Evaluating the Effectiveness of Different NEO Mitigation Options

Mark G. Schaffer[*], A.C. Charania[†], and John R. Olds[‡]
SpaceWorks Engineering, Inc. (SEI), Atlanta, Georgia, 30338

Several competing techniques have been proposed for deflecting NEOs (Near Earth Objects) on potential collision courses with Earth. This paper summarizes recent efforts to develop the NOMAD (NEO Objective Mitigation Analysis Decider) process as a method to compare different NEO mitigation options. NOMAD is the combination of two previously developed processes, ROSETTA (Reduced-Order Simulation for Evaluation of Technologies and Transportation Architectures) modeling and TOPSIS (Technique for Order Preference by Similarity to Ideal Solution). ROSETTA modeling is used to simulate each mitigation option from technology development through mission completion based on consistent methodologies and common analysis assumptions. The ROSETTA model generates values for in-space stage and mitigation vehicle masses, development and deployment costs, and momentum imparted to the NEO. These results are then used by TOPSIS to rank the different mitigation options with six figures of merit: effectiveness, applicability, technology readiness, research and development degree of difficulty, development cost, and deployment cost. Multiple weighting scenarios between these figures of merit are considered to display the flexibility of this ranking system based on different decision-making priorities. In this study, six mitigation options are evaluated against three different NEO test cases. The results of these evaluations are presented with four TOPSIS weighting scenarios.

Nomenclature

a = Orbit Semi-major Axis
C_3 = Square of the Residual Velocity at the Sphere of Influence (km^2/s^2)
D = NEO Diameter
DDT&E = Design, Development, Test, and Evaluation
e = Orbit Eccentricity
FOM = Figure of Merit
G = Gravitational Constant (6.6742 x 10^{-11} N-m^2/kg^2)
g_o = Gravitational Acceleration at Earth's Surface (9.807 m/s^2)
h = Height Above NEO Surface
i = Orbit Inclination with respect to the Ecliptic Plane
Isp = Rocket Engine Specific Impulse
JAT = Java Astrodynamics Toolkit
LCC = Life Cycle Cost
LEO = Low Earth Orbit
m = Spacecraft Mass
M = NEO Mass
m_f = Final Mass after Rocket Burn
m_L = Rocket Delivered Payload Mass
m_o = Initial Mass before Rocket Burn
m_p = Rocket Propellant Mass
m_s = Rocket Structural Mass
MADMEN = Modular Asteroid Deflection Mission Ejector Node

---

[*] Project Engineer, 1200 Ashwood Parkway, Suite 506, Member AIAA.
[†] Senior Futurist, 1200 Ashwood Parkway, Suite 506, Member AIAA.
[‡] Principal Engineer and CEO, 1200 Ashwood Parkway, Suite 506, Associate Fellow AIAA.

NASA = National Aeronautics and Space Administration
NEO = Near Earth Object
NOMAD = NEO Objective Multiple Analysis Decider
OEC = Overall Evaluation Criterion
p = Momentum Imparted to NEO
r = NEO Radius
RCS = Reaction Control System
$R\&D^3$ = Research and Development Degree of Difficulty
ROSETTA = Reduced-Order Simulation for Evaluation of Technologies and Transportation Architectures
TFU = Theoretical First Unit
TOPSIS = Technique for Order Preference by Similarity to Ideal Solution
TRL = Technology Readiness Level
β = Impactor momentum amplification factor (resultant momentum/incoming momentum)
ΔV = Delta-Velocity (m/s)
ε = Structural Coefficient
μ_{sun} = Gravitational Parameter of the Sun ($1.327\text{x}10^{13}$ km^3/s^2)
ρ = Magnitude of Position Vector in Heliocentric Orbit

I. Introduction

Given the knowledge that asteroids and comets have the potential to impact the Earth and cause widespread damage, researchers are proposing various mitigation techniques that might be used to alter the course of such objects and thus prevent impact. Several mitigation options have been proposed[1,2]. Some of these options include the following:

- Nuclear Detonation (standoff or surface/subsurface)
- Kinetic Impactor
- Gravity Tractor
- Mass Driver
- Propulsive Tug
- Focused or Pulsed Laser Ablation of Surface Material
- Enhanced Yarkovsky Effect (albedo changing approaches)

NEO mitigation techniques vary both in their approach and requirements. Because each technique is often promoted by a different advocate, they are generally presented with differing initial conditions and mission parameters, making direct comparisons between them difficult.

While direct comparison of the effect of these mitigation options can be made by determining the momentum imparted by each option on a target NEO based on similar initial conditions and mission parameters, there are other metrics that need to be considered for mission and technology development planning. Applicability to the composition and rotation properties of the NEO, technological readiness, degree of development difficulty, development cost, and deployment cost are important additional factors that should be included in any planetary defense evaluation process.

Several studies have been released in recent years comparing different NEO mitigation options. R.B. Adams et al. at the NASA Marshall Space Flight Center proposed a method for comparing different mitigation techniques that included parametric sizing, multidisciplinary analyses, and complete mission modeling[2]. While results for individual mitigation options were generated, no analytical method was used to compare and rank the different options. G. Rogers and N. Izenberg at Johns Hopkins University compared the efficiency of various NEO mitigation options based on the momentum imparted but did not consider any other ranking criteria[3].

More recently, Colombo et al. at the University of Glasgow in the United Kingdom performed multi-criteria analysis of potential mitigation options sized over a varied trade space of initial masses and warning times using the dominance method[4]. Their analyses, however, only considered change in minimum orbit intersection distance and technology readiness as ranking criteria.

To fairly compare a wide range of proposed NEO mitigation options, an analysis must use a consistent methodology and common analysis assumptions to accurately model these techniques and consider a set of multidisciplinary metrics in the comparison and ranking of the different options being considered.

II. Objective

The decision-maker selecting the best mitigation option for use against a potential NEO impactor has both knowledge of each option and a desired outcome. This knowledge may come from engineering experience and computational modeling of those options. The desired outcome may be quantified by criteria such as effectiveness, cost, applicability, etc. The objective of the development effort described here is to create a useful process for decision-makers that utilizes the capabilities of computational modeling and expert judgment to determine the optimum NEO mitigation technique for a given scenario.

In order to illustrate the capabilities of this process, three sample case studies are presented in this study. The first, Apophis, is an actual near-Earth asteroid that has close approaches to Earth in 2029 and 2036[5]. The second and third, D'Artagnan and Athos, are fictional asteroids developed by Lynch and Peterson for the 2004 Planetary Defense Conference as planning scenarios for mitigation options[6]. The physical and orbital characteristics of these test case bodies are shown in Tables 1 and 2.

Table 1. NEO Test Cases Physical Characteristics[6,7,8].

Name	Mass (kg)	Diameter (m)	Type	Composition	Rotation Period (hrs)
Apophis	2.1E+10	250	Unknown	Unknown	30.5
D'Artagnan	2.7E+09	130	Monolith	Silicaceous	0.32
Athos	1.1E+10	200	Rubble-Pile	Silicaceous	3.3

Table 2. NEO Test Cases Orbital Characteristics[6,7,8].

Name	Semi-major Axis (AU)	Eccentricity	Inclination (deg)	Date of Discovery	Date of Impact
Apophis	0.92	0.19	3.3	6/19/2004	4/13/2036
D'Artagnan	0.90	0.29	4.8	2/22/2007	9/14/2012
Athos	0.79	0.19	5.1	2/22/2008	3/1/2019

III. Process Overview

The process developed to help prioritize various NEO mitigation techniques is referred to as the NEO Objective Mitigation Analysis Decider (NOMAD). NOMAD is a process conceptualized and developed by the authors at SpaceWorks Engineering, Inc. (SEI). It is based in part upon previous processes that deal with the prioritization of candidate technologies for advanced aerospace applications also utilized at SEI[9,10,11].

A. Overview

NOMAD consists of two parts, a Reduced-Order Simulation for Evaluation of Technologies and Transportation Architectures (ROSETTA) model[9], and a Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) evaluation model[12].

The computational core of the process is a ROSETTA model. This core model quantitatively determines various Figures of Merit (FOMs) including effectiveness, development cost, and deployment cost. Effectiveness is a direct measure of the momentum imparted to the NEO by the mitigation technique. Development cost includes the cost of maturing any necessary technologies, design, development, test, and evaluation (DDT&E) costs, and facilities construction and development costs. Deployment costs cover the procurement and operations costs including spacecraft acquisition, mission operations and management, and launch costs.

In addition to this analytical core, NOMAD accommodates various inputs for qualitative parameters such as applicability, Research and Development Degree of Difficulty (R&D^3), and Technology Readiness Level (TRL). Applicability qualifies the ability of different mitigation options to handle various NEO properties, including composition, type, and rotation. R&D^3 is a measure of the level of difficulty in developing a particular mitigation option considered on a 1-5 scale where 1 represents little to no difficulty and 5 represents extreme difficulty[13]. Finally, TRL is a measure of the current level of maturation of a technology, ranging on a scale from 1-9, where a new technology whose basic principles have been observed and reported has a TRL rating of 1, and a completely mature technology that has been proven in successful mission operations has a TRL rating of 9[14].

TOPSIS is then used with these different FOMs to determine rankings for the different mitigation options. Each FOM is subject to a weight multiplier based on the weighting scenario being considered. A diagram of the NOMAD process flow is shown in Figure 1.

