LA-UR-15-23198

A New Vision for Fusion Energy Research:

Fusion Rocket Engines for Planetary Defense

G. A. Wurden[1], T. E. Weber[1], P. J. Turchi[2], P. B. Parks[3], T. E. Evans[3],

S. A. Cohen[4], J. T. Cassibry[5], E. M. Campbell[6]

[1]Los Alamos National Laboratory
[2]Santa Fe, NM
[3]General Atomics
[4]Princeton Plasma Physics Laboratory
[5]University of Alabama, Huntsville
[6]Sandia National Laboratory

Abstract

We argue that it is essential for the fusion energy program to identify an imagination-capturing critical mission by developing a unique product which could command the marketplace. We lay out the logic that this product is a fusion rocket engine, to enable a rapid response capable of deflecting an incoming comet, to prevent its impact on the planet Earth, in defense of our population, infrastructure, and civilization. As a side benefit, deep space solar system exploration, with greater speed and orders-of-magnitude greater payload mass would also be possible.

The US Department of Energy's magnetic fusion research program, based in its Office of Science, focuses on plasma and fusion science[1] to support the long term goal of environmentally friendly, socially acceptable, and economically viable electricity production from fusion reactors.[2] For several decades the US magnetic fusion program has had to deal with a lack of urgency towards and inconsistent funding for this ambitious goal. In many American circles, fusion isn't even at the table[3] when it comes to discussing future energy production. Is there another, more urgent, unique, and even more important application for fusion?

Fusion's unique application

As an on-board power source and thruster for fast propulsion in space,[4] a fusion reactor would provide unparalleled performance (high specific impulse and high specific power) for a spacecraft. To begin this discussion, we need some rocket terminology. Specific impulse is defined as $I_{sp} = v_e / g$, where g is the usual Earth's gravitational acceleration constant and v_e is the rocket propellant's exhaust velocity. The rocket equation, $M_f/M_o = \exp(-\Delta V/v_e)$, allows us to relate the final mass M_f of the rocket divided by its initial mass M_o, to the change in velocity ΔV that it is capable of achieving. The rocket requires a power source with an output power $P = \alpha M_s$, where we define α to be the specific power (Watts/kg), and M_s as the mass of the power supply (including the power conditioning, structures, and any waste heat radiators).

Today's best chemical rockets produce propellant exhaust velocities (v_e) up to 4.5 km/sec. Fission (nuclear thermal) rocket engines[5] could roughly double that, to about 8.5 km/sec (< ½ eV/amu temperature equivalent), constrained by material limits.[6] Electrically driven thrusters[7] are already quite efficient and have higher propellant exhaust velocities (corresponding to ~5 eV/amu) but are usually limited in power resulting in low thrust, and are driven by limited electrical power/energy sources (photovoltaic or radioisotope). Development of high power, high thrust plasma thrusters has not been a priority, due primarily to a lack of mission need and the availability of adequate power sources in space.

In contrast, a working nuclear fusion core producing thrust through direct exhaust of hot plasma, could readily generate up to ~1000 km/s exhaust velocities, corresponding to ~10 keV/amu[8], several hundred times higher exhaust velocities than today's high power chemical and nuclear thermal rocket engines. Lesser exhaust velocities could in principle be obtained as needed, through the co-expansion of additional cold propellant, to increase the propellant mass and optimize the exhaust velocity for individual mission requirements[9]. Importantly, the power available could be of order 100's of megawatts, and possibly higher. In all cases, one has to consider tradeoffs between specific impulse, thrust, power, cost and mission requirements for any comparison between different thruster approaches.[10]

The metric for a fusion-powered rocket, as opposed to fusion-generated electricity, is based on performance per unit mass, rather than cents/kilowatt-hour. There are many pre-conceptual point designs for fusion rocket cores, ranging from generic fusion rocket systems studies[11, 12], to levitated dipoles[13], to mirror machines[14], to field reversed configurations[15], and magnetized target fusion[7, 16]. Even ST tokamaks[17] and laser fusion sources[18] have been suggested (although present incarnations aren't reactors, and even so, are much too massive). At the highest level, the unresolved research problem is that we need a working, compact, high thrust-to-mass ratio fusion core. It is clear that the present magnetic fusion approach, involving large tokamaks, *i.e.*, ITER-like, are not matched to the needs for spacecraft propulsion. Alternative fusion reactor designs, more compact and far less massive, will be required. The 2003 Report to FESAC on "Non-electric Applications of Fusion"[4] clearly recognized this application and that a fusion core for spacecraft propulsion might look different than today's mainline fusion approaches. Some requirements would be more stringent and some more relaxed. For example, with a rocket, the thrust-to-mass ratio is a critical parameter; hence having a high-β plasma (β is the ratio of the plasma kinetic energy density to magnetic energy density) is extremely important to reduce the mass of the magnets and their power supplies. Tritium could be carried on short missions, so a breeding blanket is not even needed. First wall requirements could be relaxed (good vacuum in space, and plasma-wall interactions less important for short duration missions). Furthermore, *low* neutron emissions are desirable to reduce the shielding and waste heat radiator mass, thereby improving specific power of the system, meaning that advanced fuels (such as D-He^3) would be preferred over DT.

Why does our civilization need faster spacecraft? Planetary Defense!

Most prior works[8-18] considering the need for fusion rocket engines have focused on manned exploration of the solar system, the large distances involved, and in particular, for the need to get people to Mars[19] or Jupiter[20] quickly enough so that health risks from radiation and possible psychological effects on crews are minimized during long duration missions. However as numerous events have shown, from the Cretaceous-tertiary extinction to the recent meteorite explosion over Chelyabinsk, the solar system can be a dangerous place. Given this history and the potential for large impacts there is *the clear need to be able to quickly protect the Earth from an incoming comet or asteroid by altering the intruder's orbit.* Ways of doing this depend in part on how far out in time the object is identified, and are surveyed in 2004 NASA[21] and 2010 NRC (NAS) reports[22]. For decades of warning, (which may be the case for most discovered asteroids with three to seven year orbits), one can develop different deflection techniques than for cases with only months of warning. Fusion engines deployed on the surface of an asteroid have already been suggested for multi-month deflection of asteroids[23]. Unfortunately, for long-period or hyperbolic orbit objects, the < 1-year warning scenario is more likely the case. Comets typically become detectable to telescopes at Mars to Jupiter distances as they approach the Sun (3-7 astronomical units (AU)). Further, newly discovered comets with this type of orbit would also have extremely high closing velocities (in the 40-80 km/s range, significantly faster than asteroids), with the closing speed depending on what component of the Earth's orbital vector of 30 km/sec adds or subtracts in a potential impact[24]. Plausible scenarios can be envisioned where we have only 6-18 months of warning time. Compared to asteroids in relatively short-period orbits, which in principle can be seen years in advance, **comets are the infrequent but highly destructive threat requiring rapid response.**

