AIAA–2007-5594

Energy Considerations of Hypothetical Space Drives

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The energy requirements of hypothetical, propellant-less space drives are compared to rockets. This serves to provide introductory estimates for potential benefits and to suggest analytical approaches for further study. A "space drive" is defined as an idealized form of propulsion that converts stored potential energy directly into kinetic energy using only the interactions between the spacecraft and its surrounding space. For Earth-to-orbit, the space drive uses 3.7 times less energy. For deep space travel, energy is proportional to the square of delta-*v*, whereas rocket energy scales exponentially. This has the effect of rendering a space drive 150-orders-of-magnitude better than a 17,000-s Specific Impulse rocket for sending a modest 5000 kg probe to traverse 5 ly in 50 years. Indefinite levitation, which is impossible for a rocket, could conceivably require 62 MJ/kg for a space drive. Assumption sensitivities and further analysis options are offered to guide further inquires.

Nomenclature

δ	=	modification coefficient (%)
δ_{gf}	=	modification coefficient of gravitational field (%)
δ_{gm}	=	modification coefficient of gravitational mass (%)
δ_{im}	=	modification coefficient of inertial mass (%)
δ_m	=	modification coefficient of rocket mass, including stored propellant (%)
δ_p	=	modification coefficient of expelled propellant (%)
$\mathrm{d}m$	=	mass increment (kg)
$\mathrm{d}r$	=	radius increment (m)
$\mathrm{d}t$	=	time increment (s)
$\mathrm{d}v$	=	velocity increment ($\mathrm{m \cdot s^{-1}}$)
Δv	=	velocity change ($\mathrm{m \cdot s^{-1}}$)
$\Delta v'$	=	altered velocity change ($\mathrm{m \cdot s^{-1}}$)
e	=	natural log = 2.71828…
E	=	energy (Joules)
F	=	force, thrust (Newton)
G	=	Newton's gravitational constant = $6.67 \times 10^{-11}\ \mathrm{m^3 \cdot kg^{-1} \cdot s^{-2}}$
g	=	gravitational acceleration at Earth's surface = $9.81\ \mathrm{m \cdot s^{-2}}$
g'	=	altered gravitational acceleration ($\mathrm{m \cdot s^{-2}}$)
I_{sp}	=	specific impulse (s)
K	=	kinetic energy (Joules)
m	=	mass of vehicle (kg)
m_p	=	mass of propellant (kg)
M_E	=	mass of Earth = 5.98×10^{24} kg
$\boldsymbol{n}$	=	number of repeated maneuvers
r	=	radius from the center of the Earth (m)
r_E	=	radius of Earth's surface = 6.37×10^6 m
r_O	=	radius of low Earth orbit = 6.67×10^6 m
t	=	time (s)
U	=	potential energy (Joules)
v_e	=	velocity of rocket exhaust ($\mathrm{m \cdot s^{-1}}$)
∞	=	infinity

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I. Introduction

To circumvent the propellant limits of rockets and the maneuvering limits of solar sails, a means to propel spacecraft is sought that only uses the interactions between the spacecraft and its surrounding space. Presently, the physics to provide such a device, which can be referred to as a "space drive," has not been discovered, but various approaches are being studied.[1] As both a tool to proceed with theoretical analyses and to reflect potential benefits, this paper presents energy comparisons between ideal rockets and space drives. This includes demonstrating possible pitfalls when conducting such analyses.

Estimating the potential benefits of hypothetical space drives is challenging because such breakthroughs are still only notional concepts (hence the term hypothetical). A recent publication took a first step toward assessing the potential benefits, specifically using a modified rocket equation to demonstrate that naive modifications of gravity or inertia do not produce much benefit.[2] Although this is an important first step to help correct misconceptions, it is only a first step. Here, additional assessments are offered along with discussion on their limits.

In the analyses that follow, a key feature is that energy is the basis of comparison, rather than using the metrics of rocketry. Discussion on the pitfalls of using rocket equations to assess breakthrough spaceflight follows next.

