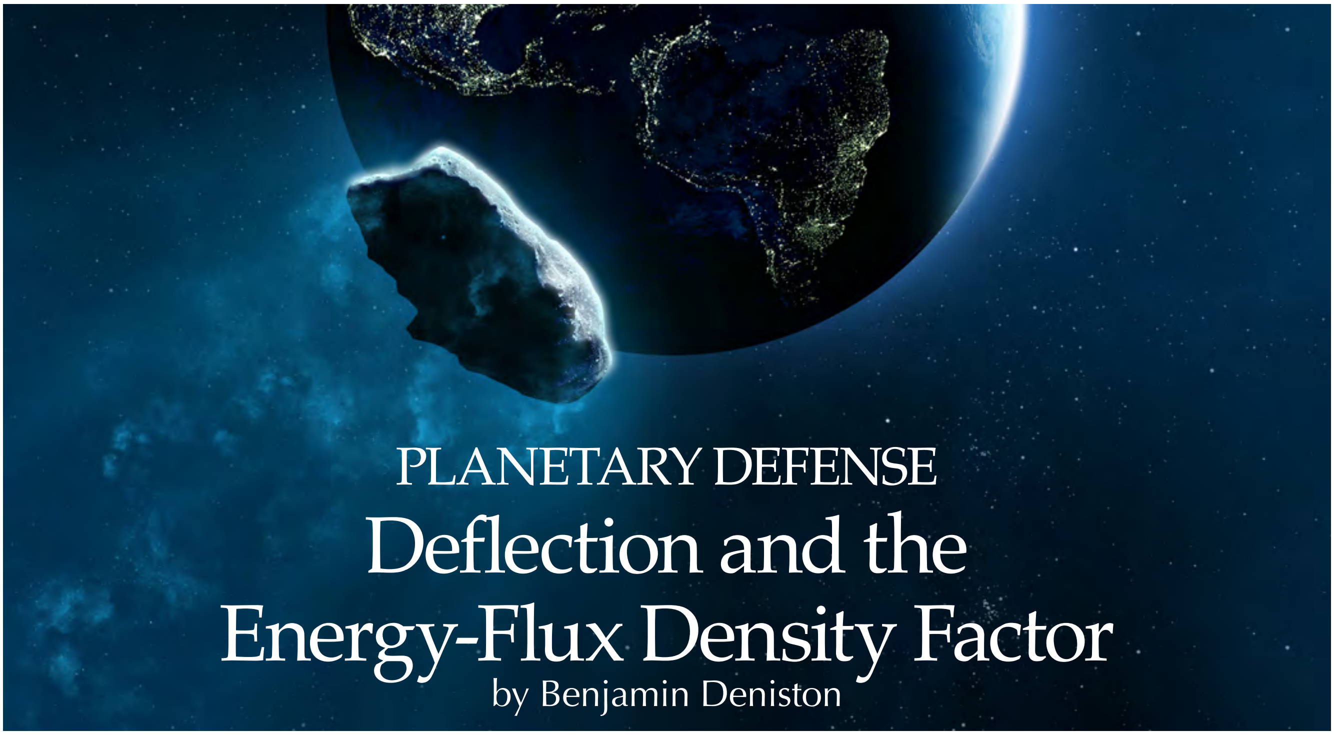

PLANETARY DEFENSE

Deflection and the Energy-Flux Density Factor

by Benjamin Deniston

Mankind is battling an array of natural disasters which continually pose a threat to life on this planet. Thanks to advancements in satellites and weather monitoring systems, our ability to forecast major storms and other extreme weather events is improving. Progress is being made in developing earthquake forecasting systems, designed to detect precursor signals which can provide early warnings before seismic events.[1] Even our Sun is being watched and analyzed more closely than ever, in an attempt to forecast "space weather" events and their effects on the Earth. However, there is another class of events that can not only be foreseen, but can be stopped from ever occurring. Asteroid and comet impacts represent a unique challenge, as we can take the necessary actions to see them coming, but also to ensure the Earth is never again struck in a catastrophic event. While it is likely that we will be able to control storms and certain extreme weather events in the not-too-distant future (if appropriate scientific/economic programs are pursued), for now asteroid defense can hold the title of the only currently preventable natural disaster.

But what are the factors determining our ability to defend the planet, and how can these limits be expanded? In defending the Earth from impacts, there are many possible scenarios we could face: a relatively small near-Earth asteroid on a short-term collision course, giving us little time to act; a large asteroid threatening a possible impact in a few decades, proving more time to act, but proving a larger foe; a worst case scenario of a large long-period comet only months away; and any number of possible variations in between.

