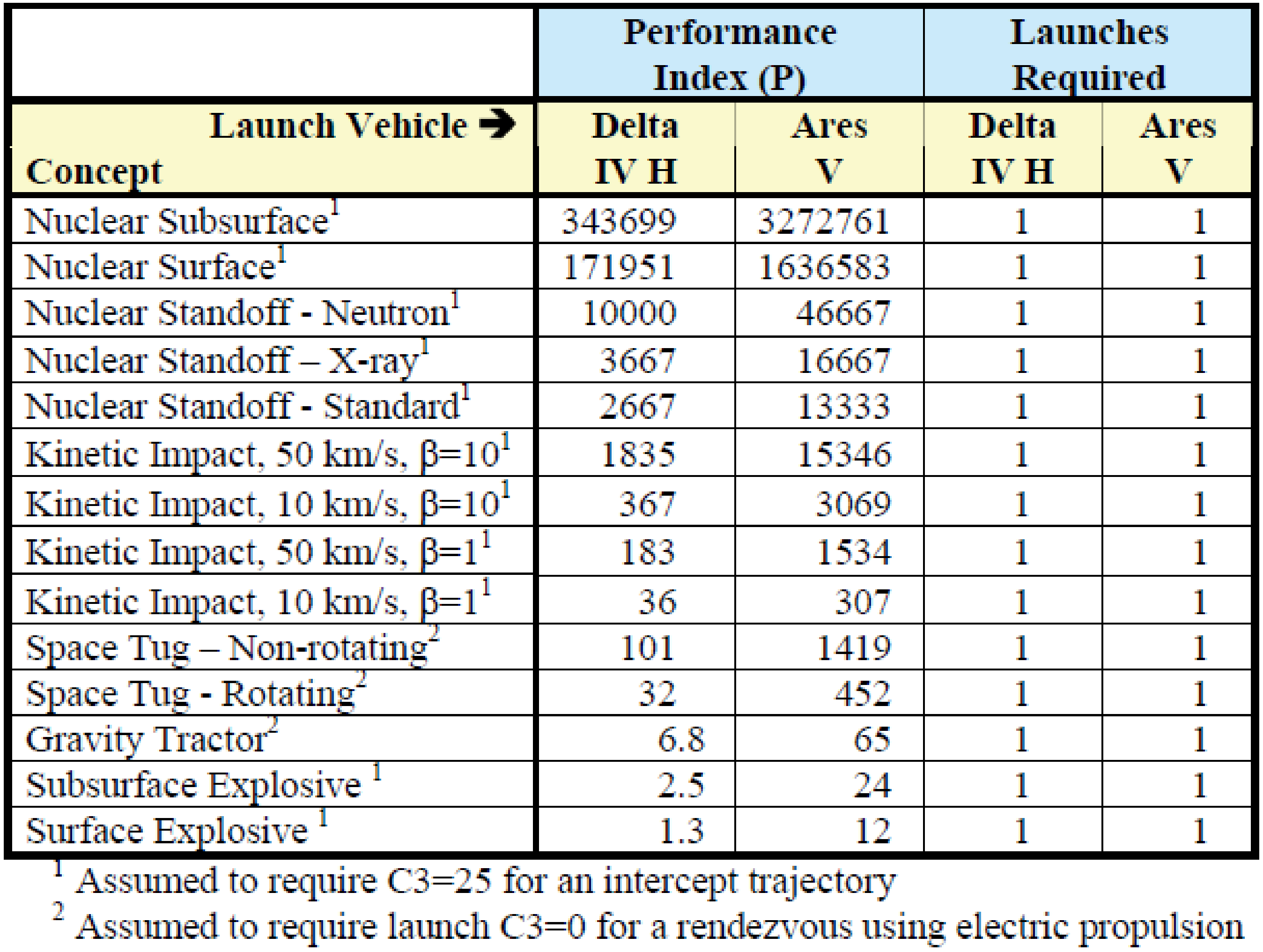
An in-situ characterization mission may provide better tracking accuracy early on, allowing for a less costly deflection mission or elimination of the threat entirely. Figure 10 shows that the ΔV grows substantially as the time to close approach decreases, which is typical of deflection scenarios.

An on-board propulsion system that can produce a change in velocity of 1 km/s is necessary to accomplish an impact with the asteroid. Assuming a liquid propulsion system with a specific impulse of 325 seconds, an estimated 1900 kg of fuel will be required, leaving a vehicle dry mass of 5200 kg.