II. Avoiding Pitfalls

The historic tendency when trying to gauge the value of an emerging technology is to use the metrics of the incumbent technology. Such provisional assessments can be seriously misleading, however, when the emerging technology uses fundamentally different operating principles. For example, the value of steamships is misleading when judged in terms of sail area and rigging.[3] Although reduced sails and rigging are indeed a consequence of steamships, the true benefit is that shipping can continue regardless of the wind conditions and with far more maneuvering control. Similarly, the benefits of a breakthrough space drive would likely surpass the operational conventions of rocketry. Issues such as optimizing specific impulse become meaningless if there is no longer any propellant. Three examples are offered next to illustrate the pitfalls of using the metrics of rocketry to describe the physics of a space drive.

A. Infinite Specific Impulse

The first and common misleading practice when describing a hypothetical space drive is to view it as a rocket with an *infinite* specific impulse. This seems reasonable at first since a higher specific impulse leads to less propellant, so an infinite specific impulse should lead to zero propellant. As shown from Eq. (4), however, specific impulse is a measure of the thrust, F, per propellant weight flow rate ($g\, dm/dt$).[4] For a true space drive, the dm/dt term would be meaningless, rendering the entire equation inappropriate for assessing propellantless propulsion.

$$I_{sp} = \frac{F}{g\dfrac{dm}{dt}} \tag{4}$$

Furthermore, as shown from Eq. (5), which is based on the energy imparted to the propellant from the rocket's frame of reference,[5] an infinite specific impulse, I_{sp}, implies that a propellantless space drive would require infinite energy (substituting $I_{sp}=\infty$). Conversely, this same equation can be used to conclude that a propellantless space drive would require zero energy if there was no propellant (substituting $m_p=0$). Neither of these extremes are necessarily the case.

$$E = \frac{1}{2} m_p \left(I_{sp} g\right)^2 \tag{5}$$

B. Inertial Modification of Rocket

To illustrate another misleading use of the rocket equation, consider the notion of manipulating the inertia of a rocket. If such a breakthrough were ever achieved, the implications and applications would likely extend beyond rocketry. Even if used on a rocket, there are a number of different ways to envision applying such an effect, each yielding considerably different conclusions; (1) apply the inertial change to the whole rocket system, (2) just to the expelled propellant, or (3) just to the rocket with its stored propellant. Just comparing two of these options can show the pitfalls of such analyses; the case where the entire rocket system's inertia is modified, and where just the rocket with its stored propellant is modified. In that latter case, it is assumed that the propellant resumes its full inertia as it is accelerated out of the rocket. This notion is similar to the science fiction concept of "Impulse Drive with Inertial Dampers" as presented in the *Star Trek* series.[6]

It should be remarked that, at present, there are no confirmed techniques to affect such a change in inertia, even though experiments are underway.[7] It is important to stress that this is only a hypothetical example to illustrate the sensitivity of the findings to the methods, rather than to suggest that this is a viable breakthrough. Numerous variations on this analysis are possible.

Consider a rocket in field-free space (Fig. 1). To derive the rocket equation, one can start with conservation of momentum, where the rocket expels an increment of propellant, dm, to produce an incremental change in the rocket's velocity, dv.

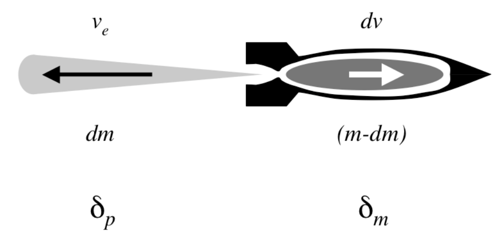

Fig. 1 Rocket in Field-Free Space

The standard equation to represent this conservation of momentum has been slightly modified in Eq. (6), where coefficients have been inserted to represent hypothetical manipulations of the inertia of the expelled propellant, δ_p, and the rocket, δ_m, where the rocket includes the stored propellant. In this hypothetical example, it is assumed that the propellant regains its full inertia as it is accelerated out of the rocket. Values of δ greater than one imply an increase, less than one imply a decrease and a δ equal to one represents no change.