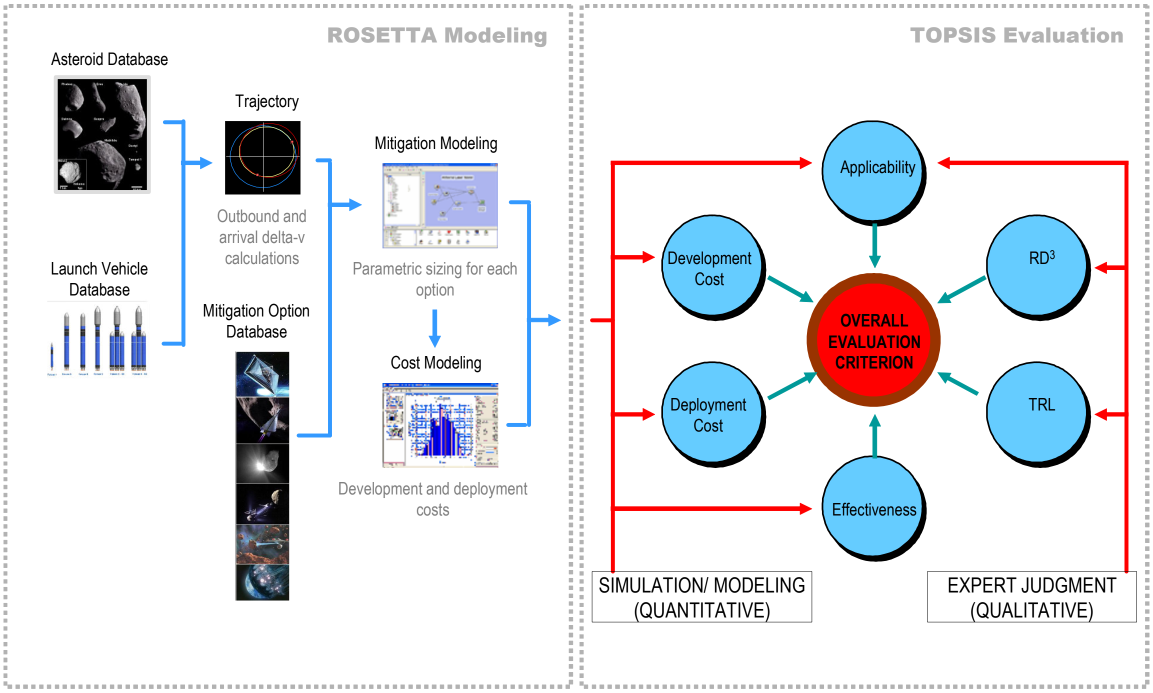

Figure 1. NOMAD Process Flow Diagram.

B. ROSETTA Parametric Sizing Model

A ROSETTA model, a type of parametric spacecraft sizing model, of the mitigation concepts being considered has been created in Microsoft Excel© and has been used to conduct a series of studies to define key variables. The ROSETTA model consists of several interconnected worksheets within an overall workbook.

A single trajectory sheet is used to determine the necessary outbound and rendezvous ΔVs for each NEO. Key inputs include the NEO semi-major axis, eccentricity, and inclination. The data generated in this trajectory sheet are then used in the sizing sheets. Sizing sheets exist for each mitigation option being considered and perform the sizing of the mitigation vehicle itself and any transfer stages necessary. The sizing sheets are also used to determine the momentum imparted to the NEO by each mitigation option.

The key outputs of this model are the dry and gross mass of each mitigation vehicle and accompanying transfer stages, the momentum imparted to the NEO, and the number of launches required to achieve a desired NEO change in velocity. These data are subsequently used to estimate the DDT&E cost, Theoretical First Unit (TFU) cost, production costs, launch costs, and mission operations costs.

C. Life Cycle Cost (LCC) Modeling

A standard life cycle cost (LCC) sub-model was developed for the ROSETTA model for each mitigation concept. The inputs for the LCC sub-model in the ROSETTA model include programmatic variables such as fiscal year, anticipated future inflation rate, dry mass without margin, and overall mission times. Some of the costs are calculated and some are left as expert inputs.

Life cycle costs are estimated using historically-based equations and analogous costs for similar space systems. These specific equations for DDT&E and TFU cost are based upon parametric historical cost estimating relationships (CERs) that scale for both mass and complexity. The top-down CERs used for this study have been correlated to historical spacecraft cost data and have been proven useful to estimate the costs of a variety of future space systems. For the purpose of this study, LCC was divided into development cost and deployment cost. Development cost consists of overall technology development costs, DDT&E for both the in-space transfer stage and mitigation stage, and facilities development costs. Deployment cost consists of acquisition costs for both the in-space transfer stage and mitigation stage, in-space operations costs, and launch costs. Overall technology development cost is defined as the cost to bring required technologies to a TRL of 6.

In addition to hardware development and acquisition costs, additional "wraps" are also included in the calculation of DDT&E and TFU costs. These costs are normally a substantial part of overall costs and should not be excluded in any LCC analysis. For this analysis, these costs include System Test Hardware (STH) costs (nominally 35% of TFU cost) and overall systems integration costs that consist of the following (30% of hardware + STH costs): Integration, Assembly, & Checkout (IACO); System Test Operations (STO); Ground Support Equipment (GSE); System Engineering & Integration (SE&I); and Program Management (PM). On top of these costs there are additional percentages to account for contingency (20%), contractor fees (5%), program support (5%) and stage integration (2%). Contingency is added here since the base hardware costs calculations are based upon dry mass without margin. In-space operations costs are broken out into cruise phase and target operations costs per month.

These costs are estimated based upon NASA operations costs as listed in both previous and projected NASA fiscal year budget documents for the Dawn, Deep Impact, Phoenix, and Mars Science Lab (MSL) missions[15]. Cruise phase operations costs (approximately $0.79M / cruise month, FY2007) are based upon the first three missions and surface operations costs (assumed to be more complex) are based only upon MSL operations estimates (approximately $4.78M/ mission month, FY2007), MSL being representative of a mission with multiple mission phases and science instruments. These estimates are taken to be rough but relevant approximations of such costs. The launch cost for the standard Delta IV Heavy launch vehicle is assumed to be $200M[16]. Ancillary facilities development costs are estimated to be $10M. Given that the transfer stage is based upon known design and manufacturing processes, a learning curve effect percentage of 95% is assumed for the transfer stage and 90% for the mitigation stages.

D. TOPSIS Evaluation Procedure

A decision-maker would attempt to select the optimal mitigation technology based on greatest benefit within a given budget. Although the budget may be known, determining the meaning of "greatest benefit" can still be tricky. Often, decision-makers try to weigh various metrics based on their notion of relative importance. For example, a DoD user may put much greater emphasis on vehicle size and operations than on life cycle cost or vehicle safety, while a NASA user may value safety first with life cycle cost a close second. Obviously, optimum technological solutions depend on the chosen weighting scenarios. Various methods may be used for applying weightings. For each case study, the TOPSIS ranking approach was used along with multiple weighting scenarios[12]. In TOPSIS, weights are allocated to each output metric or output category. Those weights, then, are multiplied by normalized outputs of each converged solution in order to arrive at an Overall Evaluation Criterion (OEC) value, as is shown in Eq. (1):

$$OEC = W_{effectiveness} \cdot N_{effectiveness} + W_{applicability} \cdot N_{applicability} + W_{TRL} \cdot N_{TRL} + W_{RD^3} \cdot N_{RD^3} + W_{LCC} \cdot N_{LCC} \quad (1)$$

The term W in the equation represents the weighting (0% to 100%) and the term N represents a normalized output value (0 to 1) for the categories effectiveness, applicability, TRL, R&D^3, and LCC, respectively. Development and deployment costs are added together to generate the LCC in this equation. The N values consist of the square root of the sum of squares multiplied by the distance of each alternative from either the positive and negative ideal to obtain a value for the relative closeness to the ideal solution. This process is repeated for each metric. Obviously, the choice of mitigation option depends on the weighting scenario favored. Even if a user favors one metric over others, he/she must consider the weights; ignoring all but one metric may not produce the same result as overweighting that same metric.

Rather than settle on a single weighting scenario, it was decided to use NOMAD to evaluate a number of weighting scenarios and graphically compare the results. This allows the decision-maker to further reduce risk by choosing to fund mitigation technologies which will satisfy broader goals, although there is an obvious danger in diluting the effectiveness of one's investment by reducing focus.

IV. Mitigation Option Modeling

A. Overview of Potential Mitigation Options

A variety of options for mitigating the threat of an NEO impact have been proposed. While a nearly exhaustive list of proposed mitigation options is presented in Table 3 for reference, only six of these options were selected for analysis in this preliminary study. NOMAD could be used, however, to analyze and compare any of these mitigation techniques, or any technique not discussed here.

Table 3. List of Proposed NEO Mitigation Options.