Of the vehicle dry mass, roughly 57% of the vehicle will consist of structures and navigational systems, leaving a possible payload mass of 2,200 kg. Reference [32] designed a similar mission and proposed that an observer spacecraft be used as a second deflector; however, this would require additional launch capability.

A performance index (P)

$$P = \frac{M_{delivered}}{M_{required}}$$

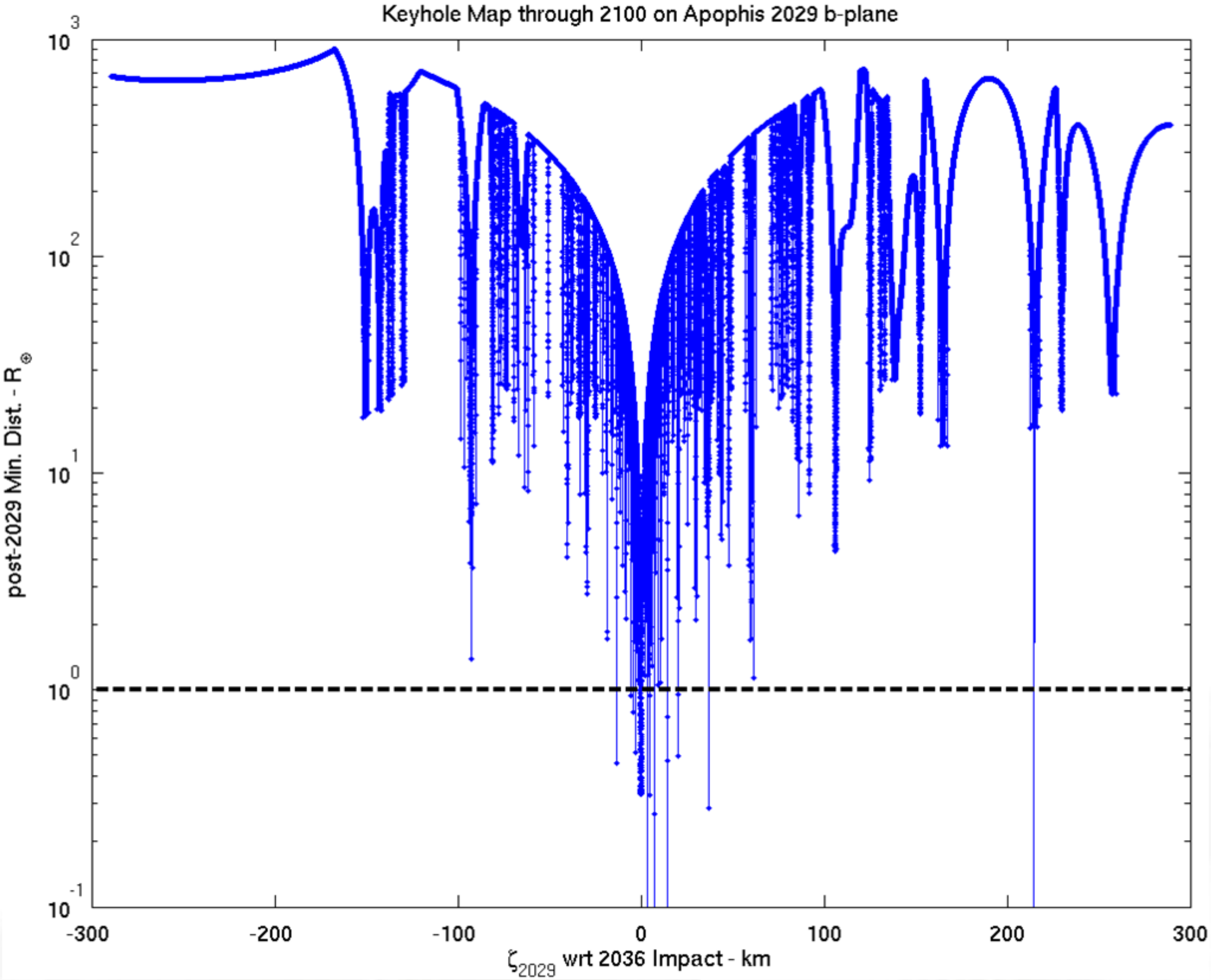


	Performance Index (P)		Launches Required	
Launch Vehicle → **Concept**	**Delta IV H**	**Ares V**	**Delta IV H**	**Ares V**
Nuclear Subsurface[1]	343699	3272761	1	1
Nuclear Surface[1]	171951	1636583	1	1
Nuclear Standoff - Neutron[1]	10000	46667	1	1
Nuclear Standoff – X-ray[1]	3667	16667	1	1
Nuclear Standoff - Standard[1]	2667	13333	1	1