$$-v_e(\delta_p)dm = dv(\delta_m)(m - dm) \tag{6}$$

Proceeding with the normal steps to derive the rocket equation, it can be shown[8] that the final result for the Δv imparted to the rocket is represented by:

$$\Delta v = v_e \ln\left(\frac{m + m_p}{m}\right)\frac{\delta_p}{\delta_m} \tag{7}$$

Consider now the implications of modifying the inertia of the whole rocket system, which implies equal changes to δ_p and δ_m. In this circumstance there is no change at all in Δv. This null finding was one of the observations reported by Tajmar and Bertolami.[2] Alternatively, consider that the inertia of the rocket with its stored propellant is somehow reduced, while the inertia of the expelled propellant regains its full value. In this case the improvement in Δv tracks inversely to δ_m. In other words a δ_m of 0.5, representing a 50% decrease in the rocket's inertia, would yield a 50% increase in Δv. Table 1 summarizes how the different assumptions yield different results.

Table 1: Different ways to modify rocket inertia

Which Inertia is Modified: *From Eq. (7)*	**Propellant** δ_p	**Rocket** δ_m	**Net Effect**
Unmodified	1	1	Baseline
Whole Rocket System	δ	δ	No Change
Just Rocket with its Stored Propellant	1	δ	$\Delta v' = (1/\delta)\Delta v$

In addition to the ambiguity and wide span of results when using the rocket equation to predict the benefits of modifying inertia, this approach does not provoke the questions needed to further explore such conjectures. For example, the issue of energy conservation is not revealed from the prior equations. Although momentum was conserved in the prior example, energy conservation is not addressed. It is presumed that any benefit must come at some expense, and since energy is a fundamental currency of mechanical transactions, it is reasonable to expect that such a benefit requires an energy expenditure. These equations do not provide the means to calculate the extra energy required to support this hypothetical change in the rocket's inertia.

C. Gravitationally Shielded Launch Pad

Another misleading use of the rocket equation is when considering the implication of a *hypothetical* gravity shield. This example is included because it highlights issues associated with the *equivalence principle*. The equivalence principle asserts that *gravitational* mass is identical to *inertial* mass. If the inertial mass is modified, then the gravitational mass would be similarly modified.

Consider placing a launch pad above a hypothetical gravity shield (Fig. 2). A naive assumption would be that the reduced gravity would make it easier for the rocket to ascend as if being launched from a smaller planet. This idea was provoked from the gravity-shielding claim[9] that was later found not to be reproducible,[10] but this scenario still serves to illustrate key issues.

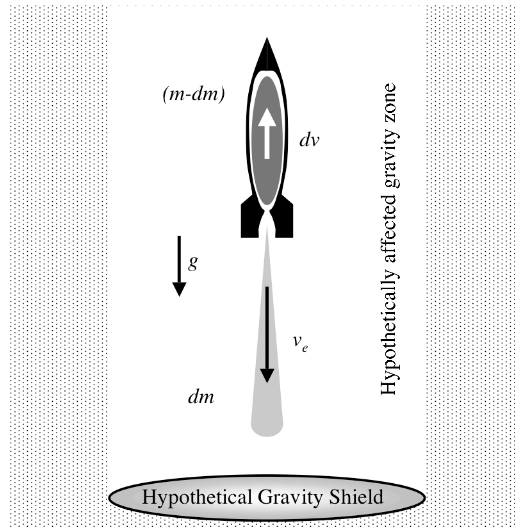

Fig. 2 Rocket Over Hypothetical Gravity Shield

There is more than one way to interpret this situation. One can consider that the gravitational field, g, is modified or one can consider that the 'gravity shield' is, instead, altering the mass of the rocket above the device. In the case where the rocket mass is modified, one can further consider that just its gravitational mass is affected or, if the equivalence principle is in effect, that both its gravitational and inertial mass are equally affected. Figure-3 illustrates these assessment options.