An example of a comet threat occurred in 2014, in addition to the better-known far-smaller Chelyabinsk meteor (20 km/s, 1.2×10^4 metric Tons, 500 kilotons impact energy) in 2013 mentioned above. The first comet discovered in 2013, just after New Years on January 3, was detected from the Sidings Springs Observatory in the Southern Hemisphere.[25] It was named C/2013 A1 (at 56 km/s, 0.7 km in diameter, weighing 3×10^8 metric Tons, it had *4 billion megatons of kinetic energy*). For nearly 3 months after first being spotted, the best determination of the orbital elements did not rule out an impact on Mars, on Oct. 19, 2014. In fact it missed Mars by only 1/3 the Earth-Moon distance, at 140,000 km (see Figure 1 below). Had it impacted, the blast would be visible in the daylight from Earth and we probably would have lost all of our spacecraft on the ground and in orbit around Mars. In this example, even with an immediate launch for an intercept (after reasonable orbit determination), one would need a transit time for the intercept of < 6 months.

Figure 1. Space artist Kim Poor's impression of a comet flyby of Mars. Comet C/2013-A1 passed extremely close to Mars on Oct. 19, 2014.

From a threat analysis point of view, we are talking about defending against low probability, high consequence events. A reasonable question to ask, is how much money and effort should we be spending to make such a defense? Though smaller impacts are far more likely than large ones (20 meter diameter once every 100 years, 1 km diameter once every million years) [26], the impact of a 1 km object (or larger) is capable of destroying our civilization. Indeed, such events with planetary wide consequences have occurred in the Earth's past. If one takes an actuarial approach, looking at damage amortized per year, versus probability of the damage occurring, there is a maximum/most probable worst case. We can see this illustrated as a sketch in Figure 2. Here we assign a value of $1M of infrastructure per person, with a world population of 10^{10} people, with a frequency of 1 km impactors estimated at 10^{-6}/year. Small impacts can destroy a city, but not a continent. Intermediate impacts in the oceans can generate tsunamis, which could destroy multiple cities far removed from the impact at one time. Bigger impacts generate huge amounts of debris, firestorms, and planetary wide darkening. From a very simplistic linear viewpoint, this would imply that a planetary defense effort "insurance policy premium" of order $10B/year would be appropriate. We are nowhere close to doing this now.

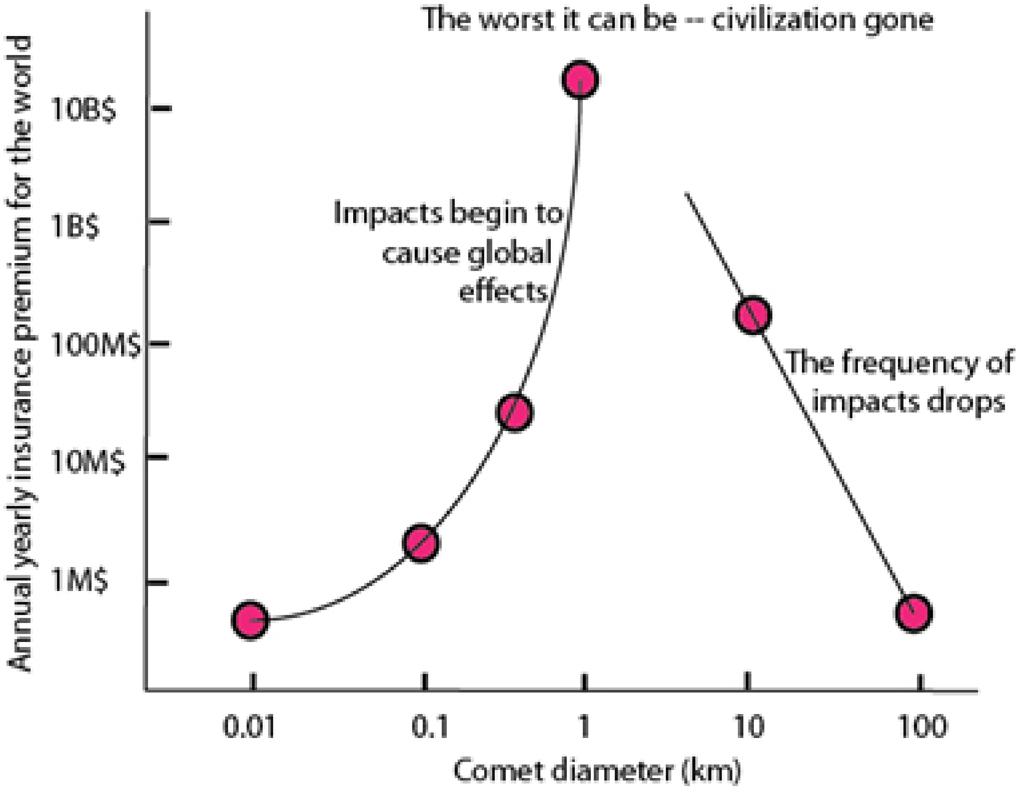

Figure 2: What is it worth spending on Planetary Defense, from an actuarial point of view?

The Nuclear Option:

To change a comet (or an asteroid) trajectory, one has to impart momentum to it. The further away from Earth that you can impart the momentum (i.e. the sooner in time), the smaller the required momentum change. For a comet, we wouldn't have much time to make the needed momentum change. One way to impart a significant momentum change quickly is to set off a nuclear explosion very close to the object (≤ 1km distance)[27]. The ablation (caused by energy from the explosion being absorbed by the object) of one side of the surface of the object will cause a resulting "rocket" effect, and the thrust will change the object's trajectory. *A 2007 NASA Report to Congress on "Near-Earth Object Survey and Deflection Analysis of Alternatives"[28] concluded that a nuclear detonation near to an asteroid or comet is the best way to achieve the required deflection, especially in the case of a large object, and limited response times.* In the 2004 NASA report[20], "nuclear deflection" (not nuclear fragmentation) is defined as using an intense radiation burst to cause sudden heating of the surface of the object, which ablates off material from the object's surface, resulting in a rocket effect. One would consider using the largest nuclear explosives ever tested (10-50 Megatons), consistent with getting them into deep space, and setting them off within 1 km distance of the target object. Rotation of the object (a show-stopper for some approaches) is inconsequential for this technique, and the relatively uniform surface irradiation might still enable deflection of objects with low structural integrity. Importantly, two international space treaties would have to be modified, first to allow nuclear explosives in orbit (as a launch vehicle is assembled), and then to permit nuclear explosions for Planetary Defense in deep space (far beyond the Earth).

