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Assessing Potential Propulsion Breakthroughs

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Assessing Potential Propulsion Breakthroughs

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Abstract

The term, *propulsion breakthrough*, refers to concepts like propellantless space drives and faster-than-light travel, the kind of breakthroughs that would make interstellar exploration practical. Although no such breakthroughs appear imminent, a variety of investigations into these goals have begun. From 1996 to 2002, NASA supported the Breakthrough Propulsion Physics Project to examine physics in the context of breakthrough spaceflight. Three facets of these assessments are now reported: (1) predicting benefits, (2) selecting research, and (3) recent technical progress. Predicting benefits is challenging since the breakthroughs are still only notional concepts, but kinetic energy can serve as a basis for comparison. In terms of kinetic energy, a hypothetical space drive could require many orders of magnitude less energy than a rocket for journeys to our nearest neighboring star. Assessing research options is challenging when the goals are beyond known physics and when the implications of success are profound. To mitigate the challenges, a selection process is described where: (a) research tasks are constrained to only address the *immediate* unknowns, curious effects or critical issues, (b) *reliability* of assertions is more important than their *implications*, and (c) reviewers judge *credibility* rather than *feasibility*. The recent findings of a number of tasks, some selected using this process, are discussed. Of the 14 tasks included, 6 reached null conclusions, 4 remain unresolved, and 4 have opportunities for sequels. A dominant theme with the sequels is research about the properties of space, inertial frames, and the quantum vacuum.

Introduction

Confronted by the physical limits of rocketry and space sails, NASA supported the Breakthrough Propulsion Physics Project from 1996 to 2002 [Millis 1999a, 2004a]. As its name suggests, the project specifically looked for propulsion *breakthroughs* from *physics* rather than refinements of technology. By breakthroughs, it is meant new propulsion methods that go beyond the limits of rocketry and space sails – the kind of breakthroughs that might make human voyages to other star systems possible. Theories and phenomena in recent scientific literature provide new approaches to seek such breakthroughs, including “warp drives” [Alcubierre 1994], wormholes [Visser 1995], vacuum fluctuation energy [Maclay 2004], and emerging physics in general.

This report focuses on the following 3 challenges of this pursuit: (1) predicting benefits, (2) selecting the best research approaches, and (3) the recent technical progress itself. To predict benefits, a number of different assessments are offered. Since little has been published toward quantifying breakthrough benefits, a variety of assessments are offered to set the groundwork for future assessments. The second challenge, that of selecting the best research approaches, is addressed by summarizing the key management strategies from a recent publication about the NASA Breakthrough Propulsion Physics Project [Millis 2004b]. And finally, extracts from recent research findings [Millis 2004a] are compiled with attention drawn to the most immediate research questions.

Predicting Benefits

Gauging the potential benefits of undiscovered propulsion breakthroughs is challenging, but addressable. The major difficulty is that such breakthroughs are still only notional concepts rather than

being a specific method from which performance can be unambiguously calculated. One prior assessment considered a Voyager-sized spacecraft using a hypothetical space drive to show that the trip time to reach our nearest neighboring star could be decreased by a factor of 6.5 just by using the leftover power of Voyager's generators [Boston 2000]. Another recent assessment considered a rocket with hypothetical modifications of inertia and gravity and showed that the benefits would be trivial [Tajmar 2005]. Performance estimates can vary considerably depending on the methods and assumptions. To pave the way for a more complete suite of assessments, a variety of methods are introduced here along with a few examples that are worked out. A key feature is that the basis of comparison is *energy*, rather than using the metrics of rocketry. Discussion on the pitfalls of using rocketry metrics for assessing breakthrough spaceflight is also provided.

Benefits of Hypothetical Modifications of Propellant Inertia

A recent publication took a first step toward assessing the potential benefits of hypothetical inertial and gravitational control, but did so in terms of rocketry [Tajmar, 2005]. A modified rocket equation was used to demonstrate that naïve modifications of gravity or inertia do not produce much benefit. Although an important first step to help correct misconceptions, this assessment did not include many other relevant comparisons. As an example of a limitation, the published analysis applied a hypothetical inertial change equally to *both* the propellant and the vehicle. It is not surprising then that there is little or no benefit. One could equally assume that *only* the inertia of the expelled propellant were increased while the inertia of the vehicle remained the same, in which case there would be more benefit.

The rocket equation is derived next for both a normal rocket and for the case where the expelled propellant's inertia is *increased as it is accelerated* out of the rocket. The inertial modification is not applied to the rest of the rocket or the stored propellant. 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 realistic potential breakthrough. Numerous variations on this analysis are possible.

The rocket equation is typically derived starting with conservation of momentum, where the momentum of the rocket in one direction must equal the momentum of expelled propellant in the other. For convenience we can set the initial velocity of the rocket to zero. Due to the one-dimensional nature of the problem, vector notation is not needed, but close attention must be paid to the proper sign assignments. Also, the following treatment only represents field-free space where no external forces are acting. Below are the conservation of momentum equations for both the rocket (r) and the modified rocket system (MRS):

The Rocket	The Modified Rocket System (MRS)	
$-v_e dm = dv_r (m - dm)$	$-v_e (\delta) dm = dv_{MRS} (m - dm)$	(1.1)

The left sides of both equations represent the momentum of the expelled propellant and the right sides represent the corresponding momentum of the accelerated rockets, and where;

- dm incremental mass of expelled propellant
- v_e exhaust velocity of propellant (opposite to the direction of the rocket motion, hence the negative sign)
- dv_r incremental change in velocity of the rocket (in the direction of motion, hence the positive sign)
- dv_{MRS} incremental change in velocity of the modified rocket system (MRS)
- m mass of both rockets (including stored propellant)

δ degree of inertia modification, where $\delta=1$ represents no modification, greater than 1 is an increase, and less than 1 is a decrease. Note that this δ is applied to the propellant as it exits the rocket; hence it acts only on the dm term on the left side of the equation. Delta (δ) is shown in parenthesis to make it easier to locate in the derivation that follows.