Name	Description
Kinetic Impactor	A spacecraft is impacted into the NEO, transferring the kinetic energy of the spacecraft to the NEO. In addition to the simple momentum transfer, the impact will cause ejecta from the impact location to be blasted into space, amplifying the effective momentum transferred to the NEO[2].
Kinetic Impactor with Explosives	This option is similar to the kinetic impactor, except that the colliding vehicle will carry chemical or nuclear explosives. These explosives are detonated at the moment of impact to generate more ejecta than an unaided impact, and therefore increase the total momentum transferred to the NEO[1].
NEO-to-NEO Collision	A variation on the kinetic impactor approach, this technique uses a smaller NEO as a kinetic impactor against a larger threatening NEO. The resulting collision between the two NEOs would change the course of the larger NEO. The small impactor NEO would need to have its own course altered by one of these deflection options in order to be placed on a collision course with the threatening NEO[1].
Standoff Nuclear Detonation	A nuclear warhead is detonated near the surface of a threatening NEO, bathing the surface in radiation and high-energy particles. The absorption of this high-energy material causes the outer layers of the NEO surface to vaporize and outgas. The momentum transfer from this outgassing causes an induced change in velocity on the NEO[17].
Surface/ Subsurface Nuclear Detonation	A nuclear warhead is detonated at or beneath the surface of the NEO with this option. The sudden release of energy blasts a portion of the NEO away from it and into space, transferring momentum to the NEO[17].
Magnetic Flux Compression	This approach utilizes the electromagnetic pulse (EMP) generated by a nuclear detonation to apply momentum to the NEO. In order to transfer the energy of the EMP pulse to the NEO, a disk of thin metallic foil is mated to its surface. Some distance from the disk, a nuclear warhead is detonated inside a large solenoid. The EMP generates a brief current inside the solenoid, which in turn generates a strong magnetic field. The metallic disk reacts to the magnetic field and applies a force to the NEO[2].
Chemical Rocket	A standard chemical rocket is attached to the NEO and used to directly apply a force to the object. This force is applied over a relatively short period of time and induces a near-instantaneous change in NEO velocity[1].
Gravity Tractor	The gravity tractor option addresses NEOs upon which attachment would be difficult or impossible. Rather than attach to the NEO, a spacecraft is parked near the NEO. The gravitational attraction of the NEO to the spacecraft is used as a tow line to gradually change the NEO's orbit. The gravity tractor vehicle uses an electric propulsion system to maintain its position next to the NEO[19].
High Specific Impulse Rocket	This approach is identical to the chemical rocket propulsion technique except that a high specific impulse, low thrust rocket, rather than a chemical rocket, is attached to the NEO. Examples of high specific impulse propulsion systems include nuclear thermal rockets, nuclear electric engines, and the Variable Specific Impulse Magnetoplasma Rocket (VASIMR) engine. Unlike a chemical rocket, these methods provide a small but steady force over an extended period of time (weeks to years)[20,21].
Mass Driver	A number of small spacecraft containing mass drivers and drilling equipment are attached to the NEO. The spacecraft drill out small pieces of the NEO and fire them away from it at high velocity using their mass drivers. These "propellant-less" engines apply a series of nearly instantaneous impulses to the NEO that, over the duration of the mission, act like steady thrust[22].
Albedo Alteration	Also known as NEO Painting, the objective of this mitigation option is to change the albedo of the asteroid by covering its surface with a chemical paint. The altered albedo changes the magnitude of the Yarkovsky effect on the NEO and thereby very gradually alters its course[1].
Laser Ablation	This method uses similar physics to the standoff nuclear detonation approach. A spacecraft with a high-energy laser is deployed either near the NEO, near the Earth, or in a stable heliocentric orbit. The spacecraft focuses its laser on the NEO, causing the material on the surface of the NEO to heat up and be expelled from the surface. This imparts a continuous momentum change to the NEO[23].
Solar Ablation	Rather than carry a high powered laser as with the laser ablation method, the solar ablation approach uses a series of mirrors and lenses to focus sunlight onto the NEO. This produces the same net effect as the laser ablation technique: material on the NEO's surface is expelled, causing a change in momentum[2].
Solar Sail	For this long duration approach, a solar sail is attached to the NEO and effectively increases its cross-sectional area. This, in turn, increases the effect of solar pressure on the NEO and acts to slowly change its course[2].

B. Launch and Transfer

In order to accurately determine the total mass available for the sizing of each mitigation option, an entire mission from initial launch to final mitigation is modeled in NOMAD. The Delta IV Heavy was selected as the launch vehicle to be used for all techniques. This selection was arbitrary: the only criterion for ensuring a fair analysis is the use of the same launch vehicle for each option.

It was assumed that the launch vehicle performs the Earth escape maneuver; a separate in-space rocket stage is sized to perform any additional maneuvers required. The remaining payload mass is used to size the mitigation technique vehicle, i.e. the mitigation technique is the final payload of the launch vehicle and in-space stage.

Mission modeling begins with selection of the target NEO. For the sake of simplicity, a Hohmann transfer trajectory from Earth to the NEO is used to determine the ΔVs necessary to intercept the target NEO. Because the goal of this study is to determine relative rankings between different mitigation options and the same trajectory is used for all cases, the Hohmann transfer is sufficient the capture the necessary trends.

In order to further simplify the Hohmann trajectory, the Earth is assumed to be in a circular orbit around the Sun of radius equal to the 1 AU. This allows the Hohmann transfer to occur from the appropriate location on the Earth's orbit to the NEO aphelion. Using the vis-viva equation, Eq. (2)[24], appropriate required velocities for the Hohmann transfer and NEO rendezvous were determined where v is the orbital velocity at a given point in the orbit, ρ is the distance from the Sun at that point, a is the semi-major axis of the orbit, and μ is the gravitational constant of the Sun.

$$v^2 = \mu_{sun}(\frac{2}{\rho} - \frac{1}{a}) \tag{2}$$

This equation was used to determine the ΔVs required for Earth departure and NEO rendezvous. For the Earth departure, the ΔV required represents the hyperbolic excess velocity after escaping the Earth's gravitational influence. Because the launch vehicle performs the Earth departure ΔV, the ΔV required for this maneuver was used to determine the characteristic energy, C_3, required for the launch vehicle. The available remaining payload from this maneuver was determined using published data about the launch vehicle[16]. This payload is assumed to include both an in-space stage (if necessary) for rendezvous maneuvers, and the mitigation technique vehicle itself.

With this total payload mass and the ΔV required for NEO rendezvous as inputs, the rocket equation, Eq. (3)[24] was used in conjunction with Eqs. (4) and (5) to determine the dry and propellant masses of the in-space stage, m_s and m_p respectively, and the total payload m_L of the in-space stage given a structural coefficient ε defined in Eq. (6)[24]. The total payload represents the mitigation technique vehicle mass. An Isp of 462.4 seconds was used to simulate the RL10B-2 engine[16]. A structural coefficient of 0.17 was selected based on historical data[25,26]. To accommodate the RL10B-2 engine, LOX and LH2 were chosen as the propellants for this in-space stage. Boil-off rates of 0.1%/day for LH2 and 0.0167%/day for LOX were used to simulate propellant boil-off during the orbit transfer[26].

$$\Delta \mathrm{V} = \mathrm{Isp} \cdot \mathrm{g_o} \cdot \ln\left(\frac{m_o}{m_f}\right) \tag{3}$$

$$m_o = m_s + m_p + m_L \tag{4}$$

$$m_f = m_s + m_L \tag{5}$$

$$\varepsilon = \frac{m_s}{(m_s + m_p)} \tag{6}$$

A more detailed Weight Breakdown Structure (WBS) for the in-space stage was formulated using historical data for in-space stages[25, 26].

C. Detailed Overview of Options Considered in Study

Six mitigation options were chosen for this study: chemical rocket propulsion, gravity tractor, high Isp rocket propulsion, kinetic impactor, mass driver, and standoff nuclear detonation. These mitigation techniques were chosen based on ease of modeling and availability of published data. Each mitigation technique was modeled individually in NOMAD based on the delivered payload mass of the in-space stage, with the exception of the high Isp rocket, which performs its own rendezvous maneuver, and the kinetic impactor, which does not require a rendezvous maneuver.

1. Kinetic Impactor

There are several concepts for kinetic impactor vehicles depending on the impact trajectory desired. Complicated orbital trajectories with multiple in-space maneuvers can be used to increase the relative velocity between the spacecraft and NEO at impact. In this study, it is assumed that the kinetic impactor is placed on its intercept course by the launch vehicle; no other in-space maneuvers are performed.

The kinetic impactor vehicle is modeled in NOMAD based on the Deep Impact and Don Quixote missions, and existing deep space and satellite vehicles[25,27,28]. The spacecraft itself has a Reaction Control System (RCS) for maneuvering, but no main propulsion system. Depleted uranium is used as a dead mass on the spacecraft for its high density, and accounts for 25% of the total vehicle mass. It is also assumed that the structural mass of the launch vehicle's spent final stage remains attached to the impactor craft in order to maximize its total momentum.

Momentum is transferred directly to the NEO from the impact of the kinetic impactor, and is amplified by the debris ejected during crater formation[29]. Modeling a kinetic impact can therefore be accomplished by considering the momentum induced to be the product of the mass of the spacecraft, the spacecraft relative inbound velocity, and a cratering amplification factor β. Values for β can range greatly depending on the composition of the NEO and the design of the impactor; values ranging from 1-10 are typical[29]. For this study, a conservative value of $\beta = 2.0$ was selected.

While the momentum transfer is a function of both the spacecraft mass and relative inbound velocity, these two parameters are generally inversely related. Higher desired velocities result in lower achievable payload masses, so mission planners would need to optimize this problem to determine the highest achievable momentum. In this study, however, a Hohmann transfer was used to determine the Earth-to-NEO trajectory to minimize total ΔV requirements. This type of transfer artificially lowers kinetic impactor's performance. To account for this loss of performance, the relative inbound velocity was multiplied by 1.5 to represent a more ideal trajectory for this technique though the transfer stage mass was kept the same. Essentially, the spacecraft is being launched into the same basic orbit but is impacting the NEO at a different location in the orbit to increase the relative velocity.

2. Standoff Nuclear Detonation

The W87 thermonuclear warhead was selected as the baseline nuclear munitions for this mitigation technique. An individual warhead has a yield of 300 kilotons of TNT and a weight of 600 lbs[30]. This device was selected for its relatively high yield-to-mass ratio compared to other modern nuclear weapons. Its small size also allows it to scale more easily to different launch vehicles and planning scenarios.

In NOMAD, the mitigation vehicle is modeled as a delivery spacecraft for the nuclear warheads. The design of this spacecraft is based on existing satellites with high payload mass fractions[25]. The vehicle is first sized to maximize delivered payload, which is assumed to be 40% of the total vehicle mass. The highest integer number of warheads that can be carried by the vehicle is calculated based on this 40% value, and the total explosive yield of the vehicle is determined. The vehicle is then resized to accommodate precisely this number of warheads.