A Rapid Response Capability Is Needed

Because mission duration would be of the essence for a comet intercept mission, you don't have the velocity change (ΔV) budget, nor the time to waste to slow down and rendezvous with an incoming comet (which would require roughly 3x the intercept ΔV of a flyby). The comet should be hit on the fly. In particular, our analysis will focus on the shortest time duration, longest range encounter possible (to maximize the time for deflection effects to develop), which is the high-speed flyby case. But you have to get the nuclear explosive there in time to do any good. Consider that with our most powerful chemical rocket ever built -- a Saturn V sitting on the pad (Figure 3) -- it takes 3-days to get out to lunar distances (Apollo going to the Moon). If you want to send even a small payload to Mars distances, it takes 9-12 months (minimum energy Hohmann transfer trajectory) with conventional rocket engines. The future NASA Space Launch Systems (SLS) heavy launch booster will have similar capability as the former Saturn V rocket.

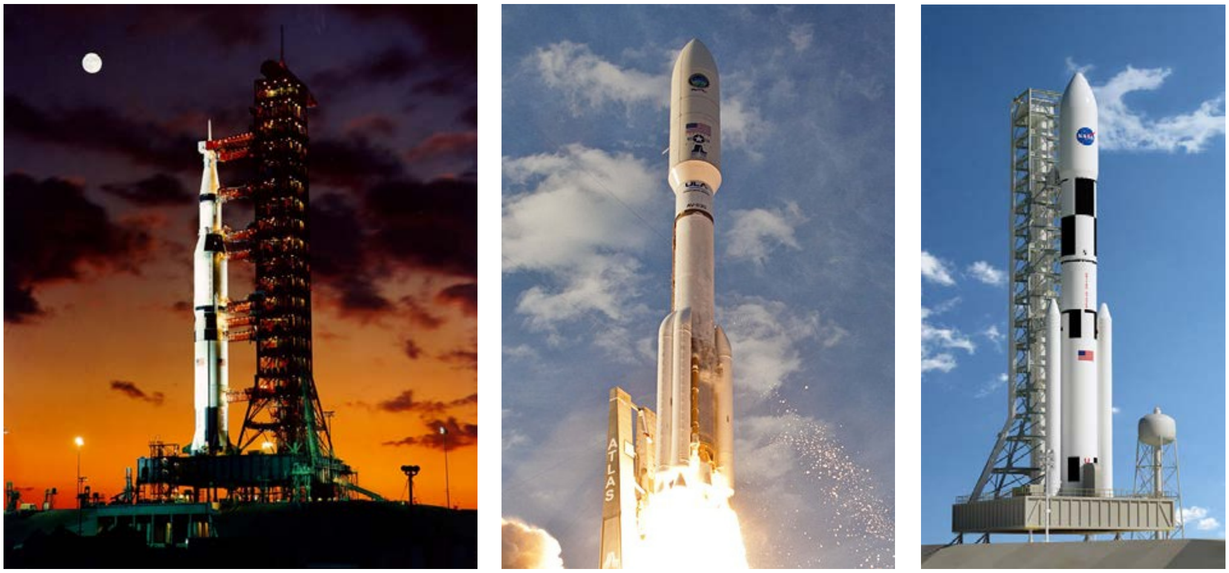

Figure 3. (Credit NASA). Examples of the best heavy lift chemical rockets: Saturn V launch vehicle sitting on the pad (left), with third stage J2 engine specific impulse of 420 seconds, and thrust of 1,000 kN. New Horizons Pluto mission at launch on an Atlas V rocket (middle). NASA's new Space Launch Systems heavy launch vehicle (right).

Nuclear Rocket Engines

As mentioned earlier, Nuclear Thermal (NT) rocket technology[29,30,31] increases the exhaust velocity from a limit of ~4.5 km/s for chemical rockets to ~8.5 km/s, which is still far below what we need for the comet intercept mission. Los Alamos Scientific Laboratory (LASL) built more than a dozen such nuclear thermal rocket engines from 1955 to 1972, with Project Rover. Those engines used the most efficient propellant (hydrogen), and exhausted the hot gas at < 3000 °K, limited by the temperature that the graphite reactor components could withstand. Aerojet and Westinghouse made a final design, of a J2 (third-stage Saturn V) engine replacement (Figure 4), called NERVA,[31] with about a factor of two higher specific impulse, I_{sp} = 900 sec, than the conventional chemical rocket engine it would replace.

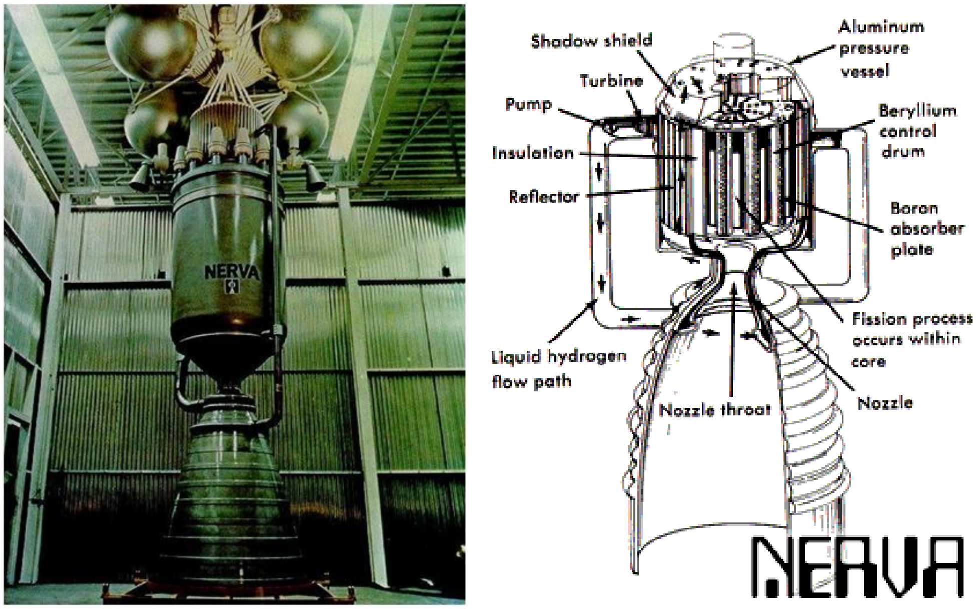
NERVA
Shadow shield
Aluminum pressure vessel
Turbine
Pump
Beryllium control drum
Insulation
Reflector
Boron absorber plate
Fission process occurs within core
Liquid hydrogen flow path
Nozzle throat
Nozzle
NERVA

Figure 4. The NERVA rocket engine, a nuclear thermal third stage replacement for the Saturn V with twice the I_{sp} of the J2 engine. It was never used in space.