The first line of defense is clear: *early detection*. No matter how large the threat is, the more warning time we have, the better off we will be. While asteroid and comet detection systems have been discussed in other locations,[2] the subject here is our ability to act on this knowledge. This takes us beyond just asteroid or comets per se, to a general consideration of our power for action within the universe.

Initial Considerations

To state the question in simple terms: 100 years ago we would have had no chance to defend the Earth from an asteroid or comet impact, while presently we have a limited ability to do so under certain circumstances, and in the future we could foreseeably develop the means to defend against threats currently outside of our defense capability – what determines these qualitative changes?

While there are countless important discoveries and technological innovations which have contributed to this process (and shouldn't have their importance dismissed), the subsuming role of ***energy-flux density*** will be considered here.[3]

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[1] See, *IGMASS: Towards International Collaboration in the Defense of Mankind,* "Progress in Seismic Forecasting," page 26, in this issue. See also, *Science Can Predict Earthquakes*, in the Winter 2011-12 issue.

[2] In this issue see, "Strategic Defense of the Earth: Observation Systems," page 16.

[3] "Energy-flux density" as specifically defined by Lyndon LaRouche, in his science of physical economics. For example, see, *So, You Wish to Learn All About Economics?: A Text on Elementary Mathematical Economics*, New York: New Benjamin Franklin Pub. House, 1984.

Table I
The Energy Density of Fuels

FUEL SOURCE	ENERGY DENSITY (J/g)
Combustion of Wood	1.8×10^4
Combustion of Coal (Bituminous)	2.7×10^4
Combustion of Petroleum (Diesel)	4.6×10^4
Combustion of H_2/O_2	1.2×10^5 (only H_2 mass considered)
Combustion of H_2/O_2	1.3×10^4 (Combined mass considered)
Typical Nuclear Fuel	3.7×10^9
Direct Fission Energy of U-235	8.2×10^{10}
Deuterium-Tritium Fusion	3.2×10^{11}
Annihilation of Anti-Matter	9.0×10^{13}

21st Century

Energy densities for wood, coal, and petroleum, do not include the mass of oxygen required for combustion, since in their typical applications, it is simply drawn from the atmosphere. Values for hydrogen combustion are given with and without considering the mass of oxygen.

This can be illustrated in first approximation by comparing the energy densities of successive power sources.

The significance is not simply found in the increase in energy, but in the physical economic implications: fundamental changes in the human species' space-time relationship with the universe, where leaps from one level to the next define new (previously impossible) modes of action. As in transportation, for example, development of systems associated with successive fuel sources create fundamentally new possibilities. On the Earth's surface, the locomotive revolution was associated with coal-fired engines, whereas the internal combustion engine required the advancement to petroleum. Airplane flight depends upon the higher energy to weight ratios of petroleum, but rocket travel from the Earth's surface to orbit (and beyond) has demanded the most efficient chemical combustion reactions possible.

Although transportation is only one expression of a broader qualitative change, it helps to introduce the concept of transformations in the physical boundaries of mankind's action within the universe. Taking this investigation further, only the energy densities of nuclear fission, to a limited degree, but ultimately thermonuclear fusion and matter-antimatter reactions, can truly provide mankind with efficient and timely access to the Solar System, as this reality is expressed in basic fuel and mass limitations. For example, we can measure the ratio of the total starting mass of a spacecraft (including all of its fuel) to its final mass upon arrival at its destination (in other words, measuring how much of the initial mass is the fuel required for the trip), and then compare how this ratio changes for different fuel sources (mass ratio). Or, the specific impulse can be determined by comparing how long one pound of fuel can provide one pound of thrust.[4]

Beyond the consideration of the energy density of a fuel source for transportation, higher levels of energy-flux density have systemic effects for the entire economy. The transitions from the hydrocarbon-based economy to the nuclear economy, and the yet-to-be realized, but desperately needed, transition to the fusion economy, are premier examples.[5]

Planetary Defense

For the asteroid and comet threats specifically, and ultimately the defense of all life on our planet, the ability to wield higher energy densities becomes crucial. We know for certain that there will be significant asteroid or comet impacts in the future. The question, then, becomes, will we take the necessary actions to deflect or destroy prospective threats before they hit?

