UNIVERSITY
of
GLASGOW

Final Report:

Goals and Metrics for Project Greenglow

BAE Systems & Rolls-Royce Study

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Executive Summary

This report documents a study performed by the University of Glasgow for BAE Systems plc and Rolls-Royce plc between October 2000 and January 2001. The report provides an overview of the main international centres of activity for speculative, advanced propulsion and a summary of the concepts being pursued by these centres. From this background the concept of a 'breakthrough' in propulsion or transportation is defined in precise quantitative terms. This is a key definition which avoids fuzzy and imprecise approaches to advances in physics and their potential application to propulsion and ultimately transportation. A set of quantitative performance metrics are then defined which can be used to evaluate potential advanced propulsion concepts. These metrics are then enhanced through a taxonomy which allows the classification of new concepts in a useful, generic manner. Finally, conclusions are drawn and recommendations are made as to the future direction for Project Greenglow.

The key conclusions of this study are that advanced propulsion based on speculative physics can be a worthwhile venture. However, a rigorous and pragmatic approach must be taken to ensure that unrealistic expectations are not raised and that speculative forms of propulsion with little or no credibility are not pursued. This rigorous and pragmatic approach is aided by a strict definition of a breakthrough in propulsion and transportation, and the use of quantitative performance metrics to evaluate the likely benefit of any future speculative propulsion device. While there are fundamental objections to some forms of speculative propulsion (such as reactionless devices based on rotating mechanisms), credible extrapolations of current physics (such as energy extraction for the zero point energy field) can in principle lead to a breakthrough in propulsion and transportation in the future.

1. Introduction

A breakthrough in advanced propulsion offers the possibility of a revolutionary change in land, sea, air and space transportation. Such a breakthrough could usher in a step-change in transportation technologies by providing reductions in cost and improvements in performance by many orders of magnitude. At present it is not clear where such a breakthrough could occur, or indeed the consequences it would bring. There are a number of areas of speculative physics, such as the zero point energy field and coupling of gravity and electromagnetism, which hold out tentative possibilities. However, enthusiasm for such speculative development and exploitation of new physics must be tempered with some rules-of-thumb:

A breakthrough in physics may not lead to a breakthrough in propulsion. For example, if demonstrated by experiment, the coupling of gravity to electromagnetism may be so weak as to exclude the possibility of useful exploitation for a practical propulsion device which outperforms conventional propulsion systems.

A breakthrough in propulsion may not lead to a breakthrough in transportation, or the breakthrough may be confined to a particular domain. For example, nuclear fission has allowed long-lived, compact and efficient propulsion for military ocean-going vessels, but for practical reasons has had little application to other domains of transportation.

History shows that there are very few revolutions in propulsion physics. Steam engines, the internal combustion engine, gas turbines and rocket engines all rely on extracting energy from an exothermal chemical reaction. The advances represented by these propulsion technologies have been in improving the thermodynamic cycle by which the latent energy in the fuel is transformed into useful work. The electric induction motor however, does represent propulsion based on new physics, but its practical exploitation has been somewhat limited. The same is true of nuclear propulsion, as discussed above.

It is clear then that future directions of research into advanced propulsion must be tempered by the realisation that any new exotic physics must ultimately be engineered into a practical device. Similarly, any new device must be evaluated in a rigorous manner which allows a comparison with other forms of advanced propulsion, whether they exploit new physics or not. Future advances in physics can appear to offer limitless potential, but wide ranging practical exploitation in transportation must be the ultimate goal.

2. International Centres of Activity

2.1 NASA Jet Propulsion Laboratory (Advanced Propulsion Group)

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The Advanced Propulsion Technology Group (APT) provides support for near-term applications of advanced propulsion, such as solar electric propulsion systems. The group also identifies and evaluates, through simulation and experiment, new concepts for advanced propulsion which may lead to significant advances. The mission statement for this activity is to:

- Identify advanced deep space propulsion concepts which offer theoretical performance significantly superior to that of state-of-the-art propulsion systems
- Evaluate the feasibility of these concepts through experiment and analysis
- Provide guidance for NASA's investment strategy in advanced propulsion technology development

These goals are achieved through in-house studies, industrial and university contracts. Unsolicited proposals can be made. An excellent, comprehensive on-line database for advanced propulsion concepts for space applications can be found at **http://sec353.jpl.nasa.gov/apc/**. The database provides a single page of description for each of over 50 advanced propulsion types with space applications. These include chemical propulsion using High Energy Density Materials and more exotic types such as the controlled use of matter-antimatter annihilation.

Recent activities of the group have included an 8000 hour vacuum chamber test of the NSTAR ion engine which was successfully flight tested on the NASA Deep Space -1 mission (DS-1). Much of the effort of the group has been centred on the propulsion technology for the DS-1 mission. In particular, ultra-long life accelerator grids have been developed for ion propulsion using Carbon-Carbon techniques and diamond coatings. This technology development has utilised test facilities with ion engine diagnostics hardware. The focus on ion propulsion is also evident in the background and profile of the 10 group members. Ion propulsion uses an intense electric field to accelerate charged ions to speeds of order 30 kms^{-1} for highly efficient deep space propulsion.

In addition to the development of ion propulsion technology, the group has recently funded activities to develop materials technologies for solar sail propulsion. Solar sails use large reflective films to exploit the momentum transported by sunlight for deep space propulsion without the use of reaction mass. Innovations include ultra-thin films with integrated rip stops and carbon mesh technology which is utilised as a flexible substrate for the sail.

The group also sponsors on-going studies of far-term advanced propulsion concepts, including novel physical phenomena. These more exotic advanced propulsion activities are led by Dr Robert Frisbee (**Robert.H.Frisbee@jpl.nasa.gov**). Concepts which have been investigated include harnessing the zero point field for power generation and some aspects of gravitational physics, mainly through contract work performed by consultant Dr Robert Forward.