To explore these options, start with the following equation for a rocket ascending in a gravitational field, Eq. (8).[11] The term on the left represents the mass and acceleration of the rocket, the first term on the rights side is the force of gravity, and the second term is the reaction force from the expulsion of an increment of propellant with an exhaust velocity, v_e, relative to the rocket.

$$m\frac{dv}{dt} = -m\,g - v_e\frac{dm}{dt} \tag{8}$$

To consider the hypothetical modifications, coefficients are inserted next to reflect modifications to the gravitational field, δ_{gf}, and to the rocket's gravitational mass, δ_{gm}, and its inertial mass, δ_{im}. As before, values of δ greater than one imply an increase, less than one a decrease, and equal to one represents no change. Also, the equation is now rearranged to isolate the inertial terms from the gravitational terms:

$$-\left(\delta_{gm}\right)m\left(\delta_{gf}\right)g = \left(\delta_{im}\right)\left[m\frac{dv}{dt} + v_e\frac{dm}{dt}\right] \tag{9}$$

The left hand side represents the gravitational contributions while the right represents the inertial contributions. It can be shown that this equation results in the following representation for the Δv of the rocket:

$$\Delta v = -\frac{\delta_{gm}}{\delta_{im}}\delta_{gf}\,g\Delta t + v_e\ln\left(\frac{m_{initial}}{m_{final}}\right) \tag{10}$$

The increment of time during which propellant is expelled is represented by Δt, and accordingly the two mass terms reflect the *initial* (higher) and *final* (lower) masses of the rocket (including its stored propellant) over this time interval. With the exception of the modification coefficients, this equation is identical to that of a normal rocket ascent in a gravitational field.

Table 2 shows how the different possible interpretations of the hypothetical gravity shield (as outlined in Fig. 3) might affect this situation. If it were assumed that the gravitational field, g, is modified, the result would be as naively expected; it would be the same as launching in a different gravitational environment. If, however, it is assumed that the device affects the mass of the rocket, there are further possibilities. If the equivalence principle is in effect, then both the gravitational and inertial mass are equally affected, resulting in no change in the rocket's Δv. If the equivalence principle is not in effect, then only the gravitational or inertial masses are affected, resulting in an analogous case to launching in a different gravitational environment.