Project Rover/NERVA was terminated in late 1972, because we weren't going to Mars with astronauts any time soon, and people were afraid of the risks of nuclear material being spread around the launch pad or into the Atlantic Ocean in case of an accident. Even so, for the high-value Planetary Defense missions, a rocket equipped with nuclear fission thermal engines might be useful for the asteroid threat, because it can get you out there ~2x faster than with a chemical rocket.

Moving to plasma propulsion can even more significantly reduce the required propellant mass. As is well known from consideration of the rocket equation, there are diminishing returns for propellant mass savings when $v_e >> \Delta V$. At this point, propellant mass no longer dominates the calculus of mission space, and the spacecraft powerplant mass (with appropriate waste heat radiators) begins to dominate the total mission mass. Plasma propulsion could be via nuclear fission electrically powered thrusters (nuclear electric propulsion - NEP), fusion electric propulsion (FEP), or eventually fusion core exhaust (fusion propulsion - FP). In a planetary defense scenario, time is of the essence. Thus, traditional low-thrust plasma propulsion schemes (such as Hall or electrostatic ion thrusters) cannot be used. Even experimental plasma thruster concepts[6, 32] could only be considered if powered with a high specific power (α) source (> 1-10 kW/kg).

The problem with typical solar or even nuclear electric propulsion (EP) techniques is that the specific power α of the energy source is much too low unless we use a fusion core with advanced (low neutron output) fuels. Controlled fusion is the only potential energy source, other than nuclear explosives or antimatter, with the required specific power. While solar-electric systems have a specific power (at the Earth distance from the Sun) of order ~ 100 w/kg, that decreases by a factor of 1/25 at Jupiter, and 1/100 at Saturn distances. Taking a fission example, the SAFE-400 nuclear Brayton cycle reactor and radiator system[33] would produce 100 kW electric power, with a mass of 584 kg, for a specific power (without a thruster) of 171 w/kg. Coupling it to an 80% efficient ion thruster of the NSTAR[34] type presently in use on the Dawn mission[35], which has an specific impulse I_{sp} = 3100 seconds (but using 40 units, with a combined weight of 1000 kg, corresponding to 100 kW of available electric energy), one would have a system specific power of 63 (W/kg), but with a thrust of only 4 Newtons. By instead invoking an open-cycle (direct thrust) fusion rocket[9], rather than the typical nuclear-electric system for which the fission reactor waste heat has to be rejected, one could greatly improve the specific power while increasing the I_{sp}, and also greatly increase the total available thrust (total power).

The Threat: Comets are more troubling than Asteroids

For long-lead time asteroid deflection missions (decade timescales), current technology has demonstrated the capability to intercept an object in the inner solar system (for example, the Ceres or Deep Impact missions). However we have not yet actually attempted deflections of asteroids with any technologies, nor compared such experiments to simulations. But comets pose a more difficult problem. They are generally large (civilization-ending, 1-10 km size), are inbound from any angle (out of the plane of the ecliptic), have high orbital speeds by the time they approach Earth, and will only provide short warning times, ~ 1 year, if we are looking.

Given the previous points, it is almost assured that a comet intercept mission will require spacecraft velocities of roughly of the comet's velocity to reach the comet in time to attempt a deflection (see Figure 5). A long period comet's speed as it approaches the Sun, is on the order of the solar system escape velocity (42.1 km/s). Knowing that the Earth's orbital speed is 30 km/second and that the Earth orbits at 1 astronomical unit (1 AU= 149,000,000 km) from the Sun, one quickly infers from this schematic diagram that an interceptor would need to cover distances of order 3-5 AU in a time less than the time to impact. Consider the 12-month warning case, and a comet discovered 10 AU out from the Sun (at the distance of Saturn). Let's suppose we should intercept in ~ ½ of the time remaining to impact of the comet with Earth. The necessary ΔV is ~ 5 AU/6 months = 53 km/sec. Just to do the flyby intercept requires a huge ΔV ! The fastest vehicle we have ever launched from the Earth, was the New Horizons spacecraft on its way to Pluto (with only a 465 kg payload @16.2 km/second, but a rocket weighing 570,000 kg at launch), which took only 9 hours to pass the Moon's orbit after launching from Earth on an Atlas V511 rocket with Centaur and Star48B upper stages [See Figure 3]. While the Pioneer, Voyager, and now New Horizons space probes have achieved solar system escape velocity, multiple planetary fly-bys were used to boost the spacecraft velocity, which requires proper planetary alignment (takes a long time and alignments rarely occur), and places the spacecraft in a very limited range of trajectories. Chemical rockets and gravity assists cannot be counted on for our proposed long-period comet intercept mission.

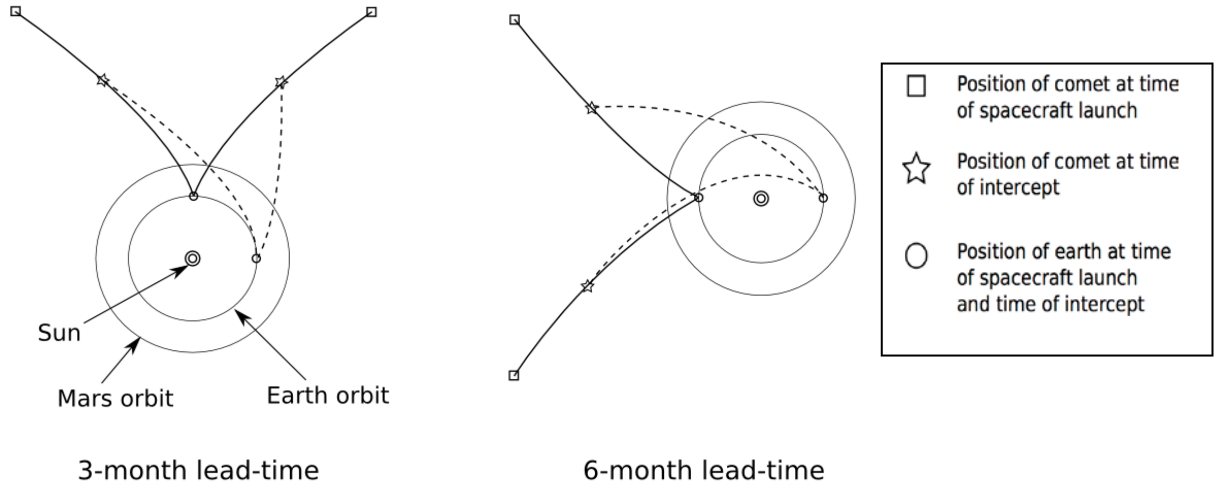
Sun
Mars orbit
Earth orbit
3-month lead-time
6-month lead-time
Position of comet at time of spacecraft launch
Position of comet at time of intercept
Position of earth at time of spacecraft launch and time of intercept

Figure 5. Approximate intercept trajectories for 3 month and 6 month lead times. Even these examples require the interceptor to cover multiple-AU distances to gain the largest possible "lever arm".