Kinetic Impact, 50 km/s, $\beta=10$[1]	1835	15346	1	1
Kinetic Impact, 10 km/s, $\beta=10$[1]	367	3069	1	1
Kinetic Impact, 50 km/s, $\beta=1$[1]	183	1534	1	1
Kinetic Impact, 10 km/s, $\beta=1$[1]	36	307	1	1
Space Tug – Non-rotating[2]	101	1419	1	1
Space Tug - Rotating[2]	32	452	1	1
Gravity Tractor[2]	6.8	65	1	1
Subsurface Explosive [1]	2.5	24	1	1
Surface Explosive [1]	1.3	12	1	1

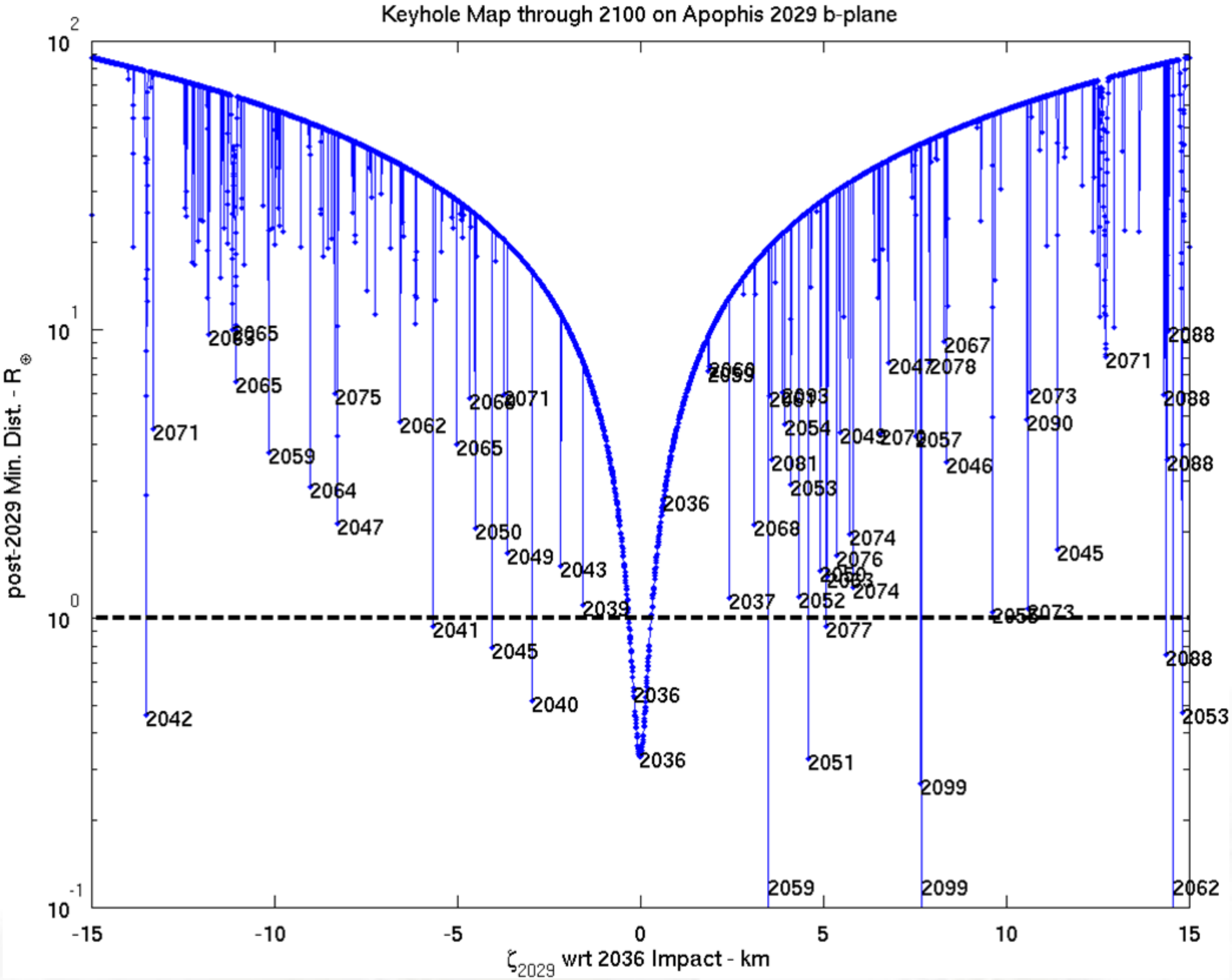
[1] Assumed to require C3=25 for an intercept trajectory

[2] Assumed to require launch C3=0 for a rendezvous using electric propulsion

Table 11. Apophis Keyhole – Deflection Performance Design Point 2



Keyhole map for a 600-km segment of the Apophis uncertainty region in the 2029 b-plane



Close-up of the keyhole map for Apophis around the 2036 keyhole.