It is standard practice when deriving the rocket equation to approximate that the expelled propellant is trivially small when compared to the mass of the rocket and its stored propellant [Berman 1961, Seifert 1959]. This simplification can be argued in view of a very short *time* increment for the expulsion. Thus, the dm term on the right-hand side of the equation is a negligible and can be zeroed, while the left-hand dm term still plays a significant role and must remain. Other derivations involving thrust and momentum conversation yield the same results without this approximation [Resnick 1977]. Repeating this analysis using this different derivation is a suitable topic for future work. Applying this ($dm \ll m$) assumption yields:

<p>The Rocket</p> $-v_e dm = mdv_r$	<p>The Modified Rocket System (MRS)</p> $-v_e (\delta) dm = mdv_{MRS}$	(1.2)
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Integrate with respect to mass and velocity:

<p>The Rocket</p> $-v_e \int_{m_i}^{m_f} \frac{1}{m} dm = \int_{v_i}^{v_f} dv_r$	<p>The Modified Rocket System (MRS)</p> $-v_e (\delta) \int_{m_i}^{m_f} \frac{1}{m} dm = \int_{v_i}^{v_f} dv_{MRS}$	(1.3)
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Where the new terms are;

- m_i Initial mass of the rockets (before expulsion of propellant)
- m_f Final mass of the rockets (after expulsion of propellant)
- v_i Initial velocity of the rockets
- v_f Final velocity of the rockets

Calculating the integrals yields:

<p>The Rocket</p> $-v_e \left[\ln(m_f) - \ln(m_i) \right] = v_f - v_i = \Delta v_r$	<p>The Modified Rocket System (MRS)</p> $-v_e (\delta) \left[\ln(m_f) - \ln(m_i) \right] = v_f - v_i = \Delta v_{MRS}$	(1.4)
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Note that the changes in velocity of the rockets are now represented as Δv 's. Distributing the sign and applying a logarithmic identity yields the celebrated Tsiolkovski equation of 1903 [Berman 1961] on the left, and a slightly modified version of the same on the right for the Modified Rocket System:

<p>The Tsiolkovski Rocket Equation</p> $\Delta v_r = v_e \ln \left(\frac{m_i}{m_f} \right)$	<p>The Modified Rocket System Equation (MRS)</p> $\Delta v_{MRS} = (\delta) v_e \ln \left(\frac{m_i}{m_f} \right)$	(1.5)
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Finally, to compare the performance improvement of the Modified Rocket System with the rocket, take the ratio of their Δv 's and require that all other values are identical:

$$\frac{\Delta v_{MRS}}{\Delta v_r} = \frac{v_e(\delta) \ln\left(\frac{m_i}{m_f}\right)}{v_e \ln\left(\frac{m_i}{m_f}\right)} \quad (1.6)$$

Reducing this yields:

$$\frac{\Delta v_{MRS}}{\Delta v_r} = \delta \quad (1.7)$$

This means that a delta of 1.10, representing a 10 percent increase in the expelled propellant's inertia, would yield a 10 percent increase in Δv . While this appears encouraging, it should be remarked that there are at present no known techniques to affect such a change in propellant inertia and the result is only meant to illustrate a potential advantage that hypothetical inertial modifications might provide. A separate issue to pursue would be to calculate the energy required to support this hypothetical change in propellant inertia. Again, the main point of the exercise is to reveal that different approaches will yield significantly different results. The implications of Equation (1.7) are considerably different than the null finding which occurs when one applies the inertial modification to both sides of the equation [Tajmar 2005].

Limits of Rocketry Analyses for Space Drives

When using the metrics of an incumbent technology to assess the potential of a new technology, results can be misleading. The example above is just one illustration of how two different assumptions of hypothetical inertial control via a rocket equation can lead to very different answers. Another misleading use of the rocket equation when contemplating breakthroughs is in the common practice of assigning an infinite specific impulse to describe a propellantless space drive. Although based on a reasonable extrapolation of the trend where higher specific impulse leads to less required propellant, this also leads to the conclusion that a propellantless space drive would require infinite energy. As shown later, this is not necessarily the case. Furthermore, since specific impulse is a measure of the thrust per propellant weight flow rate, it has no real meaning if there is no propellant flow.

Using the rocket equation to describe something that is not likely to involve a rocket is about as misleading as using the metrics of sailing ships to assess steamships [analogy from Foster 1986]. Although reduced sails and rigging is 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 breakthrough inertial or gravity control would likely surpass the operational conventions of rocketry. Although comparisons built on the incumbent methods might be useful for introductory purposes, a deeper understanding of the benefits and research approaches are better illustrated by using a common and more basic metric. For spaceflight, whether via rockets or space drives, energy is a better basis for comparison.

Specific Impulse Limits

Before proceeding to demonstrate the use of energy as a basis for comparison, 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 percent lightspeed. The

corresponding upper limit to specific impulse easily follows from the equation relating specific impulse to exhaust velocity [Seifert 1959]:

$$v_e = I_{sp} g \quad (1.8)$$

Where

I_{sp} “Specific Impulse” (sec) which is a measure of the rocket's propellant efficiency, specifically the amount of thrust per propellant weight flow rate.

g Earth's gravitational field = 9.8 m/s².

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

$$(10 \text{ percent}) \left(3.0 \times 10^8 \frac{m}{s} \right) \geq I_{sp} \left(9.8 \frac{m}{s^2} \right) \Rightarrow I_{sp} \leq 3.0 \times 10^6 s \quad (1.9)$$

Energy Comparisons for Deep Space Travel

This next assessment deals with deep space travel. In this section, both a rocket and a hypothetical space drive will be compared in terms of energy requirements. A space drive is defined as: “an idealized form of propulsion where the fundamental properties of matter and spacetime are used to create propulsive forces anywhere in space without having to carry and expel a reaction mass” [Millis 1997]. For this exercise it can be thought simply as a device that converts potential energy directly into kinetic energy. Since issues such as momentum conservation are addressed in the cited reference, they will not be elaborated on here.

Assumptions

For this introductory exercise, 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:

Both the rocket and the space drive are assumed to be 100 percent efficient with their energy conversions.

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.

Energy of a Rocket

To compare the energy of a rocket to another method that does not require propellant, we need an equation for the kinetic energy where the propellant mass is represented in terms of the vehicle's empty mass and the Δv of the mission. 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 energy imparted to the propellant from the rocket's frame of reference where the rocket has zero velocity (hence zero kinetic energy) [Berman 1961 and Seifert 1959]. This is consistent with the previously stated assumptions.

$$\Delta E = \frac{1}{2} (m_i - m_{empty}) v_e^2 \quad (2.1)$$

Where the parenthetical term is the propellant mass and:

m_{empty} mass of the vehicle without the propellant, which will be the same value used for the space drive.

m_i initial mass of the vehicle before the expulsion of propellant.

v_e exhaust velocity of the rocket.