This brings two interrelated aspects into focus: the energy required to influence the asteroids or comets themselves, and, even prior to that, the ability to reach the body in the first place.[6]

Moving spacecraft around the Solar System is not as

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[4] *The Role of Nuclear Power and Nuclear Propulsion in the Peaceful Exploration of Space*, IAEA, 2005; page 34, and Appendix VI (page 116).

[5] For example, regarding mankind's entry into the nuclear age, see, "The Isotope Economy," J. Tennenbaum, *21st Century Science and Technology*, Fall-Winter 2006. Pertaining to fusion-related directed energy research see, "The Economic Impact of Relativistic Beam Technology," June 15, 1983; EIR Research Inc.

[6] Again, this is not to dismiss the crucial role of finding and tracking asteroids and comets long before they may become a threat. While that absolutely must be done, here we focus on the ability to act on that knowledge.

Table II
Mass Ratio of Various Rocket Fuels

MODE	FUEL	MASS RATIO	SPECIFIC IMPULSE (Seconds)
Chemical	O_2/H_2	15 to 1	4,300
Fission	Heating Hydrogen Propellant (at 2,700 K)	3.2 to 1	9,600
Fission	Heating Hydrogen Propellant (at 5,000 K)	1.5 to 1	25,500
Fission	Heating Hydrogen Propellant (at 20,000 K)	1.2 to 1	66,000
Fission	Direct Fission of Uranium-235	1.001 to 1	13,000,000
Thermonuclear Fusion	Fusion of Hydrogen Isoptopes to Form Helium	1.0003 to 1	36,000,000
Annihilation of Matter	Matter-Antimatter Annihilation	1.00003 to 1	300,000,000

IAEA, LANL, *21st Century*

The mass/ratio values given here correspond to a particular trip made on an inertial (rather than continually accelerating) path. Changing the distance of destination and the desired acceleration rate would alter the values. For example, a three-day trip to Mars, undertaken with a constant acceleration and deceleration of 1-g, would give mass ratios of 1.007 for fusion, and an astronomical 1026 for chemical propulsion. Even 20,000K fission would have a mass-ratio of 50 for such an ambitious trip. Since constant acceleration also requires carrying all the fuel for the remainder of the trip, the fuel requirements increase exponentially with trip distance.

simple as moving from location A to location B, because we are dealing with orbits within a gravitational field. For example, current missions to Mars can only be launched at specific times (about every 2.17 years). This is not to wait for the planets to be close in terms of distance across Euclidean space, but it is when the orbital relationships of Earth and Mars provide a least-energy orbital pathway between them. Because changing an orbit requires a change in speed, space travel is often discussed in terms of the change in velocity required (or **delta-V**).

In the case of a potentially threatening near-Earth asteroid, for example, when decades of warning time are available, a minimal energy trajectory can be determined to intercept the asteroid, and the launch date can wait until the trajectories of the Earth and the target reach the positions which provide that relatively low energy path.

However, when there is not sufficient warning time to wait for this optimal timing, then the energy requirements can quickly jump many fold.[7] This would then require more fuel, meaning either a heavier spacecraft to start with, or a greater proportion of an unchanged total mass going towards fuel, leaving less mass free for the spacecraft upon arrival. For chemical propulsion, with its inherently low energy density, this is problematic, and can easily become untenable. But, relative to any specific scenario, higher levels of energy-flux density inherently have the potential to provide a greater delta-V. This underscores the need for more advanced propulsion systems, with fission playing a useful part, but a greater focus on the propulsion potential of fusion (while looking towards harnessing matter-antimatter reactions), in order to truly open up mankind's efficient access to the Solar System.

Defense

When it comes to altering the path of an asteroid or comet to ensure it misses the Earth, various methods have been considered, and are often categorized into different types. For example, there are "slow-push-pull" methods, in which a small amount of force is exerted over a long period of time to slowly alter the path of the asteroid or comet, and there are "quick" methods, in which a large amount of force is applied over a short period of time.[8]

Relative to many of the asteroids or comets in question, even applying an intense burst of energy quickly may not amount to much of an effect. To use the example provided in the 2010 National Research Council report cited

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[7] See, *Defending Planet Earth: Near-Earth Object Surveys and Hazard Mitigation Strategies*, page 80-84. National Research Council, 2010.