Typical nuclear weapons release the majority of their energy in the form of the X rays. However, this X ray radiation is absorbed by only a thin layer of material on the surface of the NEO. The high temperatures generated cause most of this energy to be reradiated. Nuclear weapons also release neutrons that penetrate deeper into the NEO surface. The neutrons are much more efficient in causing the necessary evaporation of material from the surface for ablation, but typically constitute only 1% of the total effective energy yield of current weapons[15]. In NOMAD, it is assumed that only the neutron energy can be harnessed for surface material ablation.

The nuclear standoff detonation method is illustrated in Figure 3. In this figure, h represents the height of the detonation above the NEO's surface, D and M represent the NEO diameter and mass respectively, and E represents the energy yield of the nuclear detonation.

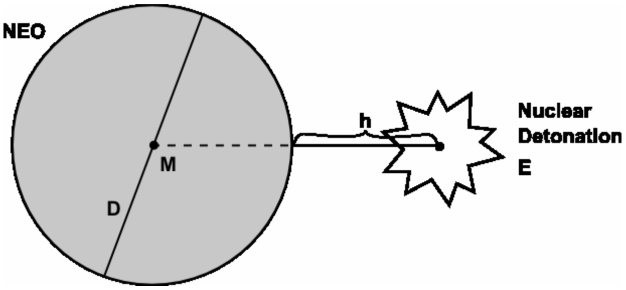

Figure 2. Positioning of Standoff Nuclear Detonation near Target NEO.

The total momentum transferred to the NEO, p, and the detonation height above the NEO, h, were determined from Figure 3. A detonation height was selected to maximize induced momentum. This plot was generated for a spherical, stony asteroid with 50% porosity. Because this is somewhat of an idealized case, a further non-optimum multiplication factor of 0.5 was applied to the momentum imparted to capture the effect of different material compositions and porosities.

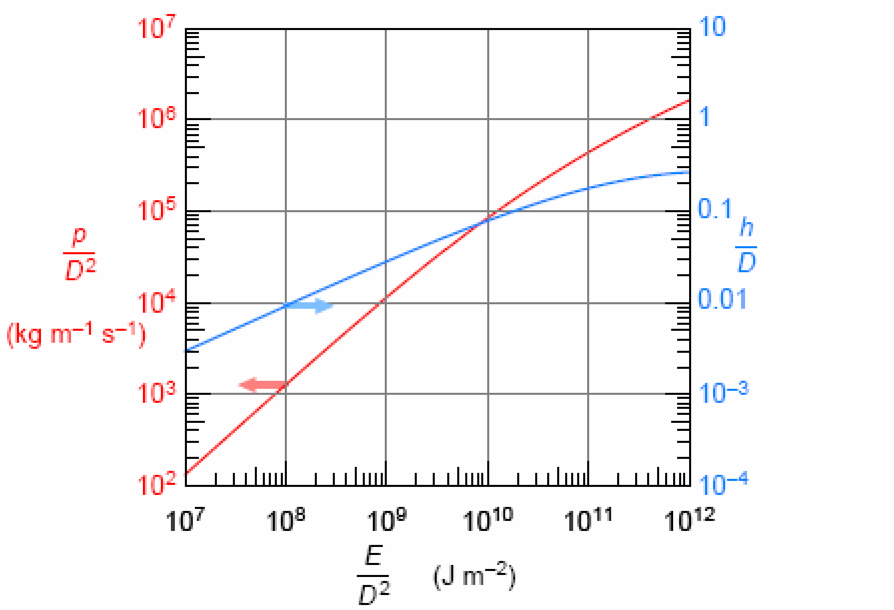

Figure 3. Maximum Momentum Imparted to a NEO via the Absorption of Neutron Energy from a Standoff Nuclear Detonation[17].

3. Chemical Rocket

The chemical rocket mitigation option was modeled in the same fashion as the in-space transfer stages, using the LH2 / LOX RL10B-2 engine with Isp of 462.4s, and the same boil-off rates. In order to attach to the NEO, 10% of the total delivered mass is allocated for attachment equipment. Attachment and docking are assumed to occur after the rendezvous stage has been detached from the chemical rocket delivered, using the chemical rocket's RCS thrusters. The rocket itself is not fired until it has been attached.

The ΔV applied to the NEO by the chemical rocket was determined using the rocket equation. Mass fractions were determined based on the chemical rocket weight breakdown statement. The NEO mass was considered to be the payload of this rocket burn.

4. Gravity Tractor

The gravity tractor spacecraft is a small vehicle that remains stationary near the NEO with respect to its heliocentric orbit. A design for the gravity tractor was first conceived by the B612 Foundation[19]. Their spacecraft is modeled after the Deep Space 1 vehicle, using the NSTAR ion engine as a main propulsion system and hypergolic

RCS. The NSTAR engine provides a maximum of 92 mN of thrust at an Isp of 3100s and with a power requirement of 2.1 kWe[19].

Momentum is transferred to the NEO from the spacecraft via the mutual attraction of the two massive bodies. The spacecraft uses its engines to maintain a stationary position near the NEO. From a system perspective, these engines are applying a thrust to the system of bodies. The exhaust of the engines must not impact the NEO or there will be no net change in system momentum. The engines are therefore placed at an angle such that their expanding exhaust region is outside the NEO, as shown in Figure 4. In this case, the NEO is assumed to be a homogenous sphere.

The spacecraft is at an unstable equilibrium point defined by Eqs. (7) and (8). Eq. (7) represents the gravitation attraction of the spacecraft to the NEO, while Eq. (8) represents the counter-acting force generated by the thrust of the engines.

$$F_{gravity} = \frac{GMm}{(r+h)^2} \tag{7}$$

$$F_{thrust} = T\cos(\theta) \tag{8}$$

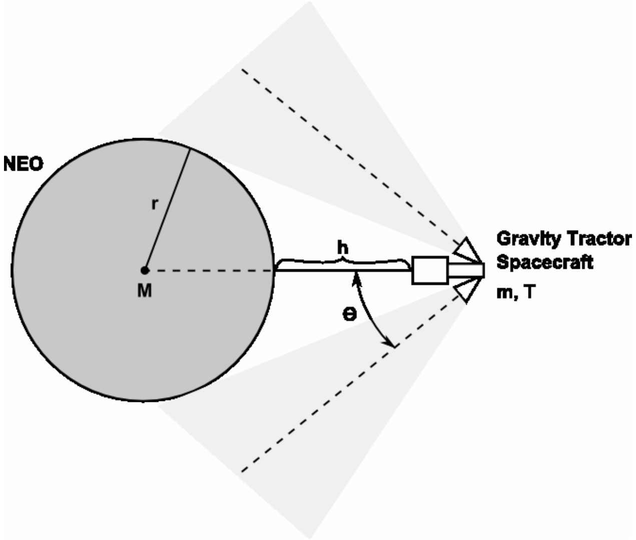

Figure 4. Positioning of Gravity Tractor near Target NEO.[19]

To solve for the equilibrium point location, these two forces must be exactly equal assuming a constant thrust. The equations are set equal and solved for h, the height above the NEO's surface. G is the gravitational constant (6.6742×10^{-11} m^3 kg^{-1} s^{-2}), M is the mass of the NEO, m is the mass of the spacecraft, r is the average radius of the NEO, and T is the thrust generated by the engines.

The momentum induced by this technique is calculated by determining the total amount of time the gravity tractor spacecraft can remain stationary. This is a function of the spacecraft's propellant, i.e. once the propellant runs out, the spacecraft can no longer remain stationary. The burn time is determined using the thrust and Isp to determine a mass flow rate, and then dividing the total propellant mass by the mass flow rate. The gravitational force between the NEO and spacecraft is integrated over the burn time to determine the total momentum transferred to the NEO.

5. High Specific Impulse Rocket

There are many different high Isp rocket concepts that could be used in the modeling of this mitigation technique. The Variable Specific Impulse Magnetoplasma Rocket (VASIMR) engine was chosen by the B612 Foundation for their Asteroid Tugboat concept[20,21] and therefore is used in this study to be representative of a high Isp rocket.

The VASIMR engine uses radio frequency waves to ionize a propellant gas, which is then accelerated through a magnetic nozzle. Its power requirements are on the order of 100 kW to 1 MW, thus requiring a nuclear reactor as a power source. The engine is capable of a range of Isps and thrusts depending on the propellant: for hydrogen, Isp can range from 10,000s to 30,000s and thrust can range from 2.5N to 7.5N[31]. For this study, the conservative values for both Isp (10,000s) and thrust (2.5N) were used and held constant. Assuming a 50% efficiency, these performance values would require 250 kW of electrical power[20].

Unlike the other mitigation options, in order to accurately simulate a high Isp rocket mission, it is assumed that the high Isp rocket vehicle uses its own engine to perform the rendezvous ΔV. Because this is a long duration burn, the Hohmann transfer is not an accurate representation of the rendezvous trajectory. A high Isp, long duration burn will require significantly more ΔV than an impulsive transfer to the same orbit. According to Hill, the ratio of long duration ΔV to impulse ΔV asymptotically approaches 2.3 as the ratio of thrust to propellant weight becomes very small[31]. Therefore, the ΔV required for the rendezvous maneuver, as calculated using the Hohmann transfer trajectory, is multiplied by 2.3 for the high Isp rocket.

To determine the total ΔV induced by the high Isp rocket onto the NEO, the rocket equation is first used to determine the amount of propellant required to perform the rendezvous maneuver (with the modified ΔV requirement). A structural coefficient of 0.80 is used to represent the VASIMR engine-powered craft[20]. It is then assumed that the remaining propellant is used to apply a thrust to the NEO, again using the rocket equation but now with the NEO mass as the payload. To accommodate for NEO rotation, a duty cycle of 30% was chosen, i.e. with nozzle vectoring capabilities, the SpaceTug will be able to fire in the required direction 30% of the time.