Next, to convert this into a form where the rocket's propellant mass ($m_i - m_{empty}$) 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 previously derived:

$$m_{empty} \left(e^{\left(\frac{\Delta v}{v_e} \right)} - 1 \right) = (m_i - m_{empty}) \quad (2.2)$$

Where the Δv is the required change in velocity for the mission. For a rendezvous mission, the Δv is twice that of just a flyby mission. Substituting this form of the rocket equation into the kinetic energy equation yields this very simple approximation:

$$\Delta E = \frac{1}{2} (v_e)^2 m_{empty} \left(e^{\left(\frac{\Delta v}{v_e} \right)} - 1 \right) \quad (2.3)$$

Energy for a Space Drive

Since a space drive has been defined for this exercise as a device that converts potential energy into kinetic energy, the basic equation of kinetic energy is used to calculate the energy requirement, where the values of vehicle mass and mission Δv are the same as with the rocket.

$$\Delta E = \frac{1}{2} m_{empty} (\Delta v)^2 \quad (2.4)$$

Comparisons

Two things are important to note regarding the energy differences between a rocket and a hypothetical space drive. First, the energy for a given Δv scales as an *exponent* for a rocket and scales as the *square* of the Δv for a space drive. 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 space drives, however, the additional maneuvers are in terms of additional kinetic energy. To illustrate this difference, consider a mission consisting of multiple maneuvers (n) each having the same incremental change in velocity (Δv_i). Notice the location of the term representing the number (n) of repeated maneuvers (Δv_i), in the following two equations. In the case of the space drive, additional maneuvers scale linearly, while for rockets they scale exponentially. This is another example to highlight why rocket conventions can be misleading when contemplating space drives:

Rocket Maneuvers

$$\Delta E = \frac{1}{2}(v_e)^2 m_{empty} \left(e^{\left((n) \frac{\Delta v_i}{v_e} \right)} - 1 \right)$$

Space Drive Maneuvers

$$\Delta E = (n) \frac{1}{2} m_{empty} (\Delta v_i)^2 \tag{2.5}$$

Numerical Example

To put this into perspective, consider a representative 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 percent 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 [Boston 2000]. The comparison is made for both a flyby mission and a rendezvous mission.

The rocket case is calculated for two different specific impulses, one set at the upper non-relativistic limit previously described, and another set at a high value achieved during electric propulsion lab tests [Byers 1969]. The *Space Drive Improvement* column is the ratio of the rocket energy to the space drive energy.

TABLE I.—COMPARISON OF DEEP SPACE MISSION ENERGY REQUIREMENTS

	Specific Impulse	Mission	Joules Required	Space Drive Improvement
Rockets				
Upper Lab Limit [Byers 69]	17,200 sec	Flyby Rendezvous	10 ⁹¹ 10¹⁶⁸	10 ⁷² 10¹⁴⁹
Non-Relativistic Upper Limit	3,000,000 sec	Flyby Rendezvous	3.8×10 ¹⁸ 1.5×10¹⁹	1.7 3.2
Space Drive	N/A N/A	Flyby Rendezvous	2.3×10 ¹⁸ 4.5×10 ¹⁸	

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 that currently used in practice—the benefits of a space drive are enormous. Even 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 better. Again, though these results are intriguing, they should only be interpreted as the magnitude of gains sought by breakthrough propulsion research. Further variations of such assessments are possible.

Energy Comparisons for Earth to Orbit

Consider 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. For the hypothetical space drive, this energy expenditure can be represented as:

$$E_{SpaceDrive} = \Delta U + \Delta K \tag{3.1}$$

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

$$\Delta U = \int_{Surface}^{Orbit} F \cdot dr = \int_{r_{Surface}}^{r_{Orbit}} G \frac{M_{Earth}}{r^2} m_{craft} dr \quad (3.2)$$

Where:

- F Force due to gravity
- G Newton's gravitational constant
- M_{Earth} mass of the Earth
- m_{craft} mass of the spacecraft
- r radius from the center of the Earth
- r_{Orbit} radius of the orbit as measured from the center of the Earth
- $r_{Surface}$ radius of the Earth's surface

As a comparative example, we can calculate the energy required by a 100 percent efficient hypothetical space drive to launch the mass of the Space Shuttle into orbit. Only the Orbiter mass (9.76×10^4 kg) is used for these comparative assessments instead of the rest of the Shuttle system elements.

$$\Delta U = \left(6.67 \times 10^{-11} \frac{m^3}{kg \cdot s^2} \right) (5.98 \times 10^{24} kg) (9.76 \times 10^4 kg) \left(\frac{1}{6.37 \times 10^6 m} - \frac{1}{6.67 \times 10^6 m} \right) = 2.75 \times 10^{11} \text{ Joules} \quad (3.3)$$

The change in kinetic energy requires solving for the orbital velocity and the velocity of the Earth's surface, as shown by:

$$\Delta K = K_{Orbit} - K_{Surface} = \frac{1}{2} m_{craft} (v_{Orbit}^2 - v_{Surface}^2) = \frac{1}{2} m_{craft} \left(\left[G \frac{M_{Earth}}{r_{Orbit}} \right] - \left[\frac{2\pi r_{Earth}}{1 \text{ day}} \right]^2 \right) \quad (3.4)$$

Where the additional terms are:

- K_{Orbit} Kinetic energy of the Shuttle Orbiter in orbit
- $K_{Surface}$ Kinetic energy of the Shuttle Orbiter when at rest relative to the Earth's surface, but where the Earth's surface is rotating
- v_{Orbit} Orbital speed
- $v_{Surface}$ Speed of the Earth's surface due to its daily rotation

Again, for the case of a hypothetical space drive placing the mass of the Space Shuttle into Low Earth Orbit (LEO), the following values apply:

$$\Delta K = \frac{1}{2} (9.76 \times 10^4 kg) \left(\left[\left(6.67 \times 10^{-11} \frac{m^3}{kg \cdot s^2} \right) \frac{5.98 \times 10^{24} kg}{6.67 \times 10^6 m} \right] - \left[\frac{2\pi (6.37 \times 10^6 m)}{86400s} \right]^2 \right) = 2.91 \times 10^{12} \text{ Joules} \quad (3.5)$$

Combining the changes in potential and kinetic energy gives the total energy required for a hypothetical space drive to put the mass of the Space Shuttle Orbiter into Low Earth Orbit:

$$E_{SpaceDrive} = 3.18 \times 10^{12} \text{ Joules} \quad (3.6)$$

To assess the required energy for the rocket, the actual values of the Space Shuttle System (STS) are used, values extracted from “STS-3 Thirds Space Shuttle Mission Press Kit, March 82,” Release no. 82 to 29. In this case the rocket *power* equation is employed and energy is calculated from the product of the rocket power and thrusting duration. The shift to describing rocket performance in terms of power is done for two reasons: first to highlight this form of the rocket equation [Berman 1961] and secondly to introduce the idea of contemplating *power* in addition to just *energy*. While power implications are not explored here in detail, they constitute a fertile area for further study.