[8] For a more detailed description of each of the following methods, and the particular benefits or limitations of each, see Chapter 4, "Preventing or mitigating an impact," of *Dealing with the Threat to Earth from Asteroids and Comets*, IAA, 2009 (pages 50 to 67); and Chapter 5, "Mitigation," of *Defending Planet Earth: Near-Earth Object Surveys and Hazard Mitigation Strategies*, National Research Council, 2010 (pages 66-88).

above, if we want to change the position of an asteroid by 2.5 Earth radii (enough to ensure if misses the Earth), this could be done by hitting the target with a kinetic impactor, to either speed it up or slow it down by a tiny amount (only 1 centimeter per second), if that speed change is induced *10 years* prior to the feared impact. The 10 year period is required for the small speed change to culminate in a large enough displacement of the target's future position. For certain medium-sized asteroids this is possible with current technologies, assuming we have a few decades of warning time.

If, instead of a kinetic impact, a gravity tractor were used, it would also have to begin exerting a small gravitational pull on the asteroid in question years to decades before the impact date (depending on the target's size), but in this case continuously applying its gravitational potential for the entire time, in order to ensure the asteroid misses the Earth.

As a function of the size of the asteroid in question and the amount of time available to act, different deflection options can be compared together on one chart, showing their effectiveness for different time and size scenarios. Such comparisons have been done as part of comprehensive reports on planetary defense, such as the examples in the graphs on the following page.

Slow-Push-Pull Methods

Gravity tractor

Using the mass of a spacecraft to gravitationally pull on the target

Attached thruster

Placing a thruster on the target, used to push it off course

Laser ablation

Using a laser to continuously vaporize a small area on the surface of the target, creating a thrust

Mass driver

An apparatus to throw the target's own material off its surface, pushing it away

Alteration of reflective or thermal properties

Painting or covering the surface of the target, changing its interaction with the Sun's radiation and very slowly altering its path

Quick Methods

Kinetic impact

Directly hitting the target with a spacecraft at a high speed

Nuclear explosive device

Using a nuclear explosive to disrupt the trajectory of the target

These comparisons of mitigation options consistently show that nuclear explosive devices are the most powerful currently available, and, hence, the only option in the cases of short warning times or large objects. However, to see what can be done with new technological developments, we must look to the role of energy-flux density as the determining factor of various mitigation methods.

Hypervelocity Kinetic Impact:

The 1992 *Near-Earth Object Interception Workshop*, held at Los Alamos National Laboratory, brought together an array of specialists contributing to various aspects of the planetary defense challenge. Included in the proceedings was a study demonstrating that in certain scenarios, a kinetic impactor can actually match the deflection potential previously only thought achievable with a thermonuclear warhead, *but only when utilizing speeds achievable only by a variation of nuclear propulsion*. This hypervelocity kinetic impact was based on the famous Project Orion, a 1960s program to develop a spacecraft that would be propelled by a series of small nuclear bombs, released out the back of the ship and then detonated behind its "pusher-plate," propelling the spacecraft. Although a fair amount of design and preparatory testing was done, Orion never got off the ground.[9]

This 1992 study ends with a specific scenario in which we would only have a short warning time, and our intercepting spacecraft could only be launched when the asteroid was only 17 hours from impact (at a distance of 1.5 million km). Comparing an Orion-like propulsion system and a standard chemical propulsion system, the author showed that the nuclear explosive propulsion design would be able to reach the target in less than 1/25th the time, and at a speed 85 times greater! As the author concluded, "the exceedingly high

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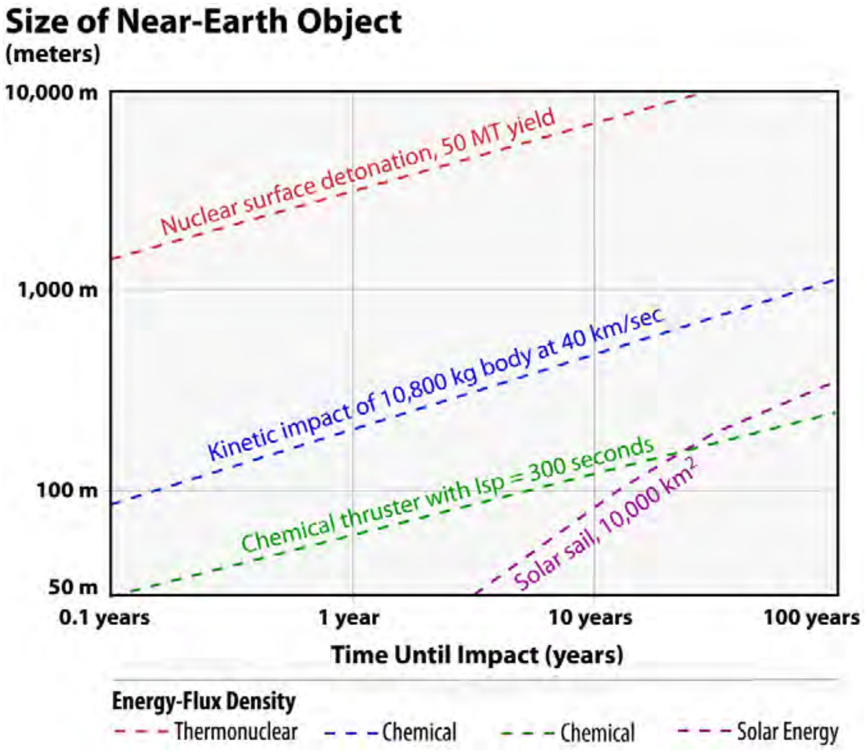
[9] Despite this, the general concept is still sound, and could even be advanced farther with current technologies.