A weight breakdown structure for the high Isp rocket vehicle is formulated based on concepts for advanced propulsion system missions using the VASIMR and other nuclear-powered rockets[20, 31].

6. Mass Driver

The mass driver concept as a NEO mitigation option was first conceived as a single large device built on the surface of a NEO that required a significant amount of infrastructure[2]. An alternative approach, called MADMEN (Multiple Asteroid Deflection Mission Ejector Node), was developed by SpaceWorks Engineering, Inc. and featured a swarm of small, modular mass driver vehicles. For a given threatening NEO, a group of MADMEN vehicles attach to the NEO, use onboard drilling machinery to drill out small pieces of the NEO, and then accelerate these pieces and fire them out of a mass driver device[22].

For this study, a 1,212 kg version of the MADMEN lander was used as the mitigation vehicle. This lander is capable of firing three shots per minute at 0.5 kg per shot and a shot velocity of 540 m/s. It is assumed that an individual lander has a 15% duty cycle, meaning it is able to fire in the appropriate direction 15% of the time. This lander is powered by a small thermonuclear reactor generating 15 kWe, with power spikes for each firing accommodated by a bank of capacitors.

An integer number of landers can be delivered by a single delivery vehicle, similar to the standoff nuclear detonation option. To determine how many landers can be delivered, the rendezvous stage is sized to achieve maximum payload capability. This maximum capability is divided by the mass of an individual lander, and the integer number of landers able to be delivered is determined. The vehicle is then resized to accommodate precisely this number of landers.

The total momentum imparted to the NEO by the MADMEN landers is determined using Eq. (9). In theory, the MADMEN lander can continue firing as long as necessary, so the active time is set equal to the time required to generated the necessary ΔV required to deflect the NEO[22].

$$\begin{aligned}\textit{Number of Landers} \cdot \textit{Shot Mass} \cdot \textit{Shot Velocity} \cdot \textit{Shot Frequency} \cdot \textit{Duty Cycle} \cdot \textit{Active Time} \\ = \textit{Total Momentum Induced}\end{aligned} \tag{9}$$

V. Process Results

A. Performance Metrics: Effectiveness and Applicability

1. Effectiveness

The ΔV induced by a single delivery of each mitigation option, i.e. a single launch and deployment, is shown in Table 4. The standoff nuclear detonation option is clearly dominant in terms of effectiveness; nuclear devices have a very high energy yield for the delivered mass compared to the other options. Depending on the scenario, the high Isp rocket, mass driver, and kinetic impactor also perform well. The gravity tractor and chemical rocket perform poorly in terms of induced velocity.

Table 4. ΔV Induced to Target NEOs by a Single Delivery of Selected Mitigation Options.

Mitigation Option	Apophis Induced ΔV (mm/s)	D'Artagnan Induced ΔV (mm/s)	Athos Induced ΔV (mm/s)
Kinetic Impactor	3.8	28.4	6.9
Standoff Nuclear Detonation	61.4	163.5	42.3
Chemical Rocket	0.5	2.2	0.6
Gravity Tractor	0.4	0.3	0.2
High Isp Rocket	4.6	25.2	6.7
Mass Driver	6.1	23.7	11.6

Induced ΔV in-and-of-itself is not a satisfactory measure of effectiveness, however. In some cases, the ΔV required to change the miss distance of the NEO with respect to the Earth is smaller than the ΔV induced by a single delivery of the mitigation vehicle. In these cases, it would be unfair to award any mitigation option a higher score for outperforming another if both options are capable of generating the required ΔV.

In order to determine the ΔVs required to change the miss distance of the NEO, the orbits of the three selected NEOs were propagated forward in time using an 8th/9th order Runge-Kutta-Fehlberg n-body numerical propagator with a variable step size. The sun, all of the planets and the Earth's moon are considered in the gravitational model, but solar pressure and the Yarkovsky effect are not modeled. The standard propagator is based on the Java Astrodynamics Toolkit (JAT) originally developed at the University of Texas.

The propagation routine itself is based on the Runge-Kutta-Fehlberg integration routine within JAT and was developed by SEI and our partner researchers at the Georgia Institute of Technology to accommodate both impulsive and low thrust perturbation models. For a given start date, a search algorithm is used to determine ΔV necessary in order to change the minimum Earth miss distance by the desired amount. For the D'Artagnan and Athos cases, a desired miss distance of greater than five Earth radii was assumed. In the Apophis case, it is assumed that the miss distance of the close approach in 2029 should be changed by 60 km in order to avoid a keyhole that would generate a second close approach in 2036[5]. For a range of solutions over a candidate period of 5 – 10 years, the algorithm takes several hours to execute on a standard PC. The solutions vary based on launch and arrival date, as ΔVs applied at different points in the NEO's orbit will have different effects. Based on the data acquired, average ΔVs required were determined and are displayed in Table 5.

Table 5. ΔV Required to Change Target NEO Miss Distance by Specified Amount.

Target NEO	Change in Miss Distance	ΔV Required (mm/s)
Apophis	60 km	0.1
D'Artagnan	5 Earth radii	150
Athos	5 Earth radii	140

Once the required ΔVs have been determined, it is possible to determine the number of launches required by each mitigation option to produce the necessary ΔV change by dividing the required ΔV by the ΔV induced by a single delivery. Certain mitigation options are inherently imprecise in their transfer of momentum, so an additional non-optimum factor is multiplied to the induced ΔV of those techniques to illustrate this effect. A non-optimum factor of 0.75 was applied to the kinetic impactor and standoff nuclear detonation methods. The number of launches required, shown in Table 6, were used as the FOM for effectiveness in TOPSIS.

Table 6. Number of Launches Required for Selected Mitigation Options to Achieve Required ΔV.

Mitigation Option	Apophis Launches Required	D'Artagnan Launches Required	Athos Launches Required
Kinetic Impactor	1	6	21
Standoff Nuclear Detonation	1	1	4
Chemical Rocket	1	69	222
Gravity Tractor	1	462	574
High Isp Rocket	1	6	21
Mass Driver	1	7	13

For Apophis, the required ΔV is small enough that every mitigation option is capable of generating the necessary ΔV with a single launch. For D'Artagnan and Athos, the ΔV requirements are significantly larger. For these two cases the standoff nuclear detonation option is clearly dominant. The kinetic impactor, high Isp rocket, and mass driver also perform well. The gravity tractor requires significantly more launches than its competitors to be effective against a NEO without a close approach, i.e. one whose required ΔV is relatively high. It should be noted that the gravity tractor was designed specifically for these close approach cases, and therefore its poor performance against NEOs without a close approach is to be expected.

2. *Applicability*

Performance is not just a measure of sheer effectiveness. NEO physical characters can have bearing on the performance of certain mitigation options. In NOMAD, three NEO properties are considered to determine mitigation technique applicability: composition, type, and rotation. Composition represents the material composition of the NEO. For the sake of simplicity, NEOs are classified here as either carbonaceous, silicaceous, metallic, or icy in composition. Similarly, NEO types are considered in this analysis to be either monolithic, a single large body, or rubble-pile, a loosely collected cloud of material. For rotation, NEOs are classified as rotating either slow or fast, notional classifications based on the average rotational velocities of the NEO population. Consideration is also taken for unknown composition, type, and rotation also based on averages of the NEO population[33].

To use applicability as a FOM, each mitigation option was given a score representing a probability of success against different classifications of NEOs. These range from 0 to 1 and are intended to literally represent the probability that the mitigation option will be successful in imparting momentum to a NEO of particular physical characteristics. Expert opinion was used to populate Tables 7-9 with estimated probabilities of success for the three classification categories; future technical work into the different mitigation options could yield more precise values for these probabilities.

Table 7. Probability of Success (0-1) of Mitigation Options against Different NEO Types.

Mitigation Option	Rubble-Pile	Monolithic	Unknown Type
Kinetic Impactor	0.1	1.0	0.3
Standoff Nuclear Detonation	0.3	1.0	0.8
Chemical Rocket	0.1	1.0	0.3
Gravity Tractor	1.0	1.0	1.0
High Isp Rocket	0.1	1.0	0.3
Mass Driver	0.1	1.0	0.3

Table 8. Probability of Success (0-1) of Mitigation Options against Different NEO Compositions.

Mitigation Option	Carbon-aceous	Silicaceous	Metallic	Icy	Unknown Composition
Kinetic Impactor	1.0	1.0	1.0	1.0	1.0
Standoff Nuclear Detonation	1.0	1.0	0.6	1.0	0.9
Chemical Rocket	1.0	1.0	1.0	1.0	1.0
Gravity Tractor	1.0	1.0	1.0	1.0	1.0
High Isp Rocket	1.0	1.0	1.0	1.0	1.0
Mass Driver	1.0	1.0	0.3	1.0	0.9

Table 9. Probability of Success (0-1) of Mitigation Operations against Different NEO Rotation Speeds.

Mitigation Option	Slow Rotation	Fast Rotation	Unknown Rotation
Kinetic Impactor	1.0	1.0	1.0
Standoff Nuclear Detonation	1.0	1.0	1.0
Chemical Rocket	1.0	0.5	0.8
Gravity Tractor	1.0	1.0	1.0
High Isp Rocket	1.0	0.5	0.8
Mass Driver	1.0	0.5	0.8

Eq. (10) was used to apply the probabilities listed in Tables 7-9 to the NEO test case properties outlined in Table 1 in order to determine an applicability rating for each mitigation option against each NEO test case. The term P represents the probability of success for each classification, and the term W is the weighting value for each classification.

$$Applicability\ Rating = P_{type} \cdot W_{type} + P_{composition} \cdot W_{composition} + P_{rotation} \cdot W_{rotation} \tag{10}$$

Because NEO type (rubble-pile vs. monolith) is an important distinction in mitigation option planning, it was weighted very heavily compared to composition and rotation: type was given a weighting value of 0.70, while rotation and composition were each given a weighting of 0.15. The calculated applicability ratings for the three test cases are presented in Table 10.