The induced comet deflection must have a sufficient effect, an Earth *miss* in distance, R_m, which can be predictable (beyond orbital element uncertainties) months in advance. For example, an Earth-Moon distance represents a "miss" of 400,000 km, whereas the Earth covers a distance in its orbit equal to the diameter of the Earth in 7 minutes. By imparting a velocity change of 10 m/sec to the comet, the remaining time (180 days = 1.5 x 10^7 seconds), produces a miss distance of ~150,000 km, ignoring any closing speed effects of the Earth itself.

By specifying the distance at which the comet is detected and characterized as a threat to earth, and the deflection needed to miss the earth, we can determine the necessary exhaust speed and time, and thereby prescribe the necessary specific power for an intercept mission. We define τ as the time needed to attain the necessary velocity increment ΔV for the postulated mission. In fact τ might be as long as the mission duration. Naturally, the shorter the thrust duration, the higher the required specific power α [in watts/kg, including any conversion inefficiencies] required to achieve the necessary ΔV . We take the initial mass of the space vehicle to be M_0, so that $M_0 = Mp+Ms +M_L$, the propellant, power supply, and payload masses respectively. Through the rocket equation, the payload mass fraction, M_L/M_o becomes,

$$M_L/M_o = \exp(-\Delta V/v_e) - M_s/M_o \qquad (1)$$

With $M_s = P/\alpha = \dot{m}\, v_e^2/2\alpha$ for a propellant mass flow rate

$$\dot{m} = M_o\,[1 - \exp(-\Delta V/v_e)]/\tau \qquad (2)$$

based on the duration of propellant exhaust τ

So,

$$M_L/M_o = \exp(-\Delta V/v_e) - (v_e^2/2\alpha\,\tau)\,[1 - \exp(-\Delta V/v_e)] \qquad (3)$$

This nonlinear equation for M_L/M_o in terms of v_e and ΔV is plotted in Stuhlinger[36], *Ion Propulsion for Space Flight*, chapter 4, pg. 79, Fig 4-8, and provides the exhaust speed and velocity change in terms of ατ. Furthermore, to begin, we postulate that the payload mass fraction (for a nuclear explosive and tracking system) is nearly negligible compared to the vehicle mass. Then, again from Stuhlinger, in this limit of negligible payload mass, the necessary exhaust speed v_e and velocity increment ΔV are then 0.5 and 0.81 times the characteristic speed $\sqrt{2\alpha\tau}$, where again α is the specific power [W/kg] and τ is the time [sec] required to attain the needed ΔV . This shows us immediately the need to accomplish high specific power in order to enable a short-time mission. In actuality, one needs a finite useful payload mass. We suggest, for example, a 50 metric ton payload (nuclear explosive, reduced shielding, terminal tracking, final maneuvering) might be appropriate, since for a one-way flyby mission, our (unmanned) payload mass can be considerably smaller than the case of the previously postulated Discovery II manned mission to Jupiter[17].

With the needed ΔV upwards of 100 km/s as indicated earlier, the exhaust speed would be 61 km/s or a specific impulse of about 6300 sec. For the 180 day mission out to Saturn (distances), then we need a specific power of 500 W/kg, to deliver negligible useful payload…and more for a finite payload fraction. Even this combination is well beyond the range of fission nuclear thermal (NT) rockets, let alone nuclear electric (NEP) propulsion.

Finally, there is one other potential solution for the comet intercept mission. In the late 1950's, Ted Taylor and Freeman Dyson's DARPA "Project Orion" study proposed a spacecraft propelled using multiple pulsed nuclear denotations[37], (replete with unique virtues and vices), with a specific impulse of more than 6000 seconds and with high specific power. Stockpiling and launching thousands of nuclear explosives, for an indeterminate time, of course has a lot of other issues. It was revisited in the later Project Daedalus study from 1973-1978 by the British Interplanetary Society[38].

Deflection Energy Requirements

In more detail we now consider how the required deflection places demands on the nuclear explosive yield needed, and it's positioning with respect to the comet.

For lateral deflection v_o in ideal, minimum energy, case, we would need an energy absorbed by the comet:

$$W_o = \mathbf{M} v_o^2/2 \qquad (4)$$

where **M** is the comet mass and the deflection velocity v_o is purely perpendicular to the comet's initial velocity V . A 1 km diameter comet, with density of 0.6 gm/cm^3 has a mass of $3x10^{11}$ kg, and a deflection of 10 m/sec corresponds to an energy $W_0 = 1.5 \times 10^7$ MJ.

Now if we consider (in the initial frame of motion of the comet) the ablated material to be treated as a rocket exhaust of average directed speed v, and we expel a mass m, then by momentum conservation:

$$\mathbf{M} v_o = mv \qquad (5)$$

The total (directed) kinetic energy in the exhaust (not counting internal energy of the plume or radiation losses) becomes:

$$mv^2/2 = \mathbf{M}vv_o/2 \qquad (6)$$

Compared to the minimum energy W_o, we therefore need more energy by a factor of $K = v/v_o$. For example, for our deflection v_o = 10 m/s and an ablatant exhaust of v = 4 km/s, the yield of the nuclear explosive must increase by K = 400. As an interesting side note, a spacecraft with a mass of 50 metric tons, closing at a speed of 100 km/second, carries a kinetic energy of $2.5\text{x}10^8$ MJ, which is more than the energy W_0 discussed above, but still much less than what the impulse energetics (and momentum conservation) requires to create this rocket plume from the comet surface.