Starting with the equation for rocket power [Berman 1961]:

$$P = \frac{1}{2} F I_{sp} g \quad (3.7)$$

Where the new terms are:

P Power

F Rocket thrust force

Applying the physics relation where energy is the product of power and time, yields the following equation for rocket energy in terms of power and thrusting duration:

$$E = \frac{1}{2} F I_{sp} g t \quad (3.8)$$

Where the new term is:

t Thrusting duration

There are three different types of rockets that make up the STS: the Space Shuttle Main Engines (SSME), the Solid Rocket Boosters (SRB), and the Orbital Maneuvering System (OMS). The total energy is the combination of the energy of each of these:

$$E_{STS} = E_{SSME} + E_{SRB} + E_{OMS} \quad (3.10)$$

Where the energy for each of these rockets is:

$$E_{SSME} = (3 \text{ engines}) \frac{1}{2} \left(470 \times 10^3 \text{ lbs Thrust / engine} \right) \left(4.45 \frac{\text{N}}{\text{lb}} \right) \left(453 \text{ s } I_{sp} \right) \left(9.8 \frac{\text{m}}{\text{s}^2} \right) (514 \text{ s BurnDuration}) = 7.17 \times 10^{12} \text{ Joules} \quad (3.11)$$

$$E_{SRB} = (2 \text{ boosters}) \frac{1}{2} \left(2.9 \times 10^6 \text{ lbs Thrust / booster} \right) \left(4.45 \frac{\text{N}}{\text{lb}} \right) \left(266 \text{ s } I_{sp} \right) \left(9.8 \frac{\text{m}}{\text{s}^2} \right) (126 \text{ s BurnDuration}) = 4.24 \times 10^{12} \text{ Joules} \quad (3.12)$$

$$E_{OMS} = (2 \text{ engines}) \frac{1}{2} \left(6 \times 10^3 \text{ lbs Thrust / engine} \right) \left(4.45 \frac{\text{N}}{\text{lb}} \right) \left(313 \text{ s } I_{sp} \right) \left(9.8 \frac{\text{m}}{\text{s}^2} \right) (200 \text{ s BurnDuration}) = 1.64 \times 10^{10} \text{ Joules} \quad (3.13)$$

Combining these values yields:

$$E_{STS} = 1.14 \times 10^{13} \text{ Joules} \quad (3.14)$$

Comparing this rocket energy value to the hypothetical space drive energy, where the efficiency of both systems is assumed to be 100 percent, yields:

$$\frac{E_{STS}}{E_{SpaceDrive}} = \frac{1.14 \times 10^{13} \text{ Joules}}{3.18 \times 10^{12} \text{ Joules}} = 3.58 \quad (3.15)$$

This means that a hypothetical space drive is potentially more than 3-and-a-half times more energy efficient. When compared to the benefits of interstellar space drives, however, this gain is small. From these cursory analyses, space drives do not appear as attractive for launching spacecraft into low orbit as they do for high Δv missions or missions that require many maneuvers. Again, such introductory comparisons should not be taken too literally. These assessments are provided to demonstrate that there are a variety of ways to assess the potential benefits of propulsion breakthroughs.

Energy for Levitation

Levitation is included here mostly to illustrate how contemplating breakthrough propulsion is different from contemplating 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 clear way how 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 distance. Levitation means hovering with no change in height. Regardless, there are a variety of ways to toy with the notion of energy and power for indefinite levitation. A few of these approaches are listed in the next session. For now, only one approach is illustrated, specifically the nullification of gravitational potential.

An object in a gravitational field has the following defined value for its gravitational potential energy:

$$E = mgh = m \frac{GM_{Earth}}{h} \quad (4.1)$$

Where:

- m mass of the object
- g acceleration due to gravity
- h levitation height as measured from the center of the Earth
- G Newton's gravitational constant
- M_{Earth} mass of the Earth

Usually this potential energy is used to compare energy differences between two relatively short differences in height (h) but in our situation we are considering this potential energy in the more absolute sense. This same value of potential energy can also be determined by calculating how much energy it would take to completely remove the object from the gravitational field, as if moving it to infinity. This is more in line with the analogy to nullify the effect of gravitational energy. This is also the same amount of energy that is required to stop an object at the levitation height (h) if it were falling in from infinity with an initial velocity of zero. To illustrate this equivalence of these treatments, start with the equation used

earlier to calculate the change in potential energy for entering orbit, but this time use different limits of integration:

$$E = \int_{\text{LevitationHeight}}^{\text{Infinity}} F \cdot dr = \int_h^{\infty} G \frac{mM_{\text{Earth}}}{r^2} dr = mGM_{\text{Earth}} \left[\frac{1}{h} - \frac{1}{\infty} \right] = m \frac{GM_{\text{Earth}}}{h} = mgh \quad (4.2)$$

It is clear that this is identical to the gravitational potential energy in Equation (4.1). Using the analogy of removing the effect of gravitational potential energy, it is reasonable to conjecture that this is one way to calculate the amount of energy required to permanently levitate an object. Inserting values representative of levitating 1-kg near the Earth's surface yields:

$$E = 1 \text{ kg} \left(9.80 \frac{\text{m}}{\text{s}^2} \right) 6.37 \times 10^6 \text{ m} = 62 \text{ M Joules} \quad (4.3)$$

Hence, to levitate 1-kg near the Earth's surface could conceivably require 62 Mega-Joules. 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.

Assessing Benefits More Generally

As illustrated with these introductory examples, there are a number of different ways to assess the potential benefits of breakthrough physics propulsion. To continue with deeper inquiry, a variety of missions and assumptions can be addressed. The following list is just a starting point for further analyses. Those items marked in bold font are the ones already introduced in this paper.

1. Deep space travel (motion from point A to B without external forces):
 - a. Rocketry baselines:
 - i. Non-relativistic Energy (velocity less than 10 percent lightspeed):
 - 1. Constant exhaust velocity and short thrust durations.**
 2. Constant thrust.
 3. Constant acceleration.
 4. Optimized for minimum trip times.
 - ii. Relativistic Energy (cases 1 to 4 above repeated with relativistic corrections).
 - b. Space Drive motion using mechanical analogies:
 - i. Non-relativistic Energy:
 - 1. Simple kinetic energy differences.**
 2. Kinetic energy under constant acceleration.
 3. Kinetic energy under constant power.
 - ii. Relativistic Energy (cases 1 to 3 above repeated with relativistic corrections).
 - c. Space Drive motion using geometric spacetime analyses:
 - i. Creating a pseudo geodesic—reshaping spacetime to induce the preferred freefall trajectory.
 - ii. Warp Drive—moving a chunk of spacetime [Alcubierre 1994].
 - iii. Wormhole—moving through a shortcut in spacetime [Visser 1995].
 - iv. Krasnikov tube—creating a faster-than-light geodesic [Krasnikov 1998].
2. Ascent to orbit (motion in a gravitational field with the destination being a stable orbit):
 - a. Rocketry ascent baselines:
 - i. **Space Shuttle System data.**
 - ii. Generic staged rocket ascent.