The Advanced Propulsion Technology Group also organises and hosts the Annual Advanced Propulsion Research Workshop and Conference at JPL. The conference attracts participants from within NASA, industry, Universities, the US Department of Defence and the US Department of Energy. The conference is an excellent opportunity to obtain information on current concepts for advanced propulsion and to disseminate new concepts to the wider community. Presentations from the 2000 meeting can be found at (**http://apc2000.jpl.nasa.gov/**)

2.2 California Institute for Physics and Astrophysics (CIPA)

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The California Institute for Physics and Astrophysics is a privately funded institute pursuing new revolutionary concepts in physics. The institute is located in Palo Alto, California and hosts a number of research fellows. The institute is seen as belonging to mainstream science, although it works on a range of novel topics which may run counter to accepted thought. The institute director has had a career in astrophysics and was formerly a staff scientist at the Lockheed-Martin Corporation Solar and Astrophysics Laboratory.

The work of CIPA is overseen by a Science Advisory Board, which consists of independent (and possibly sceptical) members of the physics and astrophysics community. The institute is staffed by funding a number of renewable two year postdoctoral fellowships.

The main thrust of CIPA is investigating the possible connection between quantum fluctuations in the vacuum and inertia. These fluctuations arise from quantum mechanics and can be viewed as due to the uncertainty principle - the so-called Zero Point Field (ZPF). The resulting sea of energy manifests itself in the Lamb shift of spectral lines and in the Casimir effect. The uncertainty principle states that it is not possible to have perfect knowledge of both the position and momentum of a particle. For a harmonic oscillator this principle leads to a minimum zero point energy, since bringing the oscillator to rest would violate the uncertainty principle. Summed over all frequencies (up to some limit) the result is the ZPF.

The hypothesis presented by CIPA (and others) is that, rather than being some fundamental property of matter, inertia can be viewed as an interaction between the vacuum energy and the constituent particles of matter. The charged particles from which matter is composed (including quarks) experience an electromagnetic interaction with the ZPF when matter is accelerated. A similar interaction is expected for the other fundamental forces of nature. The ZPF argument is appealing in that Newton's second law of motion can be derived, and is not a fundamental postulate. With this argument inertial mass can be derived from the energy density of the ZPF and a scattering function which determines the interaction of matter with the ZPF.

One objection to this hypothesis is that the neutrino (a neutral particle) has recently been found to have a small, but measurable mass. If the ZPF hypothesis is correct, neutral particles (such as neutrinos) should have no mass. However, the measurement of the neutrino mass is by indirect means and so is in part inconclusive. Another objection is that the energy density represented by the ZPF should induce a massive curvature of space, which evidently does not exist. This argument can however be countered and the formulation of the ZPF constructed such that the ZPF does not interact with itself in this manner.

The attraction of the ZPF induced inertia concept for propulsion is the implication that by using electromagnetic technology to manipulate the interaction of the ZPF and matter, it may be possible to reduce the inertial mass of a body, thus providing greater acceleration for a given motive force. Even a small induced effect could in principle have a significant potential to reduce, for example, fuel costs for long range civil air transport and space launch costs. Since the technology for manipulating electromagnetic fields is well advanced, the ZPF hypothesis appears to represent a possible near-term route to revolutionary propulsion. There is however, a simple objection to the practical exploitation of ZPF induced inertia control for propulsion which will be discussed in section 7.3.

A set of frequently asked questions concerning the ZPF hypothesis can be found at **http://www.calphysics.org/questions.html**.

2.3 The Boeing Company

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The Boeing Company is interested in advanced propulsion technologies for spacecraft and is willing to contemplate that non-rocket technologies are plausible. The company is interested in learning of, and understanding, new research activity in this area. At present, the main corporate interest in such research is to test data using a load cell or other verifiable test methods. Boeing have tested several devices with claims of reactionless propulsion and find that test data shows no reactionless propulsion effects. Oscillations of such devices lead to instantaneous reaction forces, but the time-integrated effect is null. This testing is undertaken without a fee, on the understanding that data is shared between those devising such concepts (such as reactionless propulsion devices) and the Boeing Company.

2.4 Austrian Research Centre Seibersdorf (Space Propulsion Group)

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The Austrian Research Centre Seibersdorf (ARCS) is a network of Government and privately financed research and development institutes. The ARCS is the largest Austrian national research organisation with its main site in Seibersdorf, some 30 km south of Vienna. The ARCS has a space propulsion group which will be managed within the aerospace technology/materials division from 2001. Presently, the main activities of the group are focused on field-emission-electric-propulsion. This is a micro-thruster concept utilising liquid Indium as a propellant to obtain ultra-precise micro-newton thrust levels for a range of future spacecraft control applications.

In addition to this conventional propulsion research, Dr Martin Tajmar is very active in research (theoretical and experimental) concerning possible connections between gravitation and electromagnetism for advanced propulsion concepts. For example, experimental investigation of the so-called Biefeld-Brown effect was undertaken, showing that the effect is likely to be due to a classical electric wind phenomena. Claims had been made that the phenomena was associated with a coupling between electromagnetic phenomena and gravity. It had been hoped that the effect could be exploited to provide low thrust spacecraft propulsion. However, it has been demonstrated that with the experimental bounds now set, even if a small effect does exist, the phenomenon is significantly less efficient than conventional electric propulsion thrusters. Other areas of related research which may provide more fruitful results are currently being planned.

Previous to his appointment to ARCS, Dr Tajmar was employed at the European Space Agency (ESA) centre in Noordwijk, the Netherlands, where he actively worked to generate interest in speculative advanced propulsion within the agency.

