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 have begun. During 1996–2002 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 energy can serve as a basis for comparison. A hypothetical space drive would 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: (1) research tasks are constrained to only address the *immediate* unknowns, curious effects, or critical issues; (2) *reliability* of assertions is more important than their *implications*; and (3) 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, six reached null conclusions, four remain unresolved, and four have opportunities for sequels. A dominant theme with the sequels is research about the properties of space, inertial frames, and the quantum vacuum.

KEYWORDS: spacecraft propulsion; physics; project management; relativity; antigravity

INTRODUCTION

Confronted by the physical limits of rocketry and space sails, NASA supported the breakthrough propulsion physics project from 1996 to 2002.[1–3] As its name suggests, the project specifically looked for propulsion *breakthroughs* from *physics* rather than refinements of technology. By breakthroughs, is meant new propulsion methods to 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,[4] wormholes,[5] vacuum fluctuation energy,[6] and emerging physics in general.

This report focuses on the following three challenges of this pursuit: (1) predicting benefits, (2) selecting the best research approaches, and (3) summarizing recent technical progress. To predict benefits, a number of different assessments are

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offered. Since little has been published toward quantifying benefits, a variety of analyses 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 the NASA breakthrough propulsion physics project.[3] Finally, extracts from recent research findings[2] 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 specific methods 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 the Voyager generators.[7] Another recent assessment considered a rocket with hypothetical modifications of inertia and gravity and showed that the benefits would be trivial.[8] Performance estimates 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.

Assessing Hypothetical Inertial Modifications

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.[8] 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 analysis applied its hypothetical inertial change equally to *both* the propellant and the vehicle. There is no benefit in this case. 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.

To illustrate this alternative, the rocket equation can be derived for the hypothetical case where the inertia of the expelled propellant 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. Starting with conservation of momentum, where the momentum of the rocket in one direction must equal the momentum of expelled propellant in the other, a coefficient, δ, has been inserted to represent this inertial modification,

$$-v_e \delta dm = dv(m - dm). \quad (1)$$

The left side of the equation represents the momentum of the expelled propellant and the right side represents the corresponding momentum of the accelerated rocket, and where d_m is the incremental mass of expelled propellant, v_e is the exhaust velocity of propellant (opposite to the motion of the rocket, hence the negative sign), dv is the incremental change in velocity of the rocket, m is the mass of the rocket (including stored propellant), and δ is the degree of inertia modification (a δ value of unity represents no modification, greater than unity is an increase, and less than unity is a decrease). From this starting equation, the following equation for the change in velocity of the rocket, Δv, can be derived,[9]

$$\Delta v = \delta v_e \ln\left(\frac{m_i}{m_f}\right), \tag{2}$$

where Δv is the change in velocity of the rocket, m_i is the initial mass of the rocket before the expulsion of propellant, and m_f is the final mass of the rocket after the expulsion of propellant.

This is identical to the celebrated Tsiolkovski equation of 1903,[10] with the exception of the term, δ, for the inertial modification. This means that a delta of 1.10, representing a 10% increase in the inertia of the expelled propellant, would yield a 10% increase in Δv. Although this appears encouraging, it should be remarked that there are at present no known techniques to affect such a change in propellant inertia and that this result only illustrates the potential advantage of hypothetical inertial modifications. An additional 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 **(2)** are considerably different than the null finding that occurs when one applies the inertial modification to both sides of the equation.

Limits of Rocketry Analyses for Breakthroughs

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 can lead to very different answers. Another misleading use of the rocket equation is the common practice of assigning an infinite specific impulse to describe a propellantless space drive. Although based on a reasonable extrapolation, where higher specific impulse leads to less 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.[11] Although reduced sail area 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 a more basic metric. For spaceflight, whether via rockets or space drives, energy is a better basis for comparison.

Deep Space Propulsion Energy

This next assessment deals with deep space travel. Both a rocket and a hypothetical space drive will be compared in terms of energy. 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."[12] 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 are not repeated here.

For this introductory exercise, the following assumptions are used. To more fully understand the challenges, it would be fruitful to repeat the analysis using different assumptions:

- Both the rocket and the space drive are assumed to be 100% 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 values for acceleration and deceleration.

Since a space drive has been defined as a device that converts potential energy into kinetic energy, the basic equation of kinetic energy is used to represent the space drive energy, where the values of vehicle mass and mission Δv will be the same as with the rocket.

$$\Delta E = \frac{1}{2}m(\Delta v)^2, \tag{3}$$

where m is the mass of the vehicle without the propellant and Δv is the required change in velocity for the mission.