relative velocities provide sufficient kinetic energy to deflect these malignant astral bodies without resorting to an explosive warhead, nuclear or otherwise.”[10]

Nuclear-Electric Propulsion:

Currently Russia’s Keldysh Center, Energia, and Rosatom are developing the first-ever megawatt-class electric spacecraft, using a small nuclear reactor to generate electricity to power an ion propulsion system. Despite the low thrust of electric propulsion, the very high specific impulse of this system and the ability for continuous propulsion throughout the mission expands our capability for rendezvous missions, for either mitigation (e.g. gravity tractor) or for science and characterization (determining what the asteroid or comet is made of). This will be a vast improvement over existing solar-electric propulsion systems, and entering megawatt levels of electricity generation in space will expand the number and power of scientific instruments available to spacecraft and satellites (current systems are measured in the tens of kilowatts).[11]

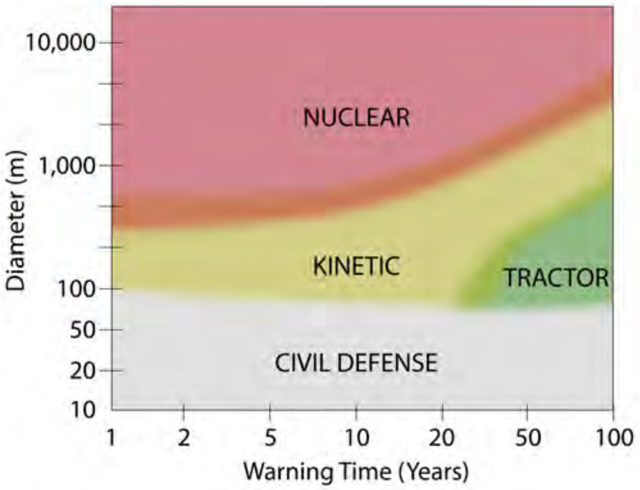


Reproduced from *Dealing with the Threat to Earth from Asteroids and Comets*, IAA, 2009, p. 66.

Nuclear-Thermal Propulsion:

Part of the 1992 Los Alamos Workshop was a technology assessment, indicating future technologies which could be developed with applications to planetary defense. Included was a brief analysis of the general benefits of nuclear-thermal propulsion systems, in which a nuclear reactor is used to heat and expel hydrogen as a propellant. Compared with existing chemical systems, nuclear-thermal propulsion promises either substantially lower launch mass for comparable missions, or quicker intercept speeds.[12]

Nuclear rockets with hydrogen propellant offer significant performance benefits over chemical rockets. They have much higher specific impulse, on the order of ~1,000 seconds compared to 450 seconds for H_2/O_2 rockets. This higher specific impulse allows nuclear rockets to achieve substantially higher final velocities than chemical rockets, at least twice as great for comparable launch weight. Alternatively, for comparable final velocities and payload, nuclear rockets can be a factor of



Adapted from *Defending Planet Earth: Near-Earth Object Surveys and Hazard Mitigation Strategies*, National Research Council, 2010, page 85.

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[10] “Nuclear Explosive Propelled Interceptor for Deflecting Comets and Asteroids on a Collision Course with Earth,” J. C. Solem, *Proceedings of the Near-Earth Object Interception Workshop*, Los Alamos National Laboratory, New Mexico, 1992, January 14-16, pages 121-130.