Table 10. Applicability Rating (0-1) of Selected Mitigation Options against Target NEOs.

Mitigation Option	Apophis Applicability Rating	D'Artagnan Applicability Rating	Athos Applicability Rating
Kinetic Impactor	0.51	1.00	0.31
Standoff Nuclear Detonation	0.85	1.00	0.48
Chemical Rocket	0.48	0.93	0.31
Gravity Tractor	1.00	1.00	1.00
High Isp Rocket	0.48	0.93	0.31
Mass Driver	0.47	0.93	0.31

Here, the gravity tractor outperforms the other mitigation options. Because it does not directly interact with the NEO, it will have a score of 1.0 against any NEO. Conversely, the chemical rocket, high Isp rocket, and mass driver all perform poorly against Apophis and Athos. Athos is a known rubble-pile, and because these methods require attachment to the NEO, their poor performance here is to be expected. It is unknown at this point whether Apophis is a monolith or rubble-pile, so technologies requiring attachment are penalized. The kinetic impactor and standoff nuclear detonation performances similarly suffer against rubble-pile type NEOs; the transfer of momentum from the impactor or explosion to the NEO would be severely limited because of energy absorption inefficiencies within the rubble-pile type body. The chemical rocket, high Isp rocket, and mass driver all perform slightly worse than the other options in all three cases because of potential difficulties in attaching these techniques to rotating bodies.

B. Technology Metrics: Readiness and Research & Development Degree of Difficulty

The TRL and R&D^3 metrics for measuring technology readiness and development degree of difficulty as defined by Mankins[13,14] were used to quantify FOMs for these two areas. Expert judgement and research into the different options was used to determine appropriate values for TRL and R&D^3. The values selected are displayed in Table 11. The kinetic impactor is the technology requiring the least amount of development for use against NEOs as the concept has already been proven in the Deep Impact mission[27]. The high Isp rocket and mass driver technologies would require serious investment before they would be able to be used in a NEO deflection mission.

Table 11. TRL (1-9) and R&D^3 (1-5) Ratings for Selected Mitigation Options.

Mitigation Option	TRL	R&D^3
Kinetic Impactor	8	1
Standoff Nuclear Detonation	7	1
Chemical Rocket	5	1
Gravity Tractor	5	2
High Isp Rocket	2	4
Mass Driver	3	3

C. Cost Metrics: Development and Deployment Costs

The costs associated with completely developing the mitigation options and deploying those options to achieve the required ΔVs for each NEO case were determined and are shown in Tables 12 and 13 respectively. These costs are presented in millions of FY2007 dollars.

Table 12. Development Costs of Selected Mitigation Options for Target NEO Missions.

Mitigation Option	Apophis Development Cost (FY$M2007)	D'Artagnan Development Cost (FY$M2007)	Athos Development Cost (FY$M2007)
Kinetic Impactor	$475	$424	$421
Standoff Nuclear Detonation	$1,049	$868	$903
Chemical Rocket	$1,040	$855	$891
Gravity Tractor	$1,387	$1,093	$1,158
High Isp Rocket	$2,603	$2,327	$2,314
Mass Driver	$856	$867	$847

Table 13. Deployment Costs of Selected Mitigation Options for Target NEO Missions.

Mitigation Option	Apophis Deployment Cost (FY$M2007)	D'Artagnan Deployment Cost (FY$M2007)	Athos Deployment Cost (FY$M2007)
Kinetic Impactor	$280	$1,547	$5,650
Standoff Nuclear Detonation	$455	$386	$2,033
Chemical Rocket	$364	$19,671	$62,332
Gravity Tractor	$451	$131,517	$165,575
High Isp Rocket	$538	$2,646	$10,777
Mass Driver	$473	$2,247	$5,435

The mass driver performs very well in terms of development cost. Though its TRL is low and R&D^3 is high, its modular design means the actual MADMEN lander is much smaller than any of the other vehicles, thus driving down its development costs. The chemical rocket also performs well in terms of development cost, but this is to be expected as chemical rockets are a proven technology with many years of manufacturing experience and infrastructure already in place. The development of the VASIMR engine for the high Isp rocket drives its development cost very high compared to the other options.

Deployment cost is largely a function of number of deliveries required. More deliveries require more launches and acquisition of more in-space stages and mitigation vehicles. Therefore, as with the effectiveness FOM, the standoff nuclear detonation largely dominations the development cost metric, with the kinetic impactor and mass driver performing well and the gravity tractor performing incredibly poorly.

D. Multiple Criteria Analysis

To fairly compare the different mitigation options and to illustrate the versatility of TOPSIS, four different weighting scenarios were chosen to be using in conjunction with Eq. (1): general focus, performance focus, cost focus, and planning focus. These weighting scenarios are outlined in Table 14. As mentioned previously, development and deployment costs were added together to generate a single LCC FOM in order to accurately portray the total cost required as a metric.

Table 14. Weighting Scenarios used for Selected Weighting Scenarios.

Figure of Merit	General Focus	Performance Focus	Cost Focus	Planning Focus
Effectiveness	0.2	0.40	0.05	0.3
Applicability	0.2	0.40	0.05	0.3
TRL	0.2	0.067	0.05	0.1
R&D3	0.2	0.067	0.05	0.1
Total LCC	0.2	0.067	0.80	0.2

For the general focus scenario, all the weight metrics are set equal. In the performance and cost focus scenarios, 80% of the weight is given to the effectiveness and applicability, and total LCC, respectively. The planning focus represents a typical mission planning scenario, where performance is weighted heavily but consideration is still given to the other metrics. These weighting scenarios were applied to the FOMs for each metric and are plotted below for each test case in Figures 5-7.

1. Apophis Results

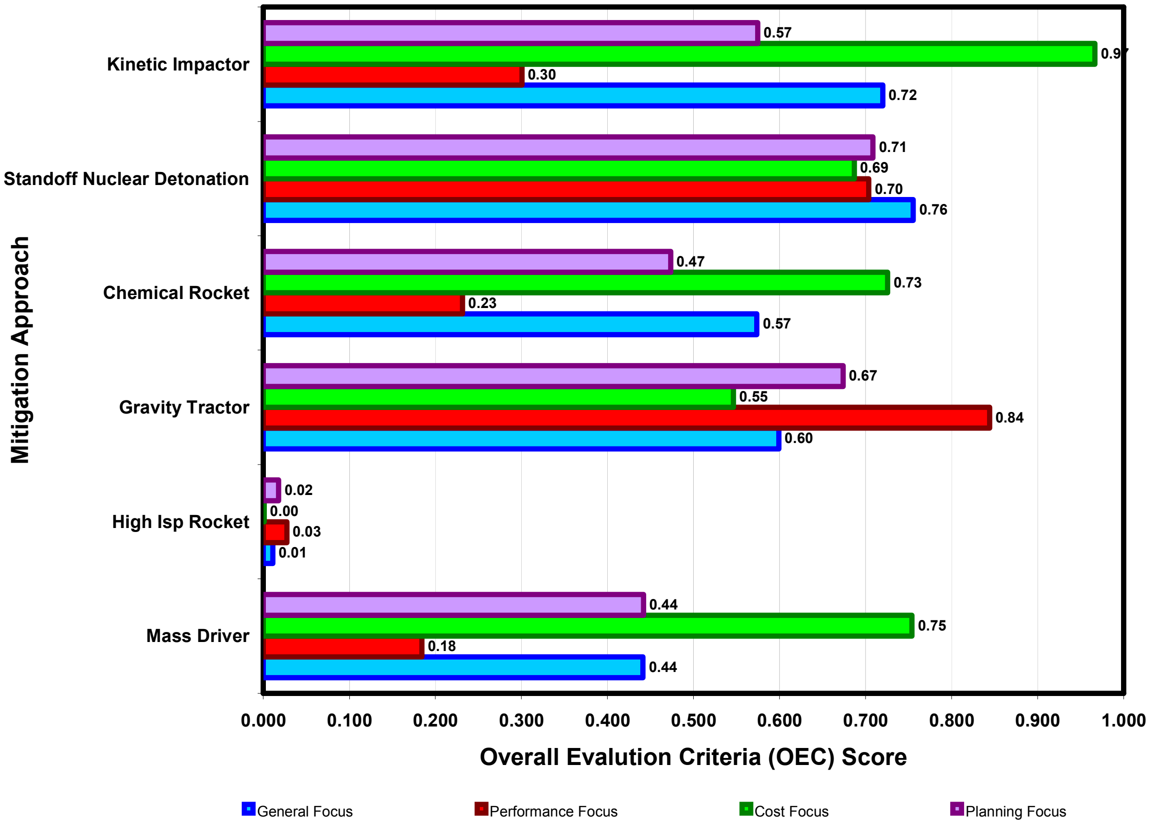

Figure 5. Mitigation Option OECs with Different Weighting Scenarios for the Apophis Test Case.

Due to the low ΔV requirements for achieving the desired change in miss distance for Apophis, every mitigation technique requires only a single launch. This has the effect of neutralizing the effectiveness and deployment cost scores, which can be seen in Figure 5. Because the performance focus weighting scenario only considers applicability to the NEO, the gravity tractor is the strongest performer in this scenario. Similarly, the cost focus weighting scenario is dominated by the development cost. The kinetic impactor therefore scores very well due to its low costs of development, whereas the high Isp rocket scores very poorly.