To compare the energy of a rocket to a space drive that does not use propellant, we need an equation for rocket energy where the propellant mass is represented in terms of the mass of the vehicle and the Δv of the mission. Combining the Tsiolkovsky rocket equation with the equation representing the energy imparted to the propellant from the rocket frame of reference, the following approximation for rocket energy can be derived.[9] This is consistent with the previously stated assumptions:

$$\Delta E = \frac{1}{2}(v_e)^2 m(e^{\Delta v/v_e} - 1). \tag{4}$$

Two things are important to note about 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 a *square* 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:

$$\Delta E = \frac{1}{2}(v_e)^2 m(e^{n\Delta v_i / v_e} - 1)_{\text{(rocket maneuvers)}} \quad \textbf{(5a)}$$

$$\Delta E = n\frac{1}{2}m(\Delta v_i)^2_{\text{(space drive maneuvers)}} \quad \textbf{(5b)}$$

In the case of the space drive, additional maneuvers scale linearly, whereas for rockets they scale exponentially. This is another example to highlight why rocket conventions can be misleading when contemplating space drives.

Numerical Example

To put this into perspective, consider a representative mission of sending a 5,000 kg probe over a distance of five 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-year 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 5,000 kg is roughly that of the Voyager probe plus the dry mass of the Centaur upper stage (4,075 kg) that propelled it out of the Earth orbit.[7] The comparison is made for both a flyby mission and a rendezvous mission.

Before proceeding, a limit should be brought to attention. For these introductory exercises, the comparisons are non-relativistic. For rockets, this implies limiting the exhaust velocity to not more than 10% lightspeed. This corresponds to a specific impulse limit of 3×10^6 sec, which is found by setting the exhaust velocity to 10% light speed in the following equation that relates specific impulse to exhaust velocity,[13]

$$v_e = I_{sp}g, \quad \textbf{(6)}$$

where I_{sp} is the specific impulse (seconds), which is a measure of the propellant efficiency of the rocket, specifically the amount of thrust per propellant weight flow rate; and g is the Earth gravitational field (9.8 m/sec^2).

The results of the comparisons are listed in TABLE 1. 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 high value achieved during electric propulsion laboratory tests.[14] The *space drive improvement* column is the ratio of the rocket energy to the space drive energy.

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 two to three 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*. Again, although these results are intriguing, they should only be

TABLE 1. Comparison of deep space mission energy requirements

	Specific Impulse	Mission Type	Joules Required	Space Drive Improvement
Space drive		flyby	2.3×10^{18}	
		rendezvous	4.5×10^{18}	
Rockets				
laboratory limit[14]	17,200 sec	flyby	10^{91}	10^{72}
		rendezvous	10^{168}	10^{149}
non-relativistic upper limit	3,000,000 sec	flyby	3.8×10^{18}	1.7
		rendezvous	1.5×10^{19}	3.2

interpreted as the magnitude of gains sought by breakthrough propulsion research. Other assessments and results are possible.

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 surface and the orbital velocity. For the hypothetical space drive, this energy expenditure can be represented as

$$E_{\text{spacedrive}} = \Delta U + \Delta K, \quad \textbf{(7)}$$

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 surface and at orbit. The change in potential energy, which requires expending work to raise a mass in a gravitational field, is represented by

$$\Delta U = \int_{r_{\text{surface}}}^{r_{\text{orbit}}} G\frac{M_{\text{Earth}}}{r^2} m\,dr, \quad \textbf{(8)}$$

where G is the Newton gravitational constant. M_{Earth} is the mass of the Earth, m is the mass of the spacecraft, r is the distance from the center of the Earth, r_{orbit} is the radius of the orbit as measured from the center of the Earth, and r_{surface} is the radius of the Earth surface. The change in kinetic energy requires solving for the orbital velocity and the velocity of the Earth surface and can be shown to take the form[9]

$$\Delta K = \frac{1}{2}m\left[\left(G\frac{M_{\text{Earth}}}{r_{\text{orbit}}}\right) - \left(\frac{2\pi r_{\text{Earth}}}{24}\right)^2\right]. \quad \textbf{(9)}$$

For the case of placing the shuttle orbiter ($m = 9.76\times10^4$ kg) into a typical low Earth orbit (*altitude*, 400 km; $r_{\text{orbit}} = 6.67\times10^6$ m), the energy required is found to be 3.18×10^{12} Joules.

To assess the required energy for a rocket to accomplish the same mission, the following equation is used:[10]

$$E = \left(\frac{1}{2}FI_{sp}g\right)t, \quad \textbf{(10)}$$

where the new terms are F, the rocket thrusting force, and t, the thrust duration.

The parenthetical term is the rocket *power*, which is mentioned for two reasons: to show this additional form of the rocket equation and to introduce the idea of contemplating *power* in addition to just *energy*. Although power implications are not explored here in detail, they constitute a fertile area 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), the total energy for delivering the Shuttle orbiter via rockets is found to be 1.14×10^{13} J.