- b. Space Drive ascent using mechanical analogies:
 - i. **Simple kinetic and potential energy differences using Space Shuttle data.**
 - ii. Ascent under constant power.
- 3. Levitating in a gravitational field:
 - a. Rocketry levitation baseline: Levitation duration at the Earth's surface.
 - b. Space Drive levitation using mechanical analogies;
 - i. **Normal physics definition of work, where zero change in height equates to zero energy expenditure.**
 - ii. Comparison to continual down thrust of a reaction mass (rocket and helicopter analogy).
 - iii. Comparison to normal accelerated motion in free space, where distance is traversed.
 - iv. **By negating gravitational potential, as if moving a mass to infinity.**
 - v. Comparing to kinetic energy associated with escape velocity.
 - vi. Thermodynamic approach: Seeking equations for the energy and power to keep a system in a stationary state away from its equilibrium condition, where the equilibrium condition is free-fall motion of a mass in a gravitational field and the stable non-equilibrium condition is levitation at a given height.
 - vii. Assuming a “gravity shield,” but for illustrative purposes consider it located under half of a vertical wheel to calculate the energy associated with the increasing rotation rate of the wheel.
 - viii. Calculating the energy of oscillation about an median hovering height, but where an energy cost is incurred for both the upward and downward excursions, and where damping losses are included.
 - ix. Analyze using the “impulse” treatment (force x duration, rather than force x distance).
 - c. Space Drive levitation in terms of geometric general relativity—inducing a null geodesic where the local freefall path is a stationary trajectory.

Selecting Research Approaches

A normal challenge of any research project is directing limited resources to the best prospects. The hunt for incredible breakthroughs faces the additional challenge of making credible progress. Because the desired propulsion breakthroughs are presumably far from fruition and provocative, specific strategies were devised in the course of the NASA Breakthrough Propulsion Physics (BPP) Project to mitigate the risks and maximize progress [Millis 2004b]. The BPP Project employed the operating strategies described below. Other details, such as the specific selection criteria, evaluations equations, review process, and lessons learned, are presented in Millis [2004b].

Reliability

Although it is a common practice when advocating research to emphasize the ultimate technical benefits, this practice is not constructive on topics as visionary and provocative as breakthrough spaceflight. Instead, it is more constructive to emphasize the *reliability* of the information being offered. Compared to other propulsion research, new propulsion physics is at its infancy. It is expected, therefore, that any practical embodiment is years, perhaps decades away, if not impossible. Although breakthroughs, by their very definition, happen sooner than expected, no breakthrough is genuine until it has been *proven* to be genuine. Hence, the reliability of the information is a paramount prerequisite to the validity of any conclusions. To place the emphasis where it is needed, no research approach should be considered unless credibility is satisfactorily addressed, regardless of the magnitude of claimed benefit. Success is defined as acquiring *reliable* knowledge, rather than as achieving a breakthrough.

Immediacy

Another technique to shift the emphasis away from provocative situations and toward constructive practices is to focus the research on the *immediate* questions at hand. These immediate unknowns, issues, and curious effects can be identified by comparing established and emerging physics to the ultimate propulsion goals. The scope of any research task should ideally be set to the minimum level of effort needed to resolve an immediate “go/no-go” decision on a particular approach. This near-term focus for long-range research also makes the tasks more manageable and more affordable. Specifically, it is recommended that any proposed research be configured to reach a reliable conclusion in one to three years. Should the results be promising, a sequel can be proposed in the next solicitation cycle.

Measured

To help identify a suitable research increment and to provide managers a means to measure progress, the Scientific Method can be adapted as a readiness scale in a manner similar to how the Technology Readiness Levels are used to measure *technological* progress [Hord 1985]. The readiness scale developed for the BPP Project consists of three stages that gauge the *applicability* of the work (reflecting how research can evolve from the more general, to the more specific application), and within each of these 3 stages, the 5 steps of the *scientific method* are repeated (from recognizing the problem, through testing the hypothesis). This equates to 15 levels of relative maturity, with the most advanced level being equivalent to Technology Readiness Level 1 (Basic principles observed and reported). An abbreviated version of these “Applied Science Readiness Levels” is presented in Table II, and further details are available in Millis [2004b]. Once a research objective has been ranked relative to this scale, the next logical increment of research would be to advance that topic to the next higher readiness level. This is consistent with the *incremental* research strategy.

TABLE II.—APPLIED SCIENCE READINESS LEVELS

General Physics—deals with general underlying physics related to the application.	
SRL-1.0	Pre-science (Unconfirmed effect or new information connection)
SRL-1.1	Problem formulated
SRL-1.2	Data collected
SRL-1.3	Hypothesis proposed
SRL-1.4	Hypothesis tested & results reported
Critical Issues—deals with an immediate unknown, critical make-or-break issue, or curious effect relevant to the application.	
SRL-2.0	Pre-science (Unconfirmed effect or new information connection)
SRL-2.1	Problem formulated
SRL-2.2	Data collected
SRL-2.3	Hypothesis proposed
SRL-2.4	Hypothesis tested & results reported
Desired Effect—deals directly with the effect required by the application (e.g. inducing forces or generating energy in the case of breakthrough propulsion applications)	
SRL-3.0	Pre-science (Unconfirmed effect or new information connection)
SRL-3.1	Problem formulated
SRL-3.2	Data collected
SRL-3.3	Hypothesis proposed
SRL-3.4	Hypothesis <i>empirically</i> tested & results reported (Equivalent to TRL 1 : Basic principles observed and reported)

Iterated

To accumulate progress over the long term, it is recommended to solicit a suite of proposals every two to three years, and to let the findings of the prior suite influence the next round of selections. This provides an opportunity for new approaches, sequels to the positive results, and redirections around null results. At any point, if a research task leads to the discovery of a new propulsion or energy effect, it can be pulled out of this process into its own advancement plan. This strategic approach is recommended for high-gain/high-risk research, where cycles of peer-reviewed solicitations can examine a diverse portfolio of options, and where the decisions build on the lessons learned from prior cycles of research.

Diversified

It is far too soon, in the course of seeking spaceflight breakthroughs, to down-select to just one or two hot topics. Instead a *variety* of research approaches should be investigated in each review cycle. In simple terms, this is to diversify the research portfolio. This is different than the more common practice with advanced propulsion research where further advancements are primarily sought on the technical approaches already under study. Although this more common strategy can produce advances on the chosen topics, it faces the risk of overlooking emerging alternatives and the risk that support will wane unless the chosen topics produce unambiguous positive results.