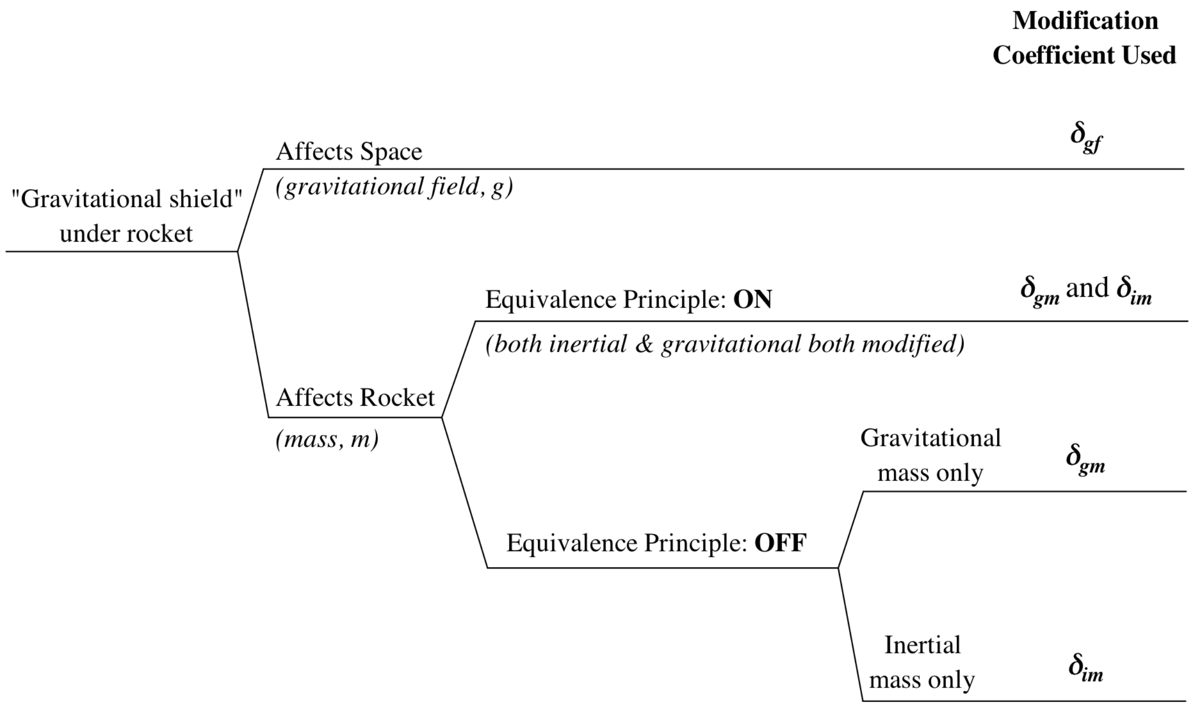

Fig. 3 Various Analyses for Gravitationally Shielded Launch Pad

Table 2: Different Analysis Results for Gravitationally Shielded Launch Pad

Modified Term *From Eq. (10)*	**Gravitational. Field** δ_{gf}	**Gravitational. Mass** δ_{gm}	**Inertial Mass** δ_{im}	**Net Effect**
Unmodified Launch	1	1	1	Baseline
Gravity Modified	δ	1	1	$g' = \delta g$
Rocket Inertial & Gravitational Mass (Equivalence Principle in effect)	1	δ	δ	No Change
Rocket Gravitational Mass (Equivalence Principle negated)	1	δ	1	$g' = \delta g$
Rocket Inertial Mass (Equivalence Principle negated)	1	1	δ	$g' = {}^{g}/_{\delta}$

As before, the energy implications of these conjectures are not illuminated with such approaches. These examples illustrate how misleading results are possible if only rocket equations are used to ponder space drive physics. To proceed with more fundamental bases, energy considerations are examined next.

III. Energy as a Basis of Comparison

Although comparisons built on the incumbent methods might be useful for introductory purposes, a deeper understanding of the benefits and issues are better illustrated by using a more fundamental basis. When considering moving a mass from one place to another, energy is the fundamental currency. Using this basis, three situations will be compared; deep space travel, Earth to orbit, and levitation. These comparisons are presented for three reasons: (1) To continue to illustrate the difference between space drive considerations and the use of rocket equations, (2) To reflect the magnitude of potential benefits compared to rockets, and (3) To provide starting points for deeper analyses.

D. Deep Space Travel Energy

To compare the energy requirements of a rocket and a hypothetical space drive, the following assumptions are used. To more fully understand the challenges, approaches and potential benefits of breakthrough propulsion, it would be fruitful to repeat the analysis using different assumptions:

- The space drive is interpreted to simply be a device that converts stored potential energy into kinetic energy.
- Both the rocket and the space drive are assumed to be 100% efficient with their energy conversions (absent of any real mechanism, this at least compares upper performance limits).
- The thrusting duration is assumed to be much shorter than the trip duration, which for interstellar travel is reasonable.
- For the rocket, constant exhaust velocity is assumed.
- Non-relativistic trip velocity and exhaust velocity are assumed.
- The energy requirements for a rendezvous mission are based on equal Δv's for acceleration and deceleration.

1. Energy of a Rocket:

To compare a rocket to another method that does not require propellant, we need an equation for rocket energy where the propellant mass is represented in terms of the vehicle's empty mass and the Δv of the mission – variables shared by the space drive. A common way to calculate the total kinetic energy of a rocket system, including both the rocket and the propellant, is just to calculate the kinetic energy imparted to the propellant from the rocket's frame of reference where the rocket has zero velocity (hence a zero contribution to the total kinetic energy).[4, 5] This is consistent with the previously stated assumptions.

$$E = \frac{1}{2} m_p \left(v_e\right)^2 \tag{11}$$

Next, to convert this into a form where the rocket's propellant mass, m_p, is represented in terms of the exhaust velocity and the mission Δv, we apply the following form of the rocket equation, which is a variation of the Tsiolkovski equation:

$$m\left(e^{\left(\frac{\Delta v}{v_e}\right)} - 1\right) = m_p \tag{12}$$

Substituting this form of the rocket equation into the kinetic energy equation yields this simple approximation:

$$E = \frac{1}{2}\left(v_e\right)^2 m\left(e^{\left(\frac{\Delta v}{v_e}\right)} - 1\right) \tag{13}$$