Summary of key points

- By far the most important requirement of a successful mitigation campaign is a warning time sufficient to carry out the mitigation mission. As a result, the most important aspect of mitigation is finding the hazardous objects many years in advance.

- Some primary impulsive deflection techniques (e.g., the kinetic energy impactor) provide relatively uncertain amounts of deflection (e.g., the momentum multiplier β is poorly known).

- An effective mitigation campaign not only needs to deflect an Earth threatening asteroid from the predicted Earth impact but it must also ensure that the deflection does not place the asteroid into a so-called keyhole which would lead to a secondary impact some years later.

Summary of key points

- A pre-impact close approach usually multiplies the effect of an earlier deflection. It is usually preferable to perform a deflection prior to this close approach to take advantage of the leverage it provides. At the same time, however, the pre-impact close approach usually magnifies orbit uncertainties, making it more difficult to verify or rule out the impact.
- Although the Apophis case considered in this study is quite unusual because of its extreme close Earth approach only 7 years before impact many potential impactors will have at least moderately close pre-impact close approaches within 50 years of impact. We estimate that up to 4% of the impactors will have pre-impact keyholes with widths narrower than 15 km.
- Asteroid close approach trajectories and their associated uncertainties are best analyzed when projected into the b-plane. In the b-plane of the impact encounter, the overlap of the uncertainty region with the circle representing the capture cross-section of the Earth determines the impact probability.

Summary of key points

- If the asteroid has a pre-impact close approach, the asteroid trajectory and associated uncertainties should be analyzed in the b-plane of this pre-impact encounter. An analysis of the location of keyholes in this b-plane would be an important part of any deflection strategy. Secondary keyholes around the primaries should also be considered.

- For the Apophis case considered in this study, the deflection to avoid impact in 2036 can be thought of as deflection out of a keyhole in the 2029 b-plane, which is approximately 610 meters wide. We have formed a detailed map of the secondary resonances and keyholes around the 2036 keyhole in the 2029 b-plane, and found over a dozen secondary keyholes with widths ranging from a few meters down to a few centimeters.

Summary of key points

- A useful tool that should be used in establishing a deflection strategy is the risk corridor across the surface of the Earth. The geopolitical implications of an aborted or failed deflection attempt must be considered.
- We have performed a preliminary design for a viable Apophis rendezvous mission which could be launched in mid-April 2021 and arrive at Apophis in early January 2022 with only a moderate arrival delta-V.
- The combination of ground-based radiometric tracking of an orbiting or hovering spacecraft, combined with optical imaging of the asteroid from the spacecraft, is sufficient to improve the knowledge of the asteroid's orbit to the sub-kilometer level, enough to discern whether or not the asteroid is truly threatening. It is not necessary to place a transponder on the surface of the asteroid to acquire this high precision tracking.

Summary of key points

- The amount of time it takes to realize these dramatic improvements in the knowledge of the asteroid’s orbit ranges from a few days to a couple months. A spacecraft need not be in place for years for these improvements to take place.

- We have outlined a design for a rendezvous spacecraft which could operate as a gravity tractor should a deflection be found necessary. The 1000-lb spacecraft would carry 5 throttle-able fixed-direction SEP thrusters, and would hover over Apophis at a distance some 50 meters greater than the asteroid’s maximum dimension.

- We have analyzed the performance of this gravity tractor mission and determined that it could deflect Apophis out of the 2036 keyhole after only two months of operation, assuming towing started in 2022. Larger deflections are obtainable for reasonable mission durations.

Summary of key points

- An important advantage of the gravity tractor deflection method is that it is a high-precision procedure. The asteroid trajectory would be very accurately known throughout the entire process, and the progress of the deflection could be closely monitored.

- In other scenarios which use much more energetic deflections (such as the kinetic energy deflection method), a gravity tractor spacecraft would still be useful, both for determining the magnitude of the primary deflection and for providing an asteroidal trim maneuver in the event the primary deflection maneuver was unsuccessful or the asteroid was headed for a keyhole.

- Each potential Earth impact is a unique scenario that may require a tailor-made mitigation response.