2.5 NASA George C. Marshall Space Flight Center (MSFC)

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Marshall is NASA's lead centre for developing future reusable space transportation systems in order to improve the safety, reliability and cost of space access. MSFC oversees NASA's technology development and demonstration programs, and develops the propulsion systems needed for NASA's science missions and the International Space Station. Demonstrating advanced technologies in the X-33, X-34, and X-37 experimental launchers will lead to improvements in future launch vehicles, and by looking 25-40 years into the future, MSFC is attempting to develop breakthroughs in propulsion.

One MSFC technology for future launch vehicles applies a magnetic levitation tract to accelerate a vehicle at speeds up to 600 mph prior to leaving the ground. Another technology under development is a rocket engine that breathes oxygen taken from the atmosphere during the climb to orbit. Propulsion systems that boost spacecraft with laser beams, and propellant-free electrodynamic tethers, may also become operational within the next 50 years.

MSFC is conducting fundamental experiments into exotic, high-energy, propulsion required to travel to the outer planets and other star systems. Solar sails propelled through space by photons may be used for an interstellar precursor mission as soon as 2010. Antimatter, fusion and fission propulsion concepts may also enable deep space missions in the 21st century. NASA Marshall is also involved in basic leading edge research on gravity manipulation, space and time warping and theories that may enable superluminal travel.

The key centre activity is Marshall's Advanced Space Transportation Program (ASTP) which looks beyond the reusable launch vehicle to develop technologies for a fully integrated space transportation system. ASTP is supporting long-term technology research in advanced chemical and non-chemical propulsion systems. Under this program, propulsion research is being undertaken in the areas of magnetic levitation, pulse detonation, beamed-power, magnetohydrodynamics, fusion, anti-matter annihilation, and breakthrough physics, including gravity modification.
(http://astp.msfc.nasa.gov/astpabout.html)

- Tethers

A space tether is a long cable used to couple spacecraft, or other masses, together. Tethers are usually made from thin strands of high-strength fibre such as Spectra or Kevlar. Tether coupling allows the transfer of energy and momentum from one object to another, and, as a result, can be used as a form of space propulsion. Tethers made from conducting materials can also be used to interact with planetary electric and magnetic fields, allowing propellantless propulsion of spacecraft in low Earth orbit. Tethers are now being seriously considered for use with the Space Shuttle and the Space Station for raising or lowering payloads. Rotating tethers have also been considered for transporting payloads to and from the Earth, Moon, Mars, and other bodies in the solar system. Inspired partly by science fiction, Marshall is currently exploring the idea of towering space elevators as a mass-transit system for the next century. Such elevators would be anchored by means of an enormous space tether.
(http://astp.msfc.nasa.gov/orbitaltransfer.html)

- Interstellar Propulsion Technologies

NASA is planning an interstellar precursor mission, the Interstellar Probe (IP), to explore the boundary between our solar system and nearby interstellar space. Planned for launch by 2010, the Interstellar Probe will ultimately travel at least 250 astronomical units (AU) from the Earth. Missions to 500 - 1000 AU are also being considered. The ASTP team is researching several possible concepts for solving the interstellar propulsion problem. For the near-term IP mission, both solar sails and high-power electric propulsion are relevant. For more ambitious missions to another star, then matter-antimatter annihilation, fusion, and beamed energy are of interest.
(http://astp.msfc.nasa.gov/interstelprop.html)

- Gasdynamic Mirror Fusion Propulsion Experiment

The Gas-Dynamic Mirror (GDM) is an example of a magnetic mirror-based fusion propulsion system. Its simple design consists of a long slender solenoid surrounding a vacuum chamber containing plasma. The bulk of the fusion plasma is confined by magnetic fields generated by a series of toroidal-shaped magnets in the central section of the device. Stronger end-located "mirror magnets" prevent the plasma from escaping too quickly out of the ends. It has been shown that the geometry of the GDM is theoretically capable of preventing the major causes of instability which plague classical fusion mirror machines. The purpose of the Gasdynamic Mirror Fusion Propulsion Experiment is to confirm the concept feasibility and to demonstrate many of the operational characteristics of a full-sized engine. This will be accomplished with a small-scale experiment to determine if a plasma can be confined within the desired physical configuration and still remain stable. If experiments continue to underpin the concept then the

device will be lengthened and the plasma temperatures raised to the threshold where fusion reactions should begin to take place.
(**http://astp.msfc.nasa.gov/gasdynamic.html**)

2.6 NASA Breakthrough Propulsion Physics Project

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In 1996, NASA established the Breakthrough Propulsion Physics Project to seek ultimate breakthroughs in space transportation, as follows:

propulsion that requires no propellant mass
propulsion that attains the maximum possible transit speeds
breakthrough methods of energy production to power such devices

Topics include experiments and theories on the coupling of gravity and electromagnetism, the quantum vacuum, hyperfast travel, and superluminal quantum effects. Because the propulsion goals are presumably far from fruition, the main emphasis is to identify affordable, near-term, and credible research that could make measurable progress toward these propulsion goals. The Breakthrough Propulsion Physics Project is managed by Marc G. Millis of the Glenn Research Center, and is sponsored jointly by the Advanced Space Transportation Program, managed by NASA MSFC, and the Advanced Concepts Program of the NASA Office of Space Science, Washington, DC. Concepts that are being considered are:

- Superluminal travel
- Tachyons

Tachyons are hypothetical faster-than-light particles and are based on projected characteristics of matter which moves faster than light. Imaginary mass is used as a way to view the momentum of tachyons, but to date none have been observed, and most physicists have now abandoned the idea that tachyons might be real. More information is at:
http://math.ucr.edu/home/baez/physics/tachyons.html

- Wormholes

Although special relativity prevents objects moving faster than light within spacetime it is known that spacetime itself can theoretically be warped and distorted, but this takes an enormous amount of matter, or energy, to create such distortions. In the case of the wormhole a shortcut is made by warping space to connect two points that were formerly separate.