2. Specific Impulse Limits

Before proceeding, a limit should be brought to attention. For these introductory exercises, the comparisons are limited to non-relativistic regimes. For rockets, this implies limiting the exhaust velocity to ≤ 10% lightspeed. The corresponding upper limit to specific impulse easily follows from the equation relating specific impulse to exhaust velocity:[4]

$$v_e = I_{sp} g \tag{14}$$

Setting the exhaust velocity to 10% of light-speed (beyond which relativistic effects must be considered), the limiting specific impulse is found to be:

$$(10\%)\left(3.0\times10^{8}\frac{m}{s}\right) \geq I_{sp}\left(9.8\frac{m}{s^2}\right) \Rightarrow \quad I_{sp} \leq 3.0\times10^{6}s \tag{15}$$

3. Energy for a Space Drive

Since a space drive has been defined for this exercise as a device that converts stored potential energy into kinetic energy, the basic equation of kinetic energy is used to calculate the required energy, where the values of vehicle mass and mission Δv are the same as with the rocket. For these first-step exercises, the source of the stored potential energy need not be specified. The first issue to deal with is the magnitude of energy.

$$E = \frac{1}{2}m(\Delta v)^2 \tag{16}$$

4. Comparisons

Two things are important to note regarding the energy differences between a rocket and a hypothetical space drive. First, the energy for a rocket is an *exponential* function of Δv, whereas the idea energy of a space drive is a squared function of Δv. This by itself is significant, but it is important to point out that a rocket and a space drive treat additional maneuvers differently.

For a rocket it is conventional to talk in terms of increases to Δv for additional maneuvers. For example, a rendezvous mission has twice the Δv (accelerate & decelerate) than just a flyby (accelerate). For space drives, however, the additional maneuvers are in terms of additional kinetic energy. To illustrate this difference, consider a mission consisting of multiple maneuvers, $\boldsymbol{n}$, each having the same incremental change in velocity, Δv. Notice, in Eqs. (17-18), the location of the term representing the number of repeated Δv maneuvers, $\boldsymbol{n}$. In the case of the space drive, additional maneuvers scale linearly, while for rockets they scale exponentially:

Rocket Maneuvers: $$E = \frac{1}{2}(v_e)^2 m\left(e^{\left((\boldsymbol{n})\frac{\Delta v}{v_e}\right)} - 1\right) \tag{17}$$

Hypothetical Space Drive Maneuvers: $$E = (\boldsymbol{n})\frac{1}{2}m(\Delta v)^2 \tag{18}$$

5. Numerical Example

To put this into perspective, consider a mission of sending a 5000 kg probe over a distance of 5 light-years in a 50-year timeframe. This range is representative of the distance to our nearest neighboring star (4.3 light-years) and the 50-yr time frame is chosen as one short enough to be within the threshold of a human career span, yet long enough to be treated with non-relativistic equations. This equates to a required trip velocity of 10% lightspeed. The probe size of 5000 kg is roughly that of the Voyager probe plus the dry mass of the Centaur Upper Stage (4075 kg) that propelled it out of Earth's orbit.[12] The comparison is made for both a flyby mission and a rendezvous mission.

The results are listed in Table 3. The rocket case is calculated for two different specific impulses, one set at the upper non-relativistic limit previously described, and another set at an actual maximum value achieved during electric propulsion lab tests.[13]

Even in the case of the non-relativistic upper limit to specific impulse – an incredibly high-performance hypothetical rocket – the space drive uses a **factor of 2 to 3 less energy**. When compared to attainable values of specific impulse – values that are still considerably higher than those currently used in spacecraft – the benefits of a space drive are enormous. For just a flyby mission, the gain is **72 orders of magnitude**. When considering a rendezvous mission, the gain is almost **150 orders of magnitude**. Again, though these results are intriguing, they should only be interpreted as the magnitude of gains *sought* by breakthrough propulsion research. Other assessments and results are possible.