The general focus and planning focus weighting scenarios yield similar results, with the gravity tractor and kinetic impactor performing the best and the high Isp rocket performing the worst. In both cases, the relative spread of scores between the mitigation options is low, i.e. they all perform fairly well, excluding the high Isp rocket.

Because the effectiveness and deployment cost metrics are essentially neutralized in this test case, the high development cost, low TRL, and high R&D^3 ratings of the high Isp rocket dominate its score. The relative difference between the other mitigation options' scores is somewhat small, so the high Isp rocket scores poorly in every weighting scenario.

Overall, the gravity tractor, standoff nuclear detonation, and kinetic impactor perform the highest and the high Isp rocket performs the lowest. It should be noted that the determination of Apophis's type as either monolithic or rubble-pile would have a profound impact on these results. A monolithic Apophis would favor the kinetic impactor or standoff nuclear detonation approach, whereas a rubble-pile Apophis would favor the gravity tractor approach.

2. D'Artagnan Results

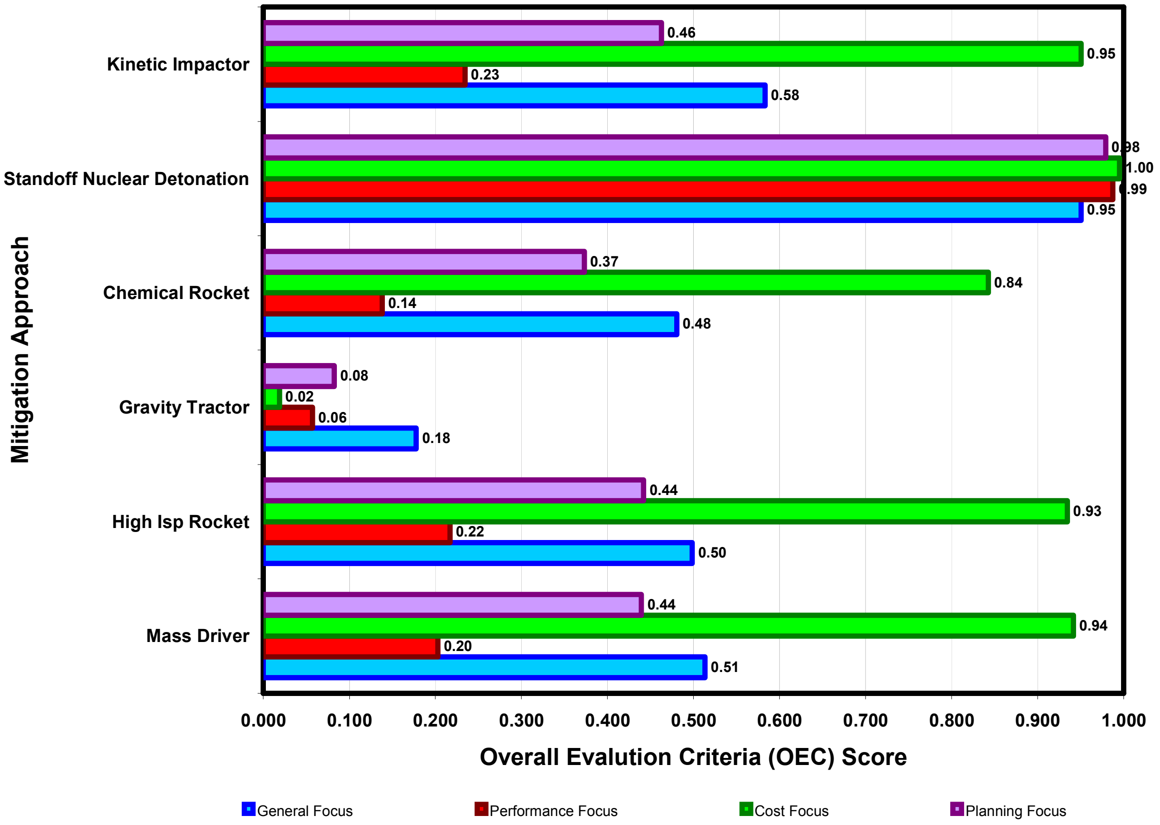

Figure 6. Mitigation Option OECs with Different Weighting Scenarios for the D'Artagnan Test Case.

As a silicaceous, monolithic asteroid with a large ΔV required for threat mitigation, D'Artagnan is the perfect test case for the standoff nuclear detonation option. The results, as seen in Figure 6, show this very clearly. The standoff nuclear detonation option dominates every weighting scenario because of its low technology requirements and very high effectiveness.

The gravity tractor is the lowest performer in this case. Its applicability to rubble-piles is irrelevant, and its high precision does not make up for the very low effectiveness. As seen in Table 6, the gravity tractor would require nearly an order of magnitude more launches than any of the other options, thus negatively impacting its effectiveness and LCC.

Although their performance is lower than other techniques, the relative low development and acquisition costs of the kinetic impactor and mass driver give these options an edge that allows them to perform reasonably well. The chemical rocket's ease of development allows it to score reasonably well in terms of cost, but its poor effectiveness severely lowers its performance weighting scenario score. Conversely, the high Isp rocket's high effectiveness but low technology development scores and high development costs make its overall OECs similar to the other methods.

Overall, the standoff nuclear detonation option is the clear winner. Its low cost, high effectiveness, and strong performance against monolithic NEOs make it the ideal solution to the D'Artagnan test case.

3. Athos Results

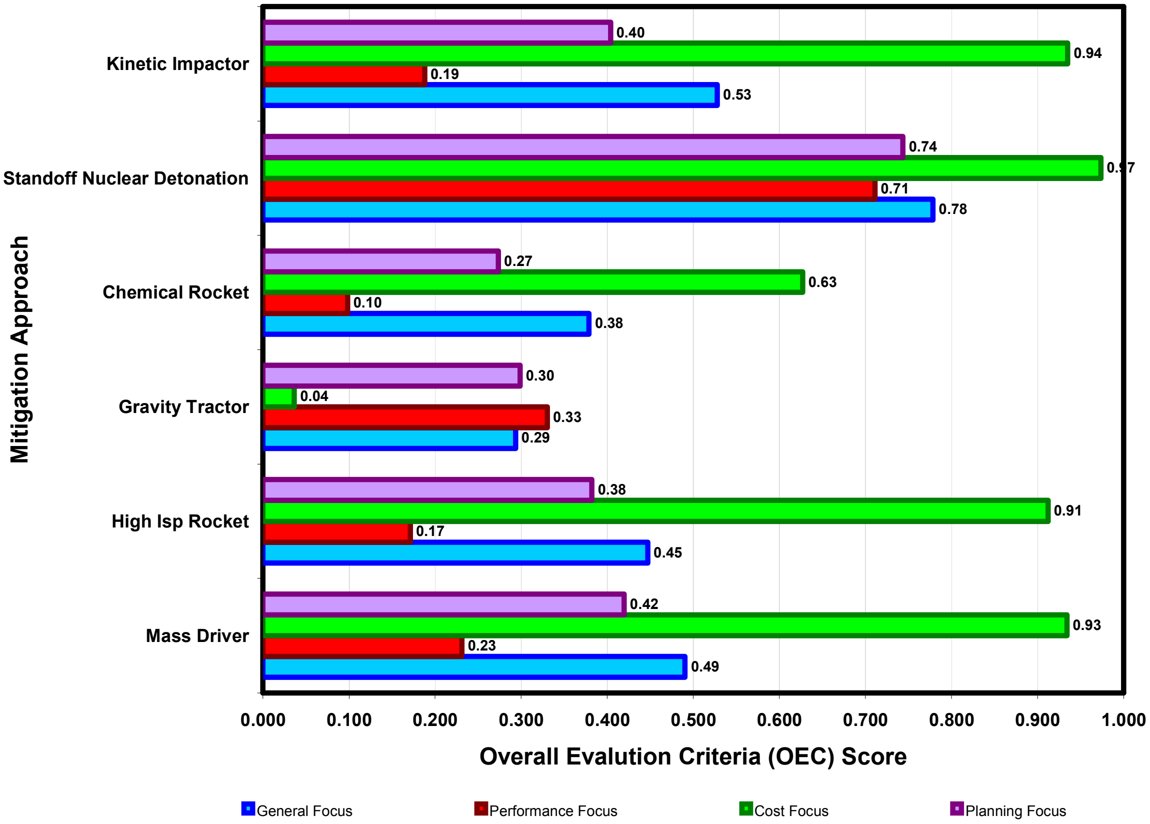

Figure 7. Mitigation Option OECs with Different Weighting Scenarios for the Athos Test Case.

Athos presents a more difficult problem than D'Artagnan. It is five times as massive and a rubble-pile, but requires a similar ΔV to achieve the required change in miss distance. The OEC results for each mitigation technique vary significantly over the four weighting scenarios, as shown in Figure 7. The kinetic impactor, high Isp rocket, and mass driver all perform well in terms of cost, but very poorly in terms of performance due to their inability to adequately handle a rubble-pile. Due to its lower effectiveness performance and large number of launches required, the chemical rocket scores worse than these three in terms of both cost and performance.

As with D'Artagnan, the standoff nuclear detonation option is the strongest performer overall by a significant margin. Due to its applicability to rubble-piles, the gravity tractor outperforms every method save the standoff nuclear detonation in the performance focus weighting scenario, but performs very poorly in the cost focus scenario because of the large number of launches required.

VI. Conclusions

This paper has outlined an effort to develop a process for comparing different NEO mitigation options using a consistent methodology and common analysis assumptions. To accurately model these techniques, an entire mitigation mission from Earth departure to mission completion is simulated. In order to determine the momentum the different options impart to the NEO, interactions with the NEO are approximated by combining published data about each technique with first-order estimates and Newtonian physics.