- Spacetime warping or Alcubierre's Warp Drive

Although objects cannot move faster than light within spacetime, according to special relativity, a moving section of spacetime may be created by expanding it behind the spacecraft and then by contracting it in front. The idea of expanding spacetime is not new, and the "inflationary universe" view suggests that local points in spacetime effectively expanded faster than the speed of light during the early moments of the Big Bang.

- Quantum paradoxes
- Time travel
- Negative mass propulsion

It is theoretically possible to create a continuously propulsive effect by the juxtaposition of negative and positive mass. Such a proposal does not violate conservation of momentum or energy. A crucial assumption behind the success of this is that negative mass has negative inertia. Their combined interactions result in a sustained acceleration of both masses in the same direction. This concept dates back to 1957 when an analysis of the properties of hypothetical negative mass was undertaken by Bondi, and has been revisited in the context of propulsion by Winterberg and Forward in the 1980s. It is still not known whether negative mass exists, or if it is even theoretically allowable in all contexts, but methods have been suggested for identifying negative mass in the context of the search for wormholes.

- General Relativity

In general relativity the coupling between gravity and electromagnetism is described in terms of how mass warps spacetime, against which electromagnetism is measured. In simple terms this means that gravity appears to bend light, red-shift light, and to slow time. These observations, and the general relativistic formalism that describes them, are experimentally supported. Although gravity's effects on electromagnetism and spacetime have been observed, the reverse possibility has not been verified either way, and would require non-standard extensions to general relativity.

- Zero point energy

The most compelling evidence for vacuum energy is the Casimir effect. When two metal plates are close enough the vacuum energy will push them together. The cavity between the plates will exclude long wavelength modes of the zero point field resulting in a lower energy and pressure within the cavity. This effect has been experimentally demonstrated and quantified.

- Teleportation

2.7 US Air Force Research Laboratory

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Web: http://www.afrl.af.mil/

Propulsion Directorate

The Propulsion Directorate develops propulsion and related technologies for the Air Force including: turbine and rocket engines, advanced propulsion systems, fuels, propellants, lubricants, and aircraft power. Its headquarters are at the Wright Research Site, Wright-Patterson Air Force Base, Ohio, and are supplemented by additional personnel and research facilities located at Edwards Research Site, Edwards Air Force Base, California. The Directorate is structured into five divisions based upon logical groupings of technology areas. The divisions are:

- Integration and Operations
- Power
- Rocket Propulsion
- Propulsion Sciences and Advanced Concepts
- Turbine Engines

(http://www.pr.afrl.af.mil/)

Power Systems Branch

This branch plans, formulates, manages and executes research, and exploratory and advanced development programs to provide advanced power systems for aircraft in missile, terrestrial, and special applications. It translates projected Air Force system capability requirements into power system technology development programs. The program covers

- Cryogenic Power Systems
- High Power Research
- Collisional Plasma and Discharge Physics
- Superconducting Coated Conductors

Rocket Propulsion Division

The Rocket Propulsion Division formulates, manages, directs, and performs basic and applied research, as well as exploratory and advanced development programs, to advance the technology of space launch, orbital transfer, tactical, ballistic missile, ballistic missile defence, and spacecraft propulsion systems. The Division plans, implements, and directs, in-house and contractual research and development programs in chemical rockets, solar, electric, and other advanced propulsion systems for transition to space system users.

Spacecraft Branch - Orbital Manoeuvring Propulsion
The Spacecraft Branch creates technologies for spacecraft propulsion systems. The branch creates and develops technologies which were considered “exotic” until relatively recently. Electric propulsion systems are here, and solar propulsion will come soon. The branch is also responsible for traditional monopropellant and bipropellant system technologies.

Propulsion Sciences & Advanced Concepts Division
The Propulsion Sciences and Advanced Concepts Division plans, formulates, and conducts research, exploratory and advanced development programs in advanced concepts and scientific areas related to advanced air breathing, rocket and space propulsion. The division designs and analyses advanced propulsion concepts and promotes the application of advanced propulsion science and technology to military and commercial systems. Current research efforts involve:

- Polynitrogen Chemistry

Researchers at the Air Force Research Laboratory, Edwards Research Site, have achieved a breakthrough in polyatomic nitrogen chemistry that may allow future advances in high energy rocket propellants or explosives.

- Rocket-Based Combined Cycle Propulsion

This is a technology under development which combines turbojet and rocket propulsion. The advantages are quick response time and operational flexibility, combined with lower launch costs. This technology is a strong candidate for military space plane propulsion.

- Pulse Detonation Propulsion

This technology has the potential tō reduce hardware weight, complexity, and costs by significantly reducing the amount of turbomachinery. Fuel and oxidisers are mixed and ignited in a tube, and then a detonation pulse is propagated rearward, exiting and producing thrust. Pulses occur many times per second, and such a system is infinitely throttleable in rocket mode. Currently the lab is working with several contractors and NASA to mature this technology. Pulse detonation propulsion is applicable both to space and air propulsion.

- Laser Lightcraft

The futuristic concept of a small laser-propelled spacecraft has completed its first research flights. To this end the laser-propelled vehicle flies on a beam of laser light by harnessing the energy of a laser beam and converting it into propulsive thrust. The lightcraft receives 350 kJ pulses from a 10kW CO_2 laser at a rate of 28 times per second upon the concentrating mirror that forms its rear section. The function of this parabolic mirror is to focus the pulsed laser energy into a ring-shaped "absorption/propulsion" chamber. The laser beam is concentrated to extremely high intensities, sufficient to momentarily combust the inlet air into a highly luminous plasma (at 10,000-30,000 K), with instantaneous pressures of tens of atmospheres to provide thrust. For in-space operations the lightcraft will carry its own working fluid.

- High Energy Density Matter

The lab is identifying, producing, characterising, and stabilising atomic and molecular level chemical compounds that have the potential to be developed into revolutionary high energy propellant ingredients. These chemical species have significantly higher performance limits than conventional, or near-term, advanced propellants.