Impartial

When inviting research the edge of knowledge, controversial ideas are encountered. Considering that most historic breakthroughs originally sounded like fringe ideas, it is not surprising that many of the proposals for breakthrough spaceflight might sound *too* visionary at first, or at least unfamiliar. It is therefore difficult to sort out the fringe ideas that may one day evolve into tomorrow's breakthroughs from the more numerous, erroneous fringe ideas. During proposal reviews, it is common to have some reviewers reflexively assume that unfamiliar ideas will not work. To *reliably* determine technical feasibility, however, is beyond the scope of a proposal review—constituting a full research task unto itself. Instead of expecting proposal reviewers to judge technical feasibility, it is recommended to have reviewers judge if the task is leading to a result that other researchers will consider as a reliable conclusion on which to base future investigations. This includes both the possibility of determining which approaches are nonviable as well as which are candidates for deeper inquiry. This posture of judging credibility rather than pre-judging feasibility is one of the ways of being open to visionary concepts while still sustaining credibility.

Empirical

When seeking advancements that can eventually lead to new technology, there is a decided preference toward tangible observations over purely analytical studies—all other factors being equal, such as cost, technical maturity, etc. Experiments, being hardware, are considered closer than theory to becoming technology. Also, experiments are considered a more direct indicator of how nature works. Theories are interpretations to explain observations of nature, while the empirical data *is* nature, partially revealed within the constraints of the given experiment.

Published

The final recommendation to mitigate the risks of pursuing visionary, high-gain research is to ensure that the research findings are published, regardless of outcome. Results, pro or con, set the foundations for guiding the next research directions. Although there can be a reluctance to publish null results—where a

given approach is found not to work—such dissemination will prevent other researchers from repeatedly following dead-ends.

Recent Technical Progress

The findings of over a dozen separate research tasks related to breakthrough propulsion physics were recently published [Millis 2004a]. These findings are rearranged here according to which tasks proved non-viable, which remain unresolved, and which are candidates for further research. Under each of these headings, the different approaches are only briefly described, but pertinent reference citations are offered for follow-up inquiries.

It should be stressed that even interim positive results do not imply that a breakthrough is inevitable. Often the opportunity for sequels is more a reflection of the embryonic state of the research. Reciprocally, a dead-end conclusion on a given task does not imply that broader topics are equally defunct. Both the null and positive results should be strictly interpreted within the context of the immediate research task. This is consistent with the operating strategy to focus on the immediate stage of the research, and the strategy to put a higher priority on the reliability of the information rather than on producing broad-sweeping claims.

It should also be stressed that these task summaries do not reflect a comprehensive list. It is expected that new concepts will continue to emerge in such an embryonic field and that further, more applicable references may already be in the open literature.

Non-Viable Approaches

Oscillation Thrusters and Gyroscopic Antigravity

A large number of mechanical devices that claim to produce net external thrust, using just the motion of internal components, are often proposed. These devices fall into two categories, oscillation thrusters and gyroscopic devices. Their appearance of creating net thrust is attributable to misinterpretations of normal mechanical effects. The following short explanations were excerpted and edited from a NASA website about commonly submitted erroneous breakthroughs [Thomas 2002].

Oscillation thrusters move a system of internal masses through a cycle where the motion in one direction is quicker than in the return direction. When the masses are accelerated quickly, the device has enough reaction force to overcome the friction of the floor and the device slides. When the internal masses return slowly in the other direction, the reaction forces are not sufficient to overcome the friction to move the device. The net effect is that the device moves in one direction across a *frictional* surface. In a *frictionless* environment the whole system would simply oscillate around its center of mass.

A gyroscopic thruster consists of a system of gyroscopes connected to a central body. When the central body is torqued, the gyros move in a way that *appears* to defy gravity. Actually the motion is due to gyroscopic precession and the forces are torques around the axes of the gyros' mounts. There is no net thrust created by the system.

To keep an open, yet rigorous, mind to the possibility that there has been some overlooked physical phenomena with such devices, it would be necessary to explicitly address all the conventional objections and pass at least a pendulum test. Any test results would have to be impartial and rigorously address all possible causes that might lead to a false-positive conclusion. There has not yet been any viable theory or experiment that reliably demonstrates that a genuine, external, net thrust can be obtained with one of these devices. If such tests are ever produced, and if a genuine new effect is found, then science will have to be revised, because it would then appear that such devices are violating Conservation of Momentum.

Hooper Antigravity Coils

Experiments were conducted to test assertions from US Patent 3,610,971, by W.J. Hooper that self-canceling electromagnetic coils can reduce the weight of objects placed underneath. No weight changes were observed within the detectability of the instrumentation. More careful examination led to the conclusion that Hooper may have misinterpreted thermal effects as his “Motional Field” effects [Millis 1995].

Schlicher Thrusting Antenna

Tests of a specially terminated coax, that was claimed to create more thrust than attributable to photon radiation pressure, revealed that no such thrust was present [Fralick 2001].

Podkletnov Gravity Shield

A controversial claim of “gravity shielding” using rotating superconductors and radio-frequency radiation was published based on work done at Finland's Tampere Institute [Podkletnov 1992]. A privately funded replication of the Podkletnov configuration “found no evidence of a gravity-like force to the limits of the apparatus sensitivity,” where the sensitivity was “50 times better than that available to Podkletnov.” [Quoting from Hathaway 2003].

Coronal Blowers

There are many variants of the original patent where high-voltage capacitors create thrust [Brown 1928], many of which claim that the thrust is a new physical affect akin to antigravity. These go by such terms as: “Biefeld-Brown effect,” “lifters,” “electrostatic antigravity,” “electrogravitics,” and “asymmetrical capacitors.” To date, all rigorous experimental tests indicate that the observed thrust is attributable to coronal wind [Canning 2004, Tajmar 2004, Talley 1991]. Quoting from one such finding: “... their operation is fully explained by a very simple theory that uses only electrostatic forces and the transfer of momentum by multiple collisions [with air molecules].” [Canning 2004]

Quantum Tunneling as an FTL venue

A prerequisite to faster-than-light travel is to prove faster-than-light *information* transfer. The phenomenon of quantum tunneling, where signals appear to pass through barriers at superluminal speed, is often cited as such empirical evidence. Experimental and theoretical work indicates that the information transfer rate is only *apparently* superluminal, with no causality violations. Although the leading edge of the signal does appear to make it through the barrier faster, the entire signal is still light-speed limited [Mojahedi 2000a, 2000b, and Segev 2000]. This topic still serves, however, as a tool to explore this intriguing aspect of physics.

Unresolved Approaches

Woodward's Transient Inertial Oscillations

Experiments and theories published by James Woodward claim that oscillatory changes to inertia can be induced by electromagnetic means [Woodward 2004] and a patent exists on how this can be used for propulsion [Woodward 1994]. Conservation of momentum is satisfied by evoking interpretations of Mach's principle. Independent verification experiments, using techniques less prone to spurious effects, were unable to reliably confirm or dismiss the claims [Cramer 2004]. Woodward and others continue with

experiments and publications to make the effect more pronounced and to more clearly separate the claimed effects from experimental artifacts. This oscillatory inertia approach is considered unresolved.