Table 3: Deep Spaceflight Energy Comparisons (5000-kg, 5-ly, 50-yr)

	Flyby (n=1) *(Joules)*	Compared to Space Drive	**Rendezvous** (n=2) *(Joules)*	Compared to Space Drive
Space Drive, *Eq. (18)*	$2.3\text{x}10^{18}$		$4.5\text{x}10^{18}$	
Theoretical Rocket, *Eq. (17)* I_{sp} = 3,000,000 s	$3.8\text{x}10^{18}$	1.7	$1.5\text{x}10^{19}$	3.3
Actual Rocket, *Eq. (17)* I_{sp} = 17,200 s [Byers 1969]	10^{91}	10^{72}	10^{168}	10^{149}

In the case of deep space transport, the energy was previously calculated assuming a constant exhaust velocity for the rocket and thrusting durations that were negligible compared to trip times. Although reasonable assumptions for interstellar flight, it would also be instructive to repeat the energy comparisons with assumptions of constant acceleration, constant thrust, constant power, and when optimized for minimum trip time. To further explore these notions, it would also be instructive to repeat all of these comparisons using the relativistic forms of the equations.

Newtonian equations are not the only way to further explore these notions. From the formalism of general relativity, there are a variety of transportation concepts that do not require propellant, including: a *gravitational dipole toroid* (inducing an acceleration field from frame-dragging effects),[14] *warp drives* (moving a section of spacetime faster-than-light),[15] *wormhole*s (spacetime shortcuts),[16, 17] and *Krasnikov tubes* (creating a faster-than-light geodesic).[18]

To explore these general relativity formalisms in the context of creating space drives introduces entirely different energy requirements than with the Newtonian versions explored in this paper. In the general relativity approach, one must supply enough energy to manipulate all of the surrounding spacetime so that your spacecraft naturally falls in the direction that you want it to go. Although such approaches require considerably more energy than the simple Newtonian concepts, they are nonetheless instructive.

E. Earth To Orbit Energy

Consider next the case of lifting an object off the surface of the Earth and placing it into orbit. This requires energy expenditures both for the altitude change and for the speed difference between the Earth's surface and the orbital velocity. Again, the source of this energy is not considered. The point explored first is the amount of energy required. For the hypothetical space drive, this energy expenditure can be represented as:

$$E_{SpaceDrive} = U + K \tag{19}$$

Where U is the potential energy change associated with the altitude change, and K is the kinetic energy change associated with different speeds at the Earth's surface and at orbit. The change in potential energy, which requires expending work to raise a mass in a gravitational field, is represented by:

$$U = \int_{r_E}^{r_O} G \frac{M_E}{r^2} m \, dr \tag{20}$$

The change in kinetic energy requires solving for the orbital velocity and the velocity of the Earth's surface and can be shown to take this form:[8]

$$K = \frac{1}{2} m \left[\left(G \frac{M_E}{r_O} \right) - \left(\frac{2\pi\, r_E}{24 hrs} \right)^2 \right] \tag{21}$$

For the case of using a space drive to place the shuttle orbiter (m = 9.76 x 10^4 kg) into a typical low Earth orbit, r_O, (altitude = 400 km), the energy required is found to be **3.18 x 10^{12} Joules**.

To assess the required energy for a rocket to accomplish the same mission, the following equation is used:[5]

$$E = \left(\frac{1}{2} F\, I_{sp}\, g \right) t \tag{22}$$

The parenthetical term is the rocket *power*, which is shown in this form for two reasons: to show this additional detail of the rocket equation and to introduce the idea of contemplating *power* in addition to just *energy*. While power implications are not further explored here, they constitute a fertile perspective for further study.

Entering the following values for the Space Shuttle System (extracted from "STS-3 Thirds Space Shuttle Mission Press Kit, March 82," Release #82-29), as presented in **Table 4**, into Eq. (22), the total energy for delivering the Shuttle orbiter via rockets is found to be **1.16 x 10^{13} Joules**.