Propellants Branch
The Propellants Branch plans, formulates, and directs fundamental research, exploratory, and advanced development of new propellants and propellant technology for application to military space and missile systems. It predicts and synthesises high energy density matter (HEDM), new energetic propellant ingredients, and advanced formulations. The branch develops methods for scale-up and testing of ingredients and formulations. Investigations are being carried out on advanced propulsion concepts such as dense plasma focus, laser propulsion, fusion propulsion and anti matter propulsion. Two such projects include polynitrogen chemistry and lightcraft.

2.8 NASA Institute for Advanced Concepts

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The Institute provides an independent, open forum for the external analysis and definition of space and aeronautics advanced concepts. It also provides a complement to the advanced concepts activities conducted within the NASA enterprise. The methods that the Institute employs are to focus on revolutionary concepts for systems and architectures, to be functionally independent of NASA, to be bounded only by the horizons of human imagination, and to expand its vision of future possibilities. The goal of these activities is to develop advanced concepts which will result in changes to future aerospace policies and plans. The NIAC is a virtual institute and uses electronic communications over the internet for submission of proposals and other related communications. In terms of propulsion activities NIAC has funded studies in the following areas:

- Hypersonic Aeroplane Space Tether Orbital Launch System
- Ultralight Solar Sails for Interstellar Travel
- Planetary Exploration using Biomimetics
- Space Elevator
- Hypersonic Aeroplane Space Tether Orbital Launch study
- Plasma Pulsed Power Generator
- An Advanced Counter-Rotating Disk Wing Aircraft Concept
- Enabling Exploration of Deep Space High Density Storage of Antimatter
- Tether Transport System for LEO-MEO-GEO Lunar Traffic
- Moon and Mars Orbiting Spinning Tether Transport
- Antiproton Driven, magnetically Insulated, Inertial Fusion
- The Mesicopter: A Meso-scale Flight Vehicle
- Primary Propulsion for Piloted Deep Space Exploration
- Advanced Solar and Laser Pushed Lightsail Concept
- Exploration of Jovian Atmosphere using Nuclear Ramjet Flier
- A Realistic Interstellar Explorer
- Cyclical Visits to Mars via Astronaut Hotels
- Advanced System Concept for Total In-Situ Resource Utilisation Based Propulsion and Power Systems for Unmanned and Manned Mars Exploration
- Low Cost Space Transportation using Electron Spiral Toroid Propulsion
- Rapid Manned Mars Mission with a Propagating Magnetic Wave Plasma Accelerator
- Electric Toroid Rotor Technology Development
- Environmentally-Neutral Aircraft Propulsion using Low Temperature Plasmas
- Mini-Magnetosphere Plasma Propulsion
- The Magnetic Sail

2.9 US Naval Research Laboratory

NRL DC Address:
Naval Research Laboratory
4555 Overlook Ave. S.W.
Washington, DC 20375, USA
Web: http://www.nrl.navy.mil/

The Naval Research Laboratory (NRL) is the US Navy's corporate laboratory. NRL conducts a broadly-based multidisciplinary program of scientific research and advanced technology development directed toward maritime applications of new and improved materials, equipment, systems, and ocean, atmospheric, space sciences, and related technologies. NRL is the Navy's lead laboratory in space systems research, fire research, tactical electronic warfare, microelectronic devices, and artificial intelligence. NRL has also evaluated new issues, such as the effects of intense radiation and various forms of shock and vibration on aircraft, ships, and satellites. The expanded laboratory is focusing its research efforts on new Navy strategic interests and needs in the post-cold war world. Although not abandoning its interests in blue water operations and research the Navy is also focusing on defending American interests in the world's littoral regions. The Naval Center for Space Technology's present major programs are:

- Tether Physics & Survivability Experiment
- Advanced Tether Experiment
- The Electric Propulsion Demonstration Module
- High Temperature Superconductivity Space Experiment
- Microelectronics and Photonics Test Bed

2.10 Defence Advanced Research Projects Agency

Web: http://www.darpa.mil/

The Defence Advanced Research Projects Agency (DARPA) is the central research and development organisation for the US Department of Defence (DoD). It manages and directs selected basic and applied research and development projects for DoD, and pursues research and technology where risk and payoff are both very high, and where success may provide dramatic advances for traditional military roles, missions, and dual-use applications.

DARPA Technical Offices:

- The Advanced Technology Office explores high payoff programs in the areas of maritime, communications, and early entry/special forces operations.
- The Defence Science Office (DSO) mission is to pursue the most promising discoveries and innovations in science and engineering to create paradigm shifts in defence capabilities. DSO emphasises programs in medical approaches to biological warfare defence, biology, materials, and advanced mathematics.
- The Information Systems Office mission focuses on national security and military operations through the power of information systems technology to know, to know more, to know faster, and be able to act flexibly.
- The Information Technology Office focuses on inventing the networking, computing, and software technologies vital to ensuring DoD military superiority.
- The Microsystems Technology Office mission focuses on the heterogeneous microchip-scale integration of electronics, photonics, and microelectromechanical systems (MEMS).
- The Tactical Technology Office engages in high-risk, high-payoff advanced military research based on the "system/subsystem" approach to the development of aeronautic, space, and land systems as well as embedded processors and control systems.