Abraham—Minkowski Electromagnetic Momentum

More than one approach attempts to use an unresolved question of electromagnetic momentum (Abraham-Minkowski controversy [Brevik 1982]) to suggest a new space propulsion method [Slepian 1949, Brito 2001, and Corum 2001]. The equations that describe electromagnetic momentum in vacuum are well established (photon radiation pressure), but there is still debate concerning momentum *within* dielectric media. In all of the proposed propulsion methods, the anticipated forces are relatively small (comparable to experimental noise) and critical issues remain unresolved. In particular, the conversion of an oscillatory force into a net force remains questionable and the issue of generating *external* forces from different *internal* momenta remains unproven. Even if unsuitable for propulsion, these approaches provide empirical tools for further exploring the Abraham-Minkowski controversy of electromagnetic momentum.

Inertia and Gravity Interpreted as Quantum Vacuum Effects

Theories are entering the peer-reviewed literature that assert that gravity and inertia are side effects of the quantum vacuum. The theories are controversial and face many unresolved issues. In essence this approach asserts that inertia is related to an electromagnetic drag force against the vacuum when matter is accelerated, and that gravity is the result of asymmetric distributions of vacuum energy caused by the presence of matter [Puthoff 1993, Haisch 1994, Rueda 1998, and Puthoff 2005]. The space propulsion implications of these theories have been raised [Puthoff 2002], but experimental approaches to test these assertions have not yet entered the literature.

Podkletnov Force Beam

On an Internet physics archive [Pokkletnov 2001] it is claimed that forces can be imparted to distant objects using high-voltage electrical discharges near superconductors. Between 4×10^{-4} to 23×10^{-4} Joules of mechanical energy are claimed to have been imparted to an 18.5-gram pendulum located 150 meters away and behind brick walls of a separate building. Like the prior gravity shielding claims, these experiments are difficult and costly to duplicate, and remain unsubstantiated by reliable independent sources.

Candidates for Continued Research

Space Drives

“Space drive” is a general term to encompass the ambition of propulsion without propellant. To identify the unresolved issues and research paths toward creating a space drive, seven hypothetical space drives were conceived and cursorily addressed [Millis 1997]. The two largest issues facing this ambition are to find a way for a vehicle to induce *external* net forces on itself, and secondly, to satisfy conservation of momentum in the process. As discussed below, several avenues for research remain, including: (1) investigate space from the perspective of new sources of reaction mass, (2) revisit Mach's Principle to consider coupling to surrounding mass via inertial frames, and (3) investigate the coupling between gravity, inertia, and controllable electromagnetic phenomena. These are very broad and open areas where a variety of research sequels could emerge.

Reaction mass in space.—A key aspect of conservation of momentum is the reaction mass. When an automobile accelerates, its wheels push against the road using the Earth as the reaction mass. Helicopters and aircraft use the air as their reaction mass. In space, where there are no roads or air, a rocket must

bring along propellant to thrust against. To contemplate space travel that circumvents the propellant limits of rockets, some other indigenous reaction mass must be found along with the means to induce net forces on the reaction mass.

Recent observations reveal a number of interesting phenomena of space. Although none are directly suitable as reactive media, they are at least indicative that space has substantive properties whose further study pertains to breakthrough spaceflight. Cosmological observations have revealed the *Cosmic Microwave Background Radiation*, *dark matter*, and *dark energy* [Hartle 2002], and quantum physics has revealed *zero point energy* [Milloni 1994]. The Cosmic Background Radiation is low-energy microwave radiation whose composite motion is coincident with the mean reference frame of the universe [Muller 1978]. Although too weak to be used as a reactive media, its existence and directional dependence is thought provoking in the context of space travel. *Dark matter* is the term used to encompass observations that there is more gravitating matter at galactic scales than can be observed. Some estimates are that more than 90 percent of the matter in galaxies is not directly visible. One of the key supporting empirical observations are the anomalous rotation rates of galaxies, where the galaxies appear to hold together more strongly than can be accounted for by the visible matter. From the propulsion point of view, the suitability of dark matter as a reaction mass has not yet been rigorously studied. On even larger scales, anomalous red-shifts from the most distant matter of the universe suggest that the universal expanding at an accelerating rate. The working hypothesis for this anomaly is dubbed *dark energy* and it is conjectured to be an antigravity-like effect [Seife 2003]. Again, the propulsion implications of such phenomena have not been explored. And lastly, the quantum vacuum phenomenon of zero point energy suggests that even the most empty of spaces still contain some non-zero amount of energy. This last item is discussed separately in a later paragraph.

Revisit Mach's Principle.—One of the theoretical approaches in dealing with momentum conservation for space drives is to reexamine Mach's Principle. Mach's Principle asserts that an inertial frame, specifically the property of a space to be a reference frame for acceleration, is actually created by and connected to the surrounding mass in the universe [Mach 1883]. At least one perspective views this property as being related to the gravitational potential of the masses across the universe [Barbour 1995]. A related issue is that a literal interpretation of Mach's Principle implies an absolute reference frame, coincident with the mean rest frame for all the matter in the universe [Barbour 1989]. From the space-propulsion point of view, this is a convenient perspective. Curiously, a known phenomenon that is coincident with this reference frame is the Cosmic Microwave Background Radiation.

These Machian perspectives imply a *Euclidean* view of space-time. Within general relativity, there do exist such Euclidean interpretations, which are often referred to as “optical analogies.” In this interpretation, space is represented as an optical medium with an effective index of refraction that is a function gravitational potential [de Felice 1971, Evans 1996]. Although different from the more common geometric interpretation, this interpretation has been shown to be consistent with physical observables, and transformation rules between the optical and geometric perspectives have also been published [Evans 1996]. Conveniently, it also casts the coupling between gravity and electromagnetism in more simple terms. Little attention is typically focused on this optical analogy because it does not predict any new effects that aren't already covered by the more common geometric perspective and because it raises unanswered issues with coordinate systems choices. Another consequence is that wormholes are indescribable in this perspective. From the propulsion point of view, however, issues of coordinate frames are of keen interest.

Coupling of fundamental forces.—Electromagnetism, gravity and spacetime are coupled phenomena. Given our technical proficiency at manipulating electromagnetism, this coupling hints that we might be able to use electromagnetism to affect gravity. In principle this is true. In practice, at least from the perspective of general relativity, it would take an enormous amount of electromagnetic energy to produce a perceptible gravitational effect—energy levels in the regime of $E = mc^2$, where m represents the induced mass effect. While general relativity pertains to large-scale couplings, quantum and particle physics pertains to the couplings on the atomic scale and smaller. One example of an unresolved small-scale question is the unknown inertial and gravitational properties of antimatter. Although presumed to be

equal to their normal-matter counterparts, long-duration low-gravity experiments could resolve minor differences that have not been testable in terrestrial labs [Lewis 1998]. Such experiments might also help resolve the lingering incompatibility between general relativity and quantum mechanics. As much as these pertain to general physics, they may also have implications for propulsion physics.