[11] “The role of space power in solving prospective problems in the interests of global safety, science and social economic sphere,” 2010, presentation by A. S. Koroteyev, Director of SSC Keldysh Research Centre, Academician of Russian Academy of Sciences.

[12] Workshop Summary, “Assessment of Current and Future Technologies,” *Proceedings of the Near-Earth Object Interception Workshop*, Los Alamos National Laboratory, New Mexico, 1992, January 14-16, pages 225-234.

> three to four lower in launch mass. These performance advantages are of potential benefit for NEO-intercept missions. For close-in intercepts, high velocity translates into quicker intercepts, reducing the level of risk and amount of delta-V deflection required. For distant intercepts, lower launch mass translates into lower cost. Extensive testing of nuclear engines has been carried out by the U.S. in the NERVA program, and by the former USSR. The basic feasibility of nuclear rockets has been well established. Recently, the SNTP particle bed nuclear rocket program has been disclosed by the U.S. Department of Defense. This program [was] developing a compact nuclear rocket with very high thrust/weight ratio.

Table III
Propulsion Comparisons

	CHEMICAL PROPULSION	NUCLEAR EXPLOSIVE PROPULSION
Specific Impulse	500 seconds	42,500 seconds
Rocket Velocity	6 km/second	821 km/second
Intercept Range	29,300 km	1,460,000 km
Intercept Time	804 minutes	30 minutes

"Nuclear Explosive Propelled Interceptor for Deflecting Comets and Asteroids on a Collision Course with Earth," J. C. Solem, *Proceedings of the Near-Earth Object Interception Workshop*, Los Alamos National Laboratory, New Mexico, 1992, January 14-16, page 121-130.

In 2011 a more detailed study examined how nuclear thermal systems can increase our capability to handle worst-case scenarios. Long-period comets can come at us with little warning, and often at higher speeds than asteroids. While thermonuclear explosives provide the greatest deflection capability, the propulsion systems available to deploy them still remain a limiting factor. The 2011 study, "Near-Earth object interception using nuclear-thermal rocket propulsion," showed that by reducing fuel weight requirements, nuclear-thermal propulsion increases the maximum size that could possibly be dealt with.[13]

> Comparison of propulsion technologies for this mission shows that NTR [nuclear thermal rocket] outperforms other options substantially. The discussion concludes with an estimate of the comet size (5 km) that could be deflected using NTR propulsion, given current launch capabilities.

In Defense of Progress

A variety of different mitigation options have been considered, each with particular benefits and short falls relative to specific scenarios. Given our current technological capabilities, only a few of these options are currently available, although studies, such as those cited above, do provide an indication of what can be possible with future technological developments. However, the point here is not to advocate one specific option, but to examine the considerations which cut across various options, and can provide mankind with a broad-based capability to act in the Solar System.

As discussed above, kinetic impacts can reach the capabilities of thermonuclear explosives, but only when accelerated with nuclear-explosive propulsion. The capabilities of electric propulsion for rendezvous missions to characterize and study asteroids or comets, or to utilize a gravitational tractor method to alter their trajectories, can be greatly improved when nuclear-electric is utilized instead of solar-electric. With nuclear-thermal propulsion for planetary defense, launch mass and intercept times can be reduced, and we can handle larger threats than we could with chemical propulsion systems. Even the fundamental geometry of our access to the Solar System can be revolutionized with the capabilities of nuclear fission and fusion propulsion systems.

Nuclear power is an invariant in improving our capabilities, and the concept of energy-flux density must be taken as a determining factor in planetary defense. Our nuclear fission and thermonuclear fusion capabilities in space, as a broad set of technologies, must be pursued to qualitatively transform our time-space access to, and action within, our Solar System. The best path to do this is to adopt a science-driver mission to force the challenge of making these breakthroughs. For example, developing fusion propulsion systems capable of transporting human beings to and from Mars at a constant acceleration/deceleration of 1-gravity (1-g) could be that challenge. Achieving this capability for 1-g space travel over the course of a generation or two will provide the technologies to deal with the threats posed to the Earth. This applies to defense, but also situates defense as a subsumed factor of general scientific and economic advance, in space and on Earth.

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[13] X. L. Zhang, E. Ball, L. Kochmanski, S. D. Howe, "Near-Earth object interception using nuclear thermal rocket propulsion," *Proceedings of the Institution of Mechanical Engineers Part G - Journal of Aerospace Engineering*, 2011; 225 (G2 Sp. Iss): 181-193.