2.11 National Space Development Agency of Japan (NASDA)

Web: http://www.nasda.go.jp/index_e.html

The National Space Development Agency of Japan (NASDA) was established on 1 October 1969 to act as a nucleus for the development of space and promote its peaceful use. NASDA develops satellites (including space experiments and the space station), launch vehicles, and the launching and tracking of spacecraft. Japan's space activities are: satellite observation and earth science; space science; lunar exploration; communication, broadcasting, navigation; space experiments; manned space activities; manned space technology; space medical science; basic satellite technology; and space infrastructure. NASDA will initiate a study for a reusable transportation vehicle, including an unmanned winged space plane. If necessary its development will also be initiated, taking into consideration both international and demand trends. Research into a fully reusable aerospace plane (space plane), with the capacity for horizontal take-off and landing, will be carried out in co-operation with related research institutes. A study of a manned space plane will also start up as part of the preparation for manned space activities. Another study will be initiated for an orbit transfer vehicle, capable of moving from one orbit to another, to prepare for lunar exploration.

2.12 Chinese Space Propulsion Research

There are a variety of sites that deal with Chinese activities in space, however hard specific facts are somewhat lacking and much of the reporting is therefore somewhat speculative. The principal web-sites are reviewed below.

- The Chinese Manned Space Program: Behind Closed Doors – this site purports to discuss the general status of modern Chinese space activities. There are no detailed accounts of propulsion research and nothing remotely touching on any sort of breakthrough propulsion research programme. One issue that does emerge is the fact that the Electromechanical Equipment Research Institute of Shanghai has produced designs for a new rocket engine based on liquid oxygen and kerosene fuels rather than the hypergolic nitrogen tetroxide and unsymmetrical dimethyl hydrazine which is traditionally used by China for its intercontinental rocket fleet. Whilst this does not constitute breakthrough propulsion research it does suggest that there may be other propulsion initiatives underway.
  (http://www.friends-partners.org/~mwade/articles/chidoors.htm)
- The China National Space Administration (CNSA) was established in 1993 to promote space activity on the basis of profit rather than public funding. The national medium term and long term programme for scientific and technological development, spanning 2000-2020, requires China to develop space power and, specifically, propulsion technology. No details are readily available but it is relevant that there is an explicit reference to propulsion research as a goal.
  (http://www.fas.org/spp/guide/china/agency/cnsa.htm)

2.13 Russian Space Propulsion Research

The activities of the following research centres have been analysed with regard to breakthrough propulsion research and no obvious fits were found. However it is possible that relevant activities may arise in the near future and that some of the following may be candidate centres for this. Possible contenders are shown in bold:

- Co-ordination Scientific Information Center, Russian Federation Ministry of Defence – this is a site dedicated primarily to global navigation satellite system research. The site also serves as an advertisement and contact point for international collaborative research programmes.
  http://www.rssi.ru/SFCSIC/SFCSIC_main.html
- **Institute for Physics and Power Engineering**, Russian Academy of Sciences, Kaluga Region, Obninsk – Propulsion research is undertaken here but it appears to be limited to nuclear power plants for space craft, specifically lithium cooled fast reactor-converters of up to 1MW power output aimed at installation on Mars vehicles.
  http://www.rssi.ru/IPPE/
- Institute of Terrestrial Magnetism, Ionosphere, and Radiowave Propagation, Russian Academy of Sciences – fundamental research into plasma kinetics has matured here although there are currently no explicit links to propulsion technologies.
  http://www.izmiran.rssi.ru/
- Budker Institute of Nuclear Physics, Novosibirsk, Siberia – research is being conducted on synchrotrons here, but with no direct connection to propulsion.
  http://www.inp.nsk.su/
- **Space Research Institute**, Russian Academy of Sciences, Moscow.
  http://www.iki.rssi.ru/
  - IKI Satellite Situation Centre – no breakthrough propulsion research at this site except for three academicians who are researching into the "creation of space transportation systems on the basis of large length rope utilisation", I. M. Sidorov, V. A. Frolov, and G. V. Velosova – to be found at
    http://www.iki.rssi.ru/seminar/e_199911_sid.htm
  - Space Plasma Physics – no obvious propulsion activities.
- **Moscow Institute of Physics and Technology** – This centre engages in a very wide range of space related research including superconductive materials, nonconventional energetics, alternative energy carriers, and controlled thermonuclear fusion. No details

are given of individual projects but it is possible that some, or all, of those listed are concerned with advanced/breakthrough propulsion research.
http://www.mipt.ru/index_en.html

2.14 Space Activities in South America

Web:
http://www.conae.gov.ar/caratula.html
http://www.iafbrasil2000.com.br/htms/brazilian/index.html
http://www.inpe.br/english/index.htm

South America has two functioning space agencies, in Argentina and Brazil, of which Brazil is the larger. Argentina's reasons for going into space are: development of technology, extension of the country's geography, development of the economy, and observation of natural disasters. The primary motivation is to obtain information on Argentina's development and environment with the aid of satellite imaging. There is funded space co-operation between Argentina and Brazil, however there have been difficulties in trying to achieve a common space policy between the countries.

In 1961 Brazil founded the Brazilian Space Agency. The aim was to put Brazil into the position of being able to design and build satellites and a rocket launch system. Furthermore, the aim was also to build and operate a launch site. These aims have been achieved and it is generally felt that it was a wise decision to pursue them. In 1994 congress approved a civilian space agency to establish civilian and defence objectives for space activities, with the aim of achieving dual use technology. Due to the size of Brazil and the fact that the country is not fully mapped to a scale of 1:25000, one of the main current objectives is, therefore, to build and fly a satellite to achieve this fine mapping. Brazil launched two small satellites which both failed, and so a third small satellite launch is planned. Brazil has a bilateral co-operation with Argentina, and other South American countries considering space activities may also join this bilateral co-operation. This may evolve into the formation of a South American space agency.

2.15 Fuel Cell Technologies

Fuel cells are set to provide commercially viable low volume, high power, energy sources for a very wide variety of applications, not least space vehicle services and electrical propulsion systems. Whilst fuel cells do not belong to the realm of breakthrough propulsion technologies they may yet provide an improved enabling technology for conventional electrical propulsion requirements. Some of the leading efforts are emerging from commercial operations. Three principal companies are briefly profiled below.