To fairly compare these techniques, additional metrics are considered in the ranking of the different options: applicability to the composition and rotation properties of the NEO, technological readiness, degree of development difficulty, development cost, and deployment cost. The process developed here quantifies these different factors using expert analysis and then, along with the induced change in velocity, determines an Overall Evaluation Criterion (OEC) for each technique.

Six different NEO mitigation options are evaluated relative to each other: kinetic impactor, standoff nuclear detonation, chemical rocket, gravity tractor, high Isp rocket, and mass driver. Direct comparisons between the techniques are made by applying identical starting conditions and mission parameters to each deflection option and comparing the OEC of each.

The selected mitigation techniques are applied to three sample NEO cases: Apophis, D'Artagnan, and Athos. In the Apophis case, the kinetic impactor, standoff nuclear detonation, and gravity tractor rank highest while the high Isp rocket ranks the lowest. In both the D'Artagnan and Athos cases, the standoff nuclear detonation ranks the highest and the gravity tractor ranks the lowest.

Overall, the standoff nuclear detonation is the best performer. Its very high effectiveness, generally applicability to most NEO cases, and low technology requirements allow it to score very highly in this study. It should be noted, however, that political acceptability is a powerful decision-making factor that is not considered in this process and would be a major factor in the development and deployment of nuclear weapons as a NEO mitigation technique. Depending on the scenario, the high Isp rocket and gravity tractor can perform very poorly. In cases where the number of launches is low, the development cost of the high Isp rocket will not be offset by the cost of the launches and its overall performance will suffer. The gravity tractor, alternatively, is likely the idea candidate in cases where attachment to the NEO would be difficult and the required change in NEO velocity is small. The other mitigation options vary in performance based on the scenario being considered.

The process developed in this study has been proven valuable for its flexibility and applicability to a wide variety of mitigation options and NEO candidate threats. Any number of mitigation options could be considered against any single NEO or a subset of the greater NEO population. Future studies could also incorporate additional performance metrics and alternative weighting scenarios to further broaden the scope of the rankings determined for the options being considered.

Acknowledgments

Mr. Jon G. Wallace, a colleague at SpaceWorks Engineering, Inc. (SEI), developed the gravity tractor and standoff nuclear detonation diagrams and was critical in the final editing and formatting of this document. Mr. Ben Stahl, an M.S. degree candidate in the School of Aerospace Engineering at the Georgia Institute of Technology (Atlanta, Georgia), conducted the analyses associated with the deflection ΔV requirements for all three case studies. He is also responsible for modifying the original JAT tools to propagate a perturbed n-body trajectory so that the effects of various deflection options on the resultant heliocentric orbit could be explored. Mr. Stahl's graduate research is sponsored by SEI.

References

[1]Gritzner, C., Häntschel, G., and Fasoulas, S., "Near-Earth Object Hazard Mitigation Publication Analysis," Final Report, Eurospace, 19 Jan. 2001.

[2]Adams, R., et al., "Survey of Technologies Relevant to Defense From Near Earth Objects," NASA/TP-2004-213089, NASA Marshall Space Flight Center, Alabama, July 2004.

[3]Rogers, G. and Izenberg, N., "Comparison of the Efficiency of Various Asteroid Hazard Mitigation Techniques," White Paper, NASA NEO Workshop, Vail, Colorado, 26-28 June 2006.

[4]Colombo, C., et al., "A Comparative Assessment of Different Deviation Strategies for Dangerous NEO," IAC-06-A3.5.8, 57th International Astronautical Congress, Valencia, Spain, 2-6 Oct. 2006.

[5]Chesley, S. R., "Potential Impact Detection for Near-Earth Asteroids: The Case of 99942 Apophis (2004 MN)," from *Asteroids, Comets, Meteors*, S. Ferraz-Mello & D. Lazzaro, eds., Proceedings IAU Symposium No. 229, 2005.

[6] Lynch, D. and Peterson, G., ”Athos, Porthos, Aramis & D’Artagnan—Four Planning Scenarios for Planetary Protection,” AIAA Paper 2004-1417, Planetary Defense Conference: Protecting Earth from Asteroids, Orange County, CA, Feb. 23–26, 2004.

[7] Asteroid 99942 Apophis (2004 MN4), Last accessed 19 March, 2007, URL = http://neo.jpl.nasa.gov/cgi-bin/db?name=99942, cited March 6, 2007.

[8] 99942 Apophis (2004 MN4) Physical Properties, Last accessed 19 March, 2007, URL = http://earn.dlr.de/nea/099942.htm, cited March 6, 2007.

[9] Crocker, A., Charania, A., and Olds, J., ”An Introduction to the ROSETTA Modeling Process for Advanced Space Transportation Technology Investment”, AIAA 2001-4625, Space 2001 Conference and Exposition, Albuquerque, New Mexico, 28-30 Aug. 2001

[10] Charania, A. and Olds, J., ”Application of the Abbreviated Technology Identification, Evaluation, and Selection (ATIES) Methodology to a Mars Orbit Basing (MOB) Solar Clipper Architecture,” IAC-02-U.5.01, 53rd International Astronautical Congress, Houston, Texas, 10-19 Oct. 2002.

[11] St. Germain, B., Charania, A., and Olds, J., ”A Stochastic Process for Prioritizing Lunar Exploration Technologies,” AIAA 2005-6607, Space 2006, Long Beach, California, 30 Aug. – 1 Sept., 2005.

[12] Hwang, C.-L. and K. Yoon, *Multiple Attribute Decision Making*, Number 186 in Lecture Notes in Economics and Mathematical Systems, Berlin/Heidelberg/New York: Springer-Verlag, 1981.

[13] Mankins, J., ”Research and Development Degree of Difficulty (R&D^3),” A White Paper, 10 March 1998.

[14] Mankins, J., ”Technology Readiness Levels,” A White Paper, 6 April 1995.

[15] NASA, ”FY 2008 Budget Request”, URL: http://www.nasa.gov/pdf/168652main_NASA_FY08_Budget_Request.pdf, cited 6 March 2007.

[16] Isakowitz, S., Hopkins, J., and Hopkins J., Jr., *International Reference Guide to Space Launch Systems*, AIAA, Reston, Virginia, 2004.

[17] Gennery, D., ”Deflection Asteroids by Means of Standoff Nuclear Explosions,” AIAA-2004-1439, Planetary Defense Conferece: Protecting Earth from Asteroids, Orange County, California, 23-26 Feb. 2004.

[18] Gertsch, L., Baird, J., and Worsey, P., ”Distributed-Energy Blasting for NEO Destruction”, White Paper, NASA NEO Workshop, Vail, Colorado, 26-28 June 2006.

[19] Sckweickart, R., Chapman, C., Durda, D., and Hut, P., ”Threat Mitigation: The Gravity Tractor,” White Paper 042, NASA NEO Workshop, Vail, Colorado, 26-28 June 2006.

[20] Williams, B. G., Durda, D.D., and Scheeres, D.J., ”The B612 Mission Design,”, AIAA-2004-1448, Planetary Defense Conference: Protecting Earth from Asteroids, Orange County, California, February 23-26, 2004.

[21] Sckweickart, R., Chapman, C., Durda, D., and Hut, P., ”Threat Mitigation: The Asteroid Tugboat,” White Paper 041, NASA NEO Workshop, Vail, Colorado, 26-28 June 2006.

[22] Olds, J., Charania, A., Schaffer, M., ”Multiple Mass Drivers as an Option for Asteroid Deflection Missions,” 2007 Planetary Defense Conference, Washington, D.C., 5-8 March 2007.

[23] Campbell, J. W. et al., ”The Impact Imperative: Laser Ablation for Deflectiong Asteroids, Meteoroids, and Comets from Impacting the Earth,” American Institute of Physics 0-7354-0126-8, Beamed Energy Propulsion: First International Symposium on Beamed Energy Propulsion, Huntsville, Alabama, 5-7 Nov. 2002.

[24] Prussing, J. and Conway, B., *Orbital Mechanics*, Oxford University Press, New York, New York, 1993.

[25] Larson, W. and Wertz, J., *Space Mission Analysis and Design, Third Edition*, Microcosm Press, Torrance, California, and Kluwer Academic Publisers, Dordrecht, The Netherlands, 1999.

[26] Humble, R., Henry, G., and Larson, W., *Space Propulsion Analysis and Design*, McGraw-Hill Companies, Inc., 1995.

[27] Deep Impact Legacy Site, Last accessed on March 19 2007, URL = http://deepimpact.jpl.nasa.gov/index.cfm, cited 6 March 2007.

[28] Galvez, A. and Carnelli, I., ”Learning to Deflect Near Earth Objects: Industrial Design of the Don Quijote Mission,” 56th International Astronautical Congress, Fukuoka, Japan, 17-21 Oct. 2005.

[29] Holsapple, K., ”Response of NEO to Mitigation Techniques,” presentation at 2007 Planetary Defense Conference, Washington, D.C., 5-8 March 2007.

[30] The W87 Warhead, Last accessed on March 19, 2007, URL = http://nuclearweaponarchive.org/Usa/Weapons/W87.html, cited March 6, 2007.

[31] Chang Diaz, F. R. et al., ”The VASIMR Engine: Project Status and Recent Accomplishment”, AIAA 2004-0149, 42nd Aerospace Sciences Meeting and Exhibit, Reno, Nevada, 5-8 Jan. 2004.

[32] Hill, P. and Peterson, C., *Mechanics and Thermodynamics of Propulsion* (Third printing), Addison-Wesley Publishing Company, Inc., Reading, Massachusetts, 1970.

[33] Gehrels, T., *Hazards Due to Comets and Asteroids* (T. Gehrels, ed.), University of Arizona Press, Tucson, Arizona, 1994.