Equations for long range encounter

Continuing, we now need to relate the intercept time, the specific power α, closing velocities and distances, to the deflection, earth miss distance, and required nuclear yield. Consider for the simple case of constant power and exhaust speed, then total mass flow out of the rocket can be used as a measure of time. Thus, the distance x traveled in time τ is:

$$x = \int u \, dt = \int u \, (-dM/\dot{M}) \qquad (7)$$

where M is the instantaneous mass of the spacecraft which is diminished at a rate $\dot{M}$ (>0). The limits of integration are M_o at time t = 0 and $M = M_o \exp(-u/v_e)$ at the time τ that the spacecraft has attained a speed u at constant exhaust speed v_e. The spacecraft speed is related to instantaneous mass and the exhaust speed by the rocket equation:

$$u/v_e = -\ln(M/Mo) \qquad (8)$$

The distance traveled is then:

$$x = v_e \, (M_o/\dot{M}) \int \ln M/M_o \, d(M/M_o) = v_e \, (M_o/\dot{M})[\, M/M_o \,(\ln(M/M_{o)}) - (M/M_o\,)] \qquad (9)$$

where the limits of integration are 1 and exp(-u/v_e). We therefore have:

$$x = v_e \ (M_o/\dot{M}) \ \{ 1 - [1 + (u/v_e)] \exp(-u/v_e) \} \qquad (10)$$

$$= v_e \tau \ \{ 1 - [1 + (u/v_e)] \exp(-u/v_e) \} \ / \ [1 - \exp(-u/v_e)] \qquad (11)$$

Using Stuhlingler's notation of velocities normalized to $(2\alpha\tau)^{1/2}$, then for the limit of zero payload, we have normalized speeds u* = 0.81 and v_e* = 0.5, we have u*/v_e* = 1.62, and x = 0.6 $v_e \tau$. Note, although we don't do it here, if we let the payload ratio increase to 0.2, then u* = 0.53 and v_e* = 0.707, so u*/v_e* = 0.75, and x = 0.329 $v_e \tau$ (Which would later change the coefficient in denominator of eq. (12)). More simply put, if we want a higher payload mass fraction, the spacecraft will not get as far in the same time.

With exhaust speed of the intercept vehicle $v_e = 0.5\ (2\alpha\tau)^{1/2}$ and final delta-V of the vehicle, $\Delta V = 0.81\ (2\alpha\tau)^{1/2}$, we have that the time for a flyby encounter (thrusting constantly all the way from the Earth) is:

$$\tau = \frac{\left(R_D - R_o\right)}{[\ 0.6 v_e + \left(V + V_E\right)]} \qquad (12)$$

Where R_D and R_o are the radius of detection and radius of earth's orbit, respectively, V is the comet speed (assumed to be constant, even though it gets faster as it approaches the Sun) and V_E is the appropriate speed of the earth given the variation of angle during the comet's approach for an intercept time comparable to a quarter to half of the earth's period. The sum of V + V_E represents the comet's closing speed on the Earth. The average speed of the craft, for constant exhaust velocity and constant thrust, integrating from 0 to τ, is the other term in the denominator.

Note that because the interceptor exhaust speed here is taken to be $\upsilon_e = 0.5\ (2\alpha\tau)^{1/2}$, the equation for intercept time could be solved (as a cubic equation) for a given specific power. However, it is more instructive to specify υ_e to obtain τ (under the time constraint of the incoming (undeflected) comet impact, which sets the maximum allowed τ, while also needing to intercept at large fraction of R_D, to minimize the necessary deflection impulse) and then find the necessary value of α. Our simplified estimate isn't meant to preclude a proper astrodynamics calculation for the comet and spacecraft, with curved trajectories, varying velocities, and possible out-of-the-equatorial plane considerations.

We take the solid angle represented by the comet at the intercept standoff distance r_i , the diameter of the comet d_c, and define the ablation efficiency factor ε_{abl} to include the fraction of the nuclear-explosive output in soft X-rays and the conversion of this output into the directed kinetic energy of the ablation-rocket exhaust. Since miss distance R_m can be written in terms of a deflection angle with a lever arm distance mapped back to the time of intercept, we can relate that angle with the previous equations for the needed comet impulse [4-6] to write down the necessary nuclear yield:

$$Y = \frac{16 r_i^2}{d_c^2} \frac{K}{(0.5)\varepsilon_{abl}} \left(\frac{4\pi}{3} \frac{\rho_c d_c^3}{8} \frac{V^2}{2} \right) \frac{R_m^2}{\left[\left(R_D - R_o\right) - \left(V + V_E\right)\tau \right]^2} \qquad (13)$$

Where we have the factor 0.5 in the denominator coming from averaging over the surface normal of the comet, ρ_c is the comet mass density, r_i is the intercept distance (center-to-center) and d_c is the diameter of the comet. The distance by which the comet misses the earth, at its closest approach, is R_m. Yield goes as the square of the eventual miss distance, due to required ablation energy scaling as the square of the impulse deflection velocity.

If we eliminate τ in Eq. 13, using Eq. 12, then we obtain a more interesting form:

$$Y = \frac{16 r_i^2}{d_c^2} \frac{K}{(0.5)\varepsilon_{abl}} \left(\frac{4\pi}{3} \frac{\rho_c d_c^3}{8} \frac{V^2}{2} \right) \frac{R_m^2}{\left(R_D - R_o\right)^2} \left[1 + \frac{\left(V + V_E\right)}{0.6\upsilon_e} \right]^2 \qquad (14)$$

The importance of achieving early detection (large R_D) of the comet, and a high exhaust velocity υ_e for the intercept vehicle is apparent. Clearly, the solution diverges if the detection distance approaches the Earth's orbital distance

For the case of a desired v_o = 10 m/s, with an initial comet velocity V = 25 km/s, then K = 400. With detection/characterization at 10 AU, an average earth speed component of 0.7 x 30 km/s = 21 km/s, and an interceptor rocket exhaust speed of 200 km/s, we can intercept at about 4.9 AU in 93 days, but require a specific power α = 6153 W/kg, which is well beyond anything except fusion. Using eq. (14), we can estimate the required nuclear yield. To generate an Earth miss distance R_m = 40,000 km, for a 1 km diameter comet with average density of 0.6 gm/cm^3, with a 25% ablation efficiency of a single detonation, at a distance r_i =1 km, a yield of 20 Megatons is needed. Therefore while a single detonation of only 10 Megatons isn't quite enough, the biggest nuclear device ever tested on Earth (Russian, mass of 27 metric tons, 50 MT yield) would have some margin. Furthermore, you need to make a big enough deflection to insure that the "miss distance" is measurable (beyond error bars, due to orbital parameter uncertainties, and short baselines for establishing the orbit parameters) in the time you have remaining before an impact.