Ballard Power Systems Inc.
Web: http://www.ballard.com/
Ballard is a world leader in the provision of fuel cell technology with almost all of its products targeted at the automotive market. Ballard has successfully pioneered 'Proton Exchange Membrane' (PEM) technology which allows the direct use of methanol, thereby eliminating the reformer stage in which hydrogen would otherwise be extracted by means of an additional stage in the process. A prototype fuel cell has been demonstrated using PEM technology in collaboration with DaimlerChrysler and has been implemented on a small one-person demonstration vehicle. A major new technology being marketed by Ballard Power Systems Inc is the Mark 900 fuel cell stack which uses low cost materials and is to be manufactured in the volumes required for mass produced automobiles. Fuel cells based on the Mark 900 concept are to be used for transportation, stationary, and portable applications.

International Fuel Cells (IFC)
Web: http://www.internationalfuelcells.com/spacedefense/overview.shtml
In the space sector International Fuel Cells has a significant stake underpinned by their production of fuel cells specifically aimed at that typically harsh environment. IFC have designed and manufactured fuel cell power plants for the Shuttle and this was preceded by their pioneering work for the Apollo moon missions. The power density of IFC fuel cells is of an order of five times that of

batteries. In addition to this IFC provides fuel cell technologies for sub-sea power plant installations at depths of up to 5000 feet.

IMPCO
Web: http://www.impco.ws/
This company has set up a research programme intended to focus on advancing their hydrogen fuel cell technology, particularly within the automotive market. Their intention is to produce commercially viable technology which will extend vehicle range, provide advantageous weight and cost reductions, and lead to superior safety features allowing for more rapid commercialisation. Their storage tank technology is potentially of significant space application given a stated development target of 700 bar pressure capability within an ultra-lightweight 'TriShield' hydrogen storage system. The ultimate aim is to exceed gasoline storage/range capabilities for fuel cell fuels in automobiles. The development of this sort of storage capability could have obvious relevance to space applications, despite it not being a direct form of breakthrough propulsion technology.

3. Goals and Challenges for Project Greenglow

3.1 Definitions

In order to provide clear definitions, a distinction will firstly be made between propulsion and transportation. For the purposes of this study, propulsion will be defined as the device which induces a motive force which can then be exploited to translate a useful payload. However, transportation is defined as the end-to-end system which delivers a useful payload to a desired destination. This distinction is made since advances in propulsion may have an ultimately limited influence on transportation. For example, the major advantages which the gas turbine brought to civil and military aviation have not been exploited for automotive transportation, which still relies largely on the internal combustion engine. Similarly, while gas turbines provided significant advances over propeller propulsion for aviation, future advances in air transport are now being limited by air traffic control management systems.

This distinction between propulsion and transportation will clearly be important for any future advanced propulsion systems. A major breakthrough is likely to see optimum utilisation in particular transportation regimes and its utility may be limited by operational constraints. An exotic physical phenomenon which can be exploited for propulsion, but produces a high flux of energetic radiation for example, is unlikely to be used in an urban environment. A generic, all encompassing breakthrough propulsion device is also somewhat unlikely.

In order to retain generality, the definition of goals for future research and development can be made in an abstract manner with application to propulsion and transportation on a range of scales. A clear and coherent scheme for such a definition is detailed below. To define a set of generic goals, three levels of achievement are defined in the context of either propulsion or transportation. An Advance, a Leap and a Breakthrough will now be defined as

Advance – x 10 improvement in any one of three key parameters

Leap – x 100 improvement in any one of three key parameters, or x 10 in two key parameters

Breakthrough – x 1000 improvement in any one of three key parameters, or x 10 in three key parameters, or any equivalent combination

These definitions are shown schematically in Fig. 3.1 for some arbitrary parameters P_1, P_2 and P_3. Although somewhat arbitrary, these definitions provide a coherent tool for representing various levels of achievement in either propulsion or transportation. Clearly, an order of magnitude improvement can in principle be achieved through the evolution of current technology. However, an improvement of three orders of magnitude will require some revolutionary breakthrough.

Using this scheme, the goal for Project Greenglow can clearly be stated as a Breakthrough in propulsion and its ultimate exploitation in transportation.

The objectives of the project are then clear and, importantly, are measurable. A revolutionary new concept in physics will only be classified as a breakthrough for Project Greenglow if it can be exploited to produce a breakthrough in propulsion and its ultimate exploitation in transportation, using the key parameters defined in section 3.2.

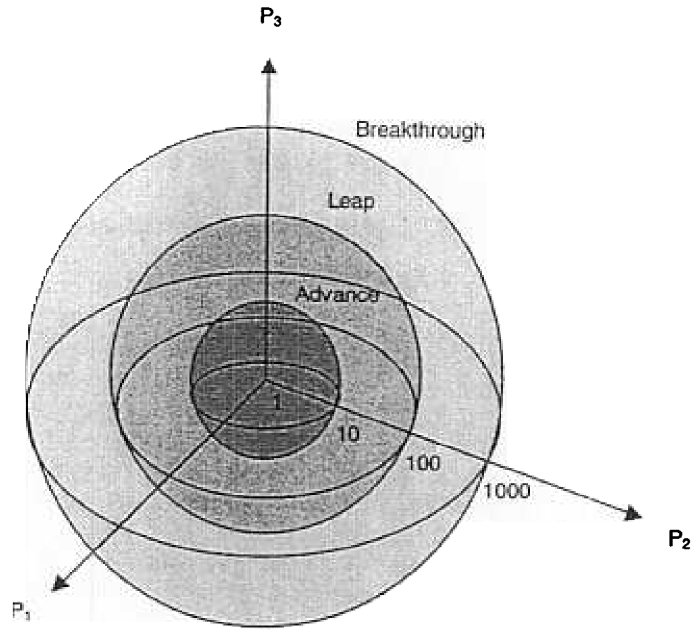


Figure 3.1. Advance, Leap and Breakthrough defined from thee parameters [P_1,P_2,P_3]