Table 4: Data and Calculations of Space Shuttle Energy to Reach Low Earth Orbit

	Space Shuttle Main Engines	Solid Rocket Boosters	Orbital Maneuvering System
Number of engines	3	2	2
F, Thrust each	470 x 10^3 lbs (2.1 x 10^6 N)	2.9 x 10^6 lbs (12.9 x 10^6 N)	6 x 10^3 lbs (271 x 10^3 N)
I_{sp}, Specific Impulse	453 s	266 s	313 s
Total power	1.40 x 10^{10} W	3.36 x 10^{10} W	8.31 x 10^8 W
t, Burn duration	514 s	126 s	200 s
E, Total energy used	7.19 x 10^{12} J	4.24 x 10^{12} J	1.66 x 10^{11} J
TOTAL COMBINED ENERGY = **1.16 x 10^{13} Joules**			

Comparing this rocket energy value to the hypothetical space drive energy, Eq. (23), where the efficiency of both systems is assumed to be 100%, indicates that the space drive is 3.65 times more energy efficient.

$$Gain = \frac{Rocket}{Space\ Drive} = \frac{1.16 \times 10^{13}}{3.18 \times 10^{12}} = 3.65 \tag{23}$$

F. Levitation Energy

Levitation is an excellent example to illustrate how contemplating breakthrough propulsion is different from rocketry. Rockets can hover, but not for very long before they run out of propellant. For an ideal breakthrough, some form of indefinite levitation is desirable, but there is no preferred way to represent the energy or power to perform this feat. Since physics defines *work* (energy) as the *product of force acting over distance*, no work is performed if there is no change in altitude. Levitation means hovering with no change in altitude.

There are a variety of ways to toy with the notion of indefinite levitation that look beyond this too-good-to-be-true zero energy requirement. For now, only one approach is illustrated, specifically the nullification of gravitational potential. Usually, Eq. (24) is used to compare gravitational potential energy differences between two relatively short differences in height (the integration limits), but in our situation we are considering this energy in the more absolute sense. This equation can be applied to calculate how much energy it would take to completely remove the object from the gravitational field, as if moving it to infinity. This is more analogous to *nullifying* the effect of gravitational energy. This is also the same amount of energy that is required to stop an object at the levitation height, *r*, if it were falling in from infinity with an initial velocity of zero (switching signs and the order of integration limits).

$$U = \int_{r_E}^{\infty} G \frac{M_E}{r^2} m \, dr \quad = \quad G \frac{M_E}{r_E} m \tag{24}$$

Using this potential energy equation, it could conceivably require **62 mega-Joules to levitate 1-kg near the Earth's surface**. As an aside, this is roughly twice as much as putting 1-kg into low Earth orbit. Again, these assessments are strictly for illustrative purposes rather than suggesting that such breakthroughs are achievable or if they would even take this form if achievable. Some starting point for comparisons is needed, and this is just one version.

To avoid confusion, the potential energy calculated here refers to the energy due to gravitational field that we want to counteract. How the vehicle achieves this feat, or where it gets the energy to induce this effect, is not specified. At this stage, estimating the energy requirements is a necessary first step.

IV. Concluding Remarks

The potential benefits of breakthrough propulsion cannot be calculated yet with certainty, but crude introductory assessments show that the performance gains could span from a factor of 2 to a factor of 10^{150} in the amount of energy required to move an object from one point to another. To send the Shuttle into orbit using a space drive could conceivable require a factor of 3.65 less energy. To send a 5000 kg probe to a destination 5 light-years distant with a trip time of 50 years, would require 150 orders of magnitude less energy. And since rockets cannot levitate indefinitely, the potential space drive improvement is infinite, but a value of 62 MJ/kg is possibly a lower limit on the amount of energy required to levitate an object at the Earth's surface.

Although these analyses are only for introductory purposes, a deeper understanding of the challenges of discovering such breakthroughs can be approached through similar assessments using different assumptions and methods. In particular, recalculating the deep space trajectories assuming constant acceleration or constant power would be useful, as well as using different approaches to calculate the energy and power required to levitate an object indefinitely.

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