This would drive you towards even larger deflections, and therefore larger yields. More detailed calculations taking into account radiation and materials effects are clearly needed.

Even so, you would need multiple intercept vehicles and payloads, not only for redundancy, but to get sufficient deflection, while also having the ability to make corrections by iterating with multiple attempts. For a successful intercept and deflection, there are at least two more difficulties which come to mind: 1). Surviving the micrometeorites on approach, and 2). detonating a nuclear explosive package with sufficiently precise timing and targeting. Due to the high closing speeds (up to ~ 100 km/second), a 10 millisecond triggering uncertainty corresponds to a 1 km error, which is about the desired standoff distance.

Back to the Future: Electricity generation and/or rocket propulsion?

As a strategic goal for fusion energy research, clean CO_2-free electricity generation does not offer a unique value proposition in the way that a fusion rocket for Planetary Defense does. There are at least 11 different ways to make electricity today, seven of which are "mostly CO_2 free" (see Table 1). All of these techniques *work* today, with varying costs, societal acceptance, risk and differing abilities to meet future demands, and all of them are simpler than an as-yet-hypothetical fusion energy reactor. Among the existing "CO_2-free" options, until cost effective large-scale storage is demonstrated, only nuclear fission has both the capability for future scalability for increased demand and steady output capability for base-load requirements. Nuclear fission of course has its many issues, including proliferation, safety and impact of accidents, spent fuel disposal and society acceptance. All of these impact the construction cost, which today in the developed world is excessive (overnight construction costs in excess of $5,000/kW) and prevents large scale deployment. There are several reactor designs and concepts that can address these concerns but they are not being actively pursued today. Given the scientific immaturity (we have yet to produce net fusion energy gain), the technical and engineering complexity envisioned for fusion power plants, the existence of well-established means of producing electricity whose cost of construction, operations, and the net cost of electricity (cents/kW-hr) is well known, and the risk adverse nature of public utilities and the energy industries, the lack of enthusiasm for electricity produced by fusion can be readily understood.

Table 1. Energy sources routinely used to make electricity today (2010).[39]

Primary Energy Source	**Nominally CO_2 Free**	**Current capacity (%)**	**Expected Lifetime (yrs)**
Natural Gas	no	80.6	100
Coal	no		400
Oil	no		< 50
Biomass	neutral	11.4	> 400

Wind	yes	0.5	> 1000
Solar photovoltaic	yes	0.06	> 1000
Solar thermal	yes	0.17	> 1000
Hydro	yes	3.3	> 1000
Wave/Tidal	yes	0.001	> 1000
Geothermal	yes	0.12	> 1000
Nuclear fission	yes	2.7	> 400

Instead of electricity, we have identified a goal for fusion research in this paper, which satisfies a need that is not provided by any other existing product. Society is beginning to understand the need for planetary defense posed by the asteroid/comet threat to mankind. Fusion rocket engines for planetary defense can satisfy a need that *ignites the human imagination*. Research in this area will address an immediate goal that will attract the next generation of researchers (and beyond) to our laboratories, universities and industry. We emphasize that we are not giving up on fusion's ultimate promise of clean abundant energy. Instead we have described an alternative goal: *developing fusion rockets for high-speed comet intercept missions as part of a planetary defense program;* which would generate a higher sense of urgency, and is of equal or greater importance to society.

Summary

A logical Planetary Defense Program would be interagency and international in nature. A Planetary Defense effort that can deal with both asteroids and comets requires several capabilities: early detection, good tracking & targeting, and early momentum change. Better (earlier) detection of potentially hazardous asteroids and comets is essential. If you can't see them in time, you can't put up a defense. In the near term we should practice deflection technologies on asteroids and short period comets, ideally ones that have no adverse consequence if the deflection doesn't match modeling. For the difficult comet intercept mission, we should begin now to develop high-specific power, high-specific impulse plasma rockets with fusion cores…because it is going to take a while. An intercept vehicle that has both a nuclear explosive payload and a nuclear rocket engine is necessary for the fast comet scenario. We emphasize that the best nuclear engine on the bottom of this rocket would be fusion powered, for performance that combines high specific power with high specific impulse, possibly reducing response times to a few months instead of the present value of years (or even "never" for comets).

The long-period comet threat will always be with us, whether or not an impact is next week, or thousands of years from now. Fusion energy is the critical science and technology needed to counter this threat.

References

---

[1] http://science.energy.gov/fes/ DOE Fusion Energy Sciences homepage

[2] http://f4e.europa.eu/ European Fusion 4 Energy homepage

[3] http://energy.gov/sites/prod/files/2014/04/f14/2014_dept_energy_strategic_plan.pdf , US DOE Energy Strategic Plan 2014-2018, Ernest Moniz, DOE/CF-0067

[4] http://science.energy.gov/~/media/fes/fesac/pdf/2003/Fesac_final_non_elec_2003.pdf , Non Electric Applications of Fusion, Report to FESAC, July 31, 2003. See chapter V.

[5] S. K. Borowski, D. R. McCurdy, T. W. Packard, "Nuclear Thermal Rocket/Vehicle Characteristics and Sensitivity Trades for NASA's Mars Design Reference Architecture (DRA) 5.0 Study", Proc. of Nuclear and Emerging Technologies for Space 2009, paper 203599, June 14-19, (2009), Atlanta, GA.

[6] Peter J. Turchi, "Propulsion Techniques", ISBN 1-56347-115-9, American Institute of Aeronautics and Astronautics, 1998

[7] P. J. Turchi, Chapter 9, "Electric Rocket Propulsion Systems", in Space Propulsion Analysis and Design, R. Humble, G. Henry and W. Larson, eds., McGraw-Hill (1995).

[8] Jason Cassibry, Ross Cortez, Milos Stanic, Andrew Watts, and William Seidler II, Rob Adams, Geoff Statham and Leo Fabisinski, "Case and Development Path for Fusion Propulsion", Journal of Spacecraft and Rockets, 52(2), 595, March-April (2015).

[9] J. F. Santarius, "Lunar He-3, Fusion Propulsion, and Space Development", April 5-7. 1988, in "The Second Conference on Lunar Bases and Space Activities of the 21st Century", NASA Conference Publications 3166, edited by W. W. Mendell, Vol. 1, 75 (1992).

[10] Norman Schulze, "Fusion Energy for Space Missions in the 21st Century", NASA Technical Memoradum 4298, August 1991.

[11] J. F. Santarius, B. G. Logan, "Generic Magnetic Fusion Rocket Model", J. of Propulsion and Power, 14(4), 519 (1998).