Space Shuttle Main Engines:
- quantity, 3
- thrust, $F = 470 \times 10^3$ lbs (2.1×10^6 Newtons) thrust/engine
- specific impulse, $I_{sp} = 453$ sec
- burn duration, $t = 514$ sec

Solid Rocket Boosters:
- quantity, 2
- thrust, $F = 2.9 \times 10^6$ lbs (12.9×10^6 Newtons) thrust/booster
- specific impulse, $I_{sp} = 266$ sec
- burn duration, $t = 126$ sec

Orbital Maneuvering System Engines:
- quantity, 2
- thrust, $F = 6 \times 10^3$ lbs (27×10^3 Newtons) thrust/engine
- specific impulse, $I_{sp} = 313$ sec
- burn duration, $t = 200$ sec

Comparing this rocket energy value to the hypothetical space drive energy, where the efficiency of both systems is assumed to be 100%, indicates that the space drive is 3.58 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.

Levitation Energy

Levitation is an excellent challenge 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 value for its gravitational potential energy defined as follows:

$$U = G\frac{M_{\text{Earth}}}{r}m. \tag{11}$$

Usually this definition is used to compare energy differences between two relatively short differences in height (r) but in our situation we are considering this potential energy in the more absolute sense. This same equation for potential energy can also be derived 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 (r) if it were falling in from infinity with an initial velocity of zero.

Using this equation, it could conceivably require 62 megaJoules to levitate 1 kg near the surface of the Earth. 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.

List of Possible Assessments

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

- Deep space travel (motion from point *A* to *B* without external forces)
  - Rocketry baselines
    - Non-relativistic energy (velocity less than 10% lightspeed)
      1. **constant exhaust velocity and short thrust durations**
      2. constant thrust
      3. constant acceleration
      4. optimized for minimum trip times
    - Relativistic energy (1–4 above repeated with relativistic corrections)
  - Space drive motion using mechanical analogies
    - Non-relativistic energy
      1. **simple kinetic energy differences**
      2. kinetic energy under constant acceleration
      3. kinetic energy under constant power
    - Relativistic energy (1–3 above repeated with relativistic corrections)
  - Space drive motion using geometric spacetime analyses
    - Creating a pseudo geodesic—reshaping spacetime to induce the preferred freefall trajectory
    - Warp drive—moving a section of spacetime[4]
    - Wormhole—moving through a shortcut in spacetime[5]
    - Krasnikov tube—creating a faster-than-light geodesic[15]

- Ascent to orbit (motion in a gravitational field with a stable orbit destination)
  - Rocketry ascent baselines
    - **Space shuttle system data**
    - Generic staged rocket ascent
  - Space drive ascent using mechanical analogies
    - **Simple kinetic and potential energy differences using space shuttle data**
    - Ascent under constant power
- Levitating in a gravitational field
  - Rocketry levitation baseline: levitation duration at the Earth surface
  - Space drive levitation using mechanical analogies
    - **Normal physics definition of work, where zero change in height equates to zero energy expenditure**
    - Comparison to continual down thrust of a reaction mass (rocket and helicopter analogy)
    - Comparison to normal accelerated motion in free space, where distance is traversed
    - **By negating gravitational potential, as if moving a mass to infinity**
    - Comparing to kinetic energy associated with escape velocity
    - 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 defined as free-fall motion in a gravitational field and the stable non-equilibrium condition is defined as levitation at a given height
    - 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
    - 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
    - Analyze using the "impulse" treatment (force$\times$duration, rather than force$\times$distance).
  - 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 project to mitigate the risks and maximize progress.[3] This project employed the operating strategies described below. Other details, such as the specific selection criteria, evaluation equations, review process, and lessons learned, are presented in the cited reference.

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 the way that technology readiness levels are used to measure *technological* progress.[16] 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 three stages, the five 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 2. After a given 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 readiness level. This is consistent with the *incremental* research strategy.