Quantum Vacuum Energy Experiments

The *uncertainty principle* from quantum mechanics indicates that it is impossible to achieve an absolute zero energy state. This includes the energy state of empty space [Milonni 1994]. It has been shown analytically [Casimir 1948], and later experimentally [Lamoreaux 1997], that this vacuum energy can squeeze parallel plates together. This “Casimir effect” is only appreciable for very small cavity dimensions (microns). Nonetheless, it is evidence that empty space can present situations where forces exist when none were naively expected. Theoretically it might be possible to induce *net* forces relative to this background energy, but the forces are extremely small [Maclay 2004]. More recent experiments have explored the physics of the quantum vacuum using MEMS technology—micro-electro-mechanical structures of machined silicon [Maclay 2000, Esquivel-Sirvent 2002]. Continued research on this phenomenon and through these techniques is expected.

Provocative Questions

In addition to the unanswered questions of reaction mass in space or the viability of vacuum energy for practical purposes, there are a variety of other provocative effects and theoretical questions that pertain to the search for new propulsion physics. One example from general relativity is that a propulsive effect could be induced by frame dragging from a twisting toroid of ultra dense matter, where an acceleration field is induced inside the toroid [Forward 1963]. Although the magnitude of the induced effect is trivial compared to the energy expenditure, this serves as an analytical approach to investigate the implications of such notions. Another curiosity is the anomalous trajectories of the Pioneer 10/11, Galileo, and Ulysses spacecraft [Anderson 1998, 1999]. Once these spacecraft were farther than about 20 astronomical units from the Sun, their actual trajectories show an unexpected deceleration on the order of 10^{-10} g's [Nieto 2004]. A report sponsored by the European Space Agency includes a proposal for a "Sputnik-5" probe to explore this anomaly [Bertolami 2002]. This same ESA study further suggests checking for evidence of violations of the equivalence principle in long duration free-fall trajectories (orbits).

Faster Than Light

As a consequence of Einstein's general relativity, the notion of warping space to circumvent the light-speed limit is an open topic in scientific literature. This approach involves altering spacetime itself rather than trying to break the light-speed limit *through* spacetime. Two prominent approaches are the *warp drive* and the *wormhole*. The warp drive concept involves moving a bubble of spacetime that carries a vehicle within [Alcubierre 1994]. A wormhole, on the other hand, is a shortcut through spacetime created by extreme spacetime warping [Morris 1998, Visser 1995]. Enormous technical hurdles face these concepts. In particular, they require enormous quantities of “negative energy” (equivalent mass of planets or suns) [Pfenning 1998], and evoke time-travel paradoxes (“closed-time-like curves”) [Everett 1996]. Given the magnitude of energy requirements to create perceptible effects, it is unlikely that experimental work will be forthcoming in the near future. Even though these theoretical concepts are unlikely to be engineered, they are at least useful for teaching the intricacies of general relativity. While laboratory experiments are still prohibitive, astronomical searches for related phenomena could be undertaken, such as looking for the characteristic signatures of a wormhole [Cramer 1995].

Summary of Research Findings

The majority of open research paths involve further study of the fundamental properties of spacetime and inertial frames, looking for candidate sources of reaction mass and the means to interact with it. As much as these are basic areas of investigation for general physics, their investigation in the context of breakthrough spaceflight introduces additional perspectives from which to contemplate these lingering unknowns. This alternative perspective might just provide the insight that would otherwise be overlooked.

Concluding Remarks

The potential benefits of breakthrough propulsion cannot yet be calculated with certainty, but crude introductory assessments show that the performance gains could span from a factor of 2 to a factor of 10^{150} improvement in the amount of energy required to move an object from one point to another. The more demanding the journey, the higher the gain. For a hypothetical non-relativistic space drive, the energy scales as the square of the Δv , while rocket energy scales exponentially for Δv . This is a considerable difference, particularly for high Δv missions..

Because of the profound implications of success and the fledgling nature of the research, special management methods are recommended to ensure credible progress. Lessons from the NASA Breakthroughs Propulsion Physics Project include: (1) constraining the research tasks to only address *immediate* unknowns, curious effects or critical issues, (2) putting more emphasis on the *reliability* of assertions than their *implications*, and (3) having reviewers judge *credibility* rather than *feasibility*.

The search for breakthrough propulsion methods is an embryonic field encompassing many differing approaches and challenges. The majority of open research paths involve further study of possible reaction masses in space, the physics of inertial frames, the properties of the quantum vacuum, and the coupling of electromagnetism, spacetime and gravity. As much as these are basic areas of investigation for general physics, their investigation in the context of breakthrough spaceflight introduces another perspective from which to contemplate these lingering unknowns. This alternative perspective might just provide an insight that would otherwise be overlooked.

Much of the research is conducted as individual discretionary efforts, scattered across various government, academic, and private organizations. In addition to the research already described, there are many more approaches emerging in the literature and at aerospace conferences. At this stage it is still too early to predict which, if any, of the approaches might lead to a breakthrough. Taken objectively, the desired breakthroughs might also remain impossible to achieve. Reciprocally, however, history has shown that breakthroughs tend to take the pessimists by surprise.

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13. ABSTRACT (Maximum 200 words) The term, propulsion breakthrough, refers to concepts like propellantless space drives and faster-than-light travel, the kind of breakthroughs that would make interstellar exploration practical. Although no such breakthroughs appear imminent, a variety of investigations into these goals have begun. From 1996 to 2002, NASA supported the Breakthrough Propulsion Physics Project to examine physics in the context of breakthrough spaceflight. Three facets of these assessments are now reported: predicting benefits, selecting research, and recent technical progress. Predicting benefits is challenging since the breakthroughs are still only notional concepts, but kinetic energy can serve as a basis for comparison. In terms of kinetic energy, a hypothetical space drive could require many orders of magnitude less energy than a rocket for journeys to our nearest neighboring star. Assessing research options is challenging when the goals are beyond known physics and when the implications of success are profound. To mitigate the challenges, a selection process is described where: research tasks are constrained to only address the immediate unknowns, curious effects or critical issues; reliability of assertions is more important than their implications; and reviewers judge credibility rather than feasibility. The recent findings of a number of tasks, some selected using this process, are discussed. Of the 14 tasks included, 6 reached null conclusions, 4 remain unresolved, and 4 have opportunities for sequels. A dominant theme with the sequels is research about the properties of space, inertial frames, and the quantum vacuum.				
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