[12] AIAA Paper SP-108-2004, 2004. Williams, C., "Application of Recommended Design Practices for Conceptual Nuclear Fusion Space Propulsion Systems," AIAA Paper 2004-3534, July 2004.

[13] Edward Teller, Alexander Glass, T. Kennith Fowler, Akira Hasegawa, John F. Santarius, "Space Propulsion by Fusion in a Magnetic Dipole", Fusion Science & Technology, 22(1), 82 (1991).

[14] J.F. Santarius, G.L. Kulcinski, L.A. El-Guebaly, G.A. Emmert, H. Khater, Z. Musicki, M.E. Sawan, I.N. Sviatoslavsky, W.F. Vogelsang, P.L. Walstrom, L.J. Wittenberg, "Critical Issues for **SOAR**: The Space Orbiting Advanced Fusion Power Reactor"; January 1988 (revised August 1988) [Presented at Fifth Symposium on Space Nuclear Power Systems, Albuquerque, NM, 11-14 January 1988; Space Nuclear Power Systems 1988 (Orbit, Malabar FL, 1989) 161].

---

[15] Y. S. Razin, G. Pajer, M. Breton, E. Ham, J. Mueller, M. Paluszek, A. H. Glasser, S. A. Cohen, "A Direct Fusion Drive for Rocket Propulsion," Acta Astronautica **105,** (2014) 145.

[16] Y.C.F. Thio et al. "High Energy Space Propulsion based on Magnetized Target Fusion," Paper AIAA 99-2703, 35th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Los Angeles, CA., 20-24 June 1999.

[17] Craig H. Williams, Leonard A. Dudzinski, Stanley K. Borowski, and Albert J. Juhasz, Glenn Research Center, Cleveland, Ohio, "Realizing "2001: A Space Odyssey": Piloted Spherical Torus Nuclear Fusion Propulsion" NASA/TM-2005-213559 , March 2005; for the 37th Joint Propulsion Conference and Exhibit, Salt Lake City, Utah, July 8–11, 2001.

[18] C. D. Orth, et al., "The VISTA spacecraft—Advantages of ICF for Interplanetary Fusion Propulsion Applications", Proc. IEEE 12th Symp. on Fusion Engineering, 2, 1017 (1987).

[19] M. Paluszek, G. Pajer, Y. Razin, S.A. Cohen, J. Slonaker, M. Walsh, Kevin Griffin, and R. Feder, "Direct Fusion Drive for a Human Mars Orbital Mission," Proc. IAC, Toronto, (2014). Also, PPPL-5064, Aug. 2014

[20] P.J. Turchi, "Fusion Rocket Based on Stabilized Liner Implosions," IEEE Trans. on Plasma Science, Special Issue on Plasma Propulsion 2014, 43(1), 240 (Jan 2015).

[21] R.B. Adams, R. Alexander, et. al., "Survey of Technologies Relevant to Defense from Near-Earth Objects", NASA/TP-2004-213089.

[22] Space Studies Board Aeronautics and Space Engineering Board, Division on Engineering and Physical Sciences National Research Council, National Academies, "Defending Planet Earth: Near-Earth Object Surveys and Hazard Mitigation Strategies" THE NATIONAL ACADEMIES PRESS (2010) Washington, D.C.

[23] J.B. Mueller, Y.S. Razin, M.A. Paluszek, A.J. Knutsen, G. Pajer, S.A. Cohen, A.H. Glasser, "Direct fusion drive rocket for asteroid deflection," Proceedings, IEPC-2013, Washington, (2013).

[24] Mike Wall, Space.com, June 18, 2014, "Earth Impact: Are Comets a Bigger Danger than Asteroids?", http://www.space.com/26264-asteroids-comets-earth-impact-risks.html

[25] Comet C/2013 A1 information, http://en.wikipedia.org/wiki/C/2013_A1, and http://mars.nasa.gov/comets/sidingspring/

[26] Table 1, NASA Office of Inspector General "NASA's Efforts to Identify Near-Earth Objects and Mitigate Hazards", IG-14-030, Sept 15, 2014.

[27] John L. Remo, "The dilemma of nuclear energy in space", Bull. Atom. Scien., 71(3) 38 (2015)

[28] NASA Near-Earth Object Survey and Deflection Analysis of Alternatives, Report to Congress, 2007, http://neo.jpl.nasa.gov/neo/report2007.html

---

[29] Finseth, J., “Overview of Rover Engine Test: Final Report,” NASA-CR-184270, Feb. 1991. http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19920005899.pdf

[30] David Buden, “Nuclear Thermal Propulsion Systems, Space Nuclear Propulsion and Power: Book 2”, ISBN-978-0-9741443-3-7, Polaris Books, 2011

[31] Robbins, W.H. and Finger, H.B., "An Historical Perspective of the NERVA Nuclear Rocket Engine Technology Program", NASA Contractor Report 187154/AIAA-91-3451, NASA Lewis Research Center, NASA, July 1991

[32] B. W. Longmier, M. Ballenger, C. S. Olsen, J. P. Squire, F. R. Chang Diaz, “Performance studies of the VASIMR VX-200”, AIAA-2011-1071, 49th AIAA Aerospace Sciences Meeting and Exhibit, Orlando, FL, Jan. 4-7, 2011.

[33] Poston, D.I. 2002, Nuclear design of SAFE-400 space fission reactor, Nuclear News, Dec 2001.

[34] Sovey, J. S., Rawlin, V. K., and Patterson, M. J.: "Ion Propulsion Development Projects in U. S.: Space Electric Rocket Test 1 to Deep Space 1." Journal of Propulsion and Power, Vol. 17, No. 3, May-June 2001, pp. 517-526.

[35] Rayman, Marc; Fraschetti, Raymond, Russell. "Dawn: A mission in development for exploration of main belt asteroids Vesta and Ceres" *Acta Astronautica* **58** (11): 605–616, (April 5, 2006).

[36] E. Stuhlinger, “Ion Propulsion for Space Flight”, McGraw-Hill, New York 1964.

[37] Freeman Dyson, “Interstellar Transport”, pg. 41-45, Physics Today, Oct. 1968

[38] Project Daedalus Study Group: A. Bond et al., *Project Daedalus – The Final Report on the BIS Starship Study*, JBIS Interstellar Studies, Supplement 1978

[39] REN21–Renewable Energy Policy Network for the 21st Century Renewables 2012–Global Status Report, 2012, http://www.map.ren21.net/GSR/GSR2012.pdf , http://en.wikipedia.org/wiki/Energy_development