TABLE 2. Applied science readiness levels

General physics—deals with general underlying physics related to the application.	
SRL-1.0	prescience (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 and results reported
Critical issues—deals with an immediate unknown, critical make-or-break issue, or curious effect relevant to the application.	
SRL-2.0	prescience (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 and 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	prescience (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 empirically tested and 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 on 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 the breakthroughs of tomorrow from the more numerous, erroneous 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 prejudging 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 analytic studies—all other factors being equal, such as cost and technical maturity. 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, whereas 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 more than a dozen separate research tasks related to breakthrough propulsion physics were recently published.[2] These findings are rearranged here according to which tasks proved non-viable, which remain unresolved, and which are candidates for additional research. Under each of these headings, the various 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

Mechanical devices are often claimed to produce net external thrust using just the motion of internal components. 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.[17]

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 and the device does not move. 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 gyro 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 false-positive conclusions. 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 U.S. 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.[18]

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.[19]

Podkletnov Gravity Shield

A controversial claim of "gravity shielding" using rotating superconductors and radio-frequency radiation was published based on work done at the Tampere Institute of Finland.[20] 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."[21]

Coronal Blowers

There are many variants of the original patent where high-voltage capacitors create thrust,[22] many of which claim that the thrust is a new effect akin to antigravity. These go by such terms as: Biefeld–Brown effect, lifters, electrostatic antigravity, electrogravity, and asymmetric capacitors. To date, all rigorous experimental tests indicate that the observed thrust is attributable to coronal wind.[23–25] 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]."[23]

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.[26,27] This topic still serves, however, as a tool to explore this intriguing aspect of physics.

Unresolved Approaches

Woodward Transient Inertial Oscillations

Experiments and theories published by James Woodward claim that oscillatory changes to inertia can be induced by electromagnetic means[28] and a patent exists on how this can be used for propulsion.[29] Conservation of momentum is satisfied by evoking interpretations of the Mach principle. Independent verification experiments, using techniques less prone to spurious effects, were unable to reliably confirm or dismiss the claims.[30] 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[31]) to suggest a new space propulsion method.[32–34] 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.[35–38] The space propulsion implications of these theories have been raised,[39] but experimental approaches to test these assertions are only beginning to enter the literature.[40]

Podkletnov Force Beam

On an internet physics archive it is claimed that forces can be imparted to distant objects using high-voltage electrical discharges near superconductors. Between 4×10^{-4} and 23×10^{-4} Joules of mechanical energy are claimed to have been imparted to a 18.5 gram pendulum located 150 meters away and behind brick walls of a separate building.[41] 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.[12] The two largest issues facing this ambition are: first, to find a way for a vehicle to induce *external* net forces on itself; and second, 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 the Mach 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*,[42] and quantum physics has revealed *zero point energy*.[43] The *cosmic background radiation* is low-energy microwave radiation whose composite motion coincides with the mean reference frame of the universe.[44] 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% 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 universe is 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.[45] Again, the propulsion implications of such phenomena have not been explored. Last, the quantum 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 later.

Revisit the Mach Principle. One of the theoretical approaches in dealing with momentum conservation for space drives is to reexamine the Mach principle. This 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.[46] At least one perspective views this property as being related to the gravitational potential of the masses across the universe.[47] A related issue is that a literal interpretation of the Mach principle implies an absolute reference frame, coincident with the mean rest frame for all the matter in the universe.[48] From the space propulsion point of view, this is a convenient perspective. Curiously, a known phenomenon that coincides 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 of gravitational potential.[49,50] 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.[50] 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 are not 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 gravitational mass effect. Although general relativity pertain 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 laboratories.[51] 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.[43] It has been shown analytically,[52] and later experimentally,[53] 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 naïvely expected. Theoretically it might be possible to induce *net* forces relative to this background energy, but the forces are extremely small.[6] More recent experiments have explored the physics of the quantum vacuum using MEMS technology—microelectromechanical structures of machined silicon.[54,55] 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 ultradense matter, where an acceleration field is induced inside the toroid.[56] Although the magnitude of the induced effect is trivial compared to the energy expenditure, this serves as an analytic approach to investigate the implications of such notions. Another curiosity is the anomalous trajectories of the Pioneer 10/11, Galileo, and Ulysses spacecraft.[57] Once these spacecraft were farther than about 20 astronomical units from the Sun, their actual trajectories show an unexpected deceleration on the order of $10^{-10}g$.[58] A report sponsored by the European Space Agency (ESA) includes a proposal for a Sputnik-5 probe to explore this anomaly.[59] This same ESA study further suggests checking for evidence of violations of the equivalence principle in long duration free-fall trajectories (i.e., 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.[4] A wormhole, on the other hand, is a shortcut through spacetime created by extreme spacetime warping.[5,60] Enormous technical hurdles face these concepts. In particular, they require enormous quantities of "negative energy" (equivalent mass of planets or suns),[61] and evoke time-travel paradoxes (closed-time-like curves).[62] 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. Although laboratory experiments are still prohibitive, astronomical searches for related phenomena could be undertaken, such as looking for the characteristic signatures of a wormhole.[63]

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 be calculated yet with certainty, but crude introductory assessments show that the performance gains could span from a factor of two to a factor of 10^{150} 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, whereas 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. Reciprocally, however, history has shown that breakthroughs tend to take the pessimists by surprise.

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