3.2 Breakthrough in Transportation

Firstly, three key parameters are defined to characterise the performance of a transportation system from a user centred view. The user centred view is important as it is the improvement in overall utility that advanced propulsion offers, rather than the detail of the propulsion device itself, which is ultimately of importance to transportation. The key performance parameters selected are defined as:

[P_1] Mass – payload delivered by the transportation system

[P_2] Speed – ratio of total distance traversed to total transit duration

[P_3] Cost Reduction– total life-cycle cost reduction

These parameters represent the key measures of utility of a transportation system from a user centred point of view. Clearly, breakthrough improvements in these parameters will be underpinned by a breakthrough in propulsion, but the exploitation of the breakthrough propulsion device must be engineered to form a transportation system. As noted in section 3.1, major advances in propulsion are usually limited to particular domains of transportation. For example, a breakthrough in aircraft speed will have only a modest impact on short haul flights, since the mean end-to-end speed is limited by transportation to and from hub airports. A near instantaneous flight from Glasgow airport to Heathrow airport would only reduce the trip time from central Glasgow to central London by approximately one third.

It should also be noted that these three key parameters are derived from a broader set of measures. For example, the range of the transportation system and the total trip time (point-to-point) results in a mean speed, as discussed above. In addition, even this set of three parameters could in principle be reduced further by defining, for example, cost per unit payload mass (specific cost) or mass per unit time (flux), although the three absolute parameters are adopted here.

In order to provide some context for the definitions of Advance, Leap and Breakthrough, three scales of transportation are defined corresponding to current experience and use. These levels are in order of an ascending distance scale and typical order of magnitudes for mass, speed and cost are provided as:

- **Personal Transportation [100 km]** 100 kg, 100 km/hr, £10
- **Global Transportation [10,000 km]** 100,000 kg, 1000 km/hr, £100,000
- **Space Transportation [1,000,000 km]** 10,000 kg, 100,000 km/hr, £100,000,000

Particular examples of these levels of transportation are found from road transport, air cargo services and spacecraft launch vehicles as:

Personal: Road Transport [100 km] 100 kg, 100 km/hr, £10

Global: 747 Cargo Transport [7000 km] 113,000 kg, 1000 km/hr, £50,000

Space: Titan IV Launch [500,000 km] 10,000 kg, 40,000 km/hr, £350,000,000

Again to provide context, using the particular examples above, a **breakthrough** in transportation technology would achieve the following startling advances:

Personal [100 km] 100 kg, **100,000 km/hr**, £10 (near instant point-point personal transportation)

Global [7000 km] 113,000,000 kg, 1000 km/hr, £50,000 (rapid, global delivery of cargo ship sized payloads)

Space [500,000 km] 10,000 kg, 40,000 km/hr, **£350,000** (lunar access at parcel courier cost/kg level)

Clearly, any of these examples of an improvement in performance of three orders of magnitude would be classified as a **breakthrough** in transportation, rather than a set of incremental advances from current technologies. The same definitions will now be applied separately to propulsion systems.

3.3 Breakthrough in Propulsion

Now that the key parameters have been defined for transportation, a similar process will be followed for propulsion. Whereas the key parameters for transportation were user centred measures of utility, the key parameters for propulsion are engineering metrics which characterise the propulsion system. These metrics are discussed in detail in section 4. The key performance metrics selected are:

- **[P_1] Effective specific Impulse** – ratio of total impulse delivered to propulsion system weight
- **[P_2] Specific Power** – ratio of total power delivered to propulsion system weight
- **[P_3] Thrust-to-Weight Ratio** – ratio of total thrust delivered to propulsion system weight

These parameters are related by the basic mechanics of propulsion, again to be discussed in section 4, and must be central to future advanced propulsion concepts to ensure that any novel or exotic physical phenomena can be exploited to fabricate a practical and revolutionary propulsion device. There is much speculative physics which, if substantiated, could lead to startling developments in physical science, but may be of somewhat limited benefit for exploitation as a propulsion device. A key example is the tenuous link between electromagnetism and gravity. Although interesting, the coupling between these two forces is likely to be extremely weak and so will be difficult to engineer a propulsion device based on any new physics.

It should be remembered that nuclear energy represents a true breakthrough in propulsion, but has not been widely utilised for transportation due to public concern. The specific energy of fissile fuel is 8×10^{13} Jkg^{-1}, over six orders of magnitude greater than the most energetic chemical fuels. The energy contained in a volume equivalent to a soft drinks can is equal to the energy stored in 50 space shuttle external tanks. While pursuing advanced propulsion based on speculative physics, it is worth considering the potential of current, well understood physical processes.

The key performance metrics for propulsion are put into context with the following examples based on road, air and rocket propulsion. An internal combustion engine, air breathing jet engine and a rocket engine have the following general performance metrics:

Personal Propulsion (Internal Combustion Engine)

- effective specific impulse = 16,000 s; specific power = 50 kW/kg; thrust-to-weight ratio = 0.3

Global Propulsion (Air Breathing Jet Engine)

- effective specific impulse = 55,000 s; specific power = 15 kW/kg; thrust-to-weight ratio = 20

Space Propulsion (Rocket Engine)

- effective specific impulse = 300 s; specific power = 60 kW/kg; thrust-to-weight ratio = 70

Using the definitions above, a breakthrough in propulsion technology would achieve the following metrics:

Personal Propulsion (Internal Combustion Engine)

- effective specific impulse = **16,000,000 s**; specific power = 50 kW/kg; thrust-to-weight ratio = 0.3 (requiring a few tens of grams of fuel for the same range as current IC engines)

Global Propulsion (Air Breathing Jet Engine)

- effective specific impulse = 55,000 s; specific power = **15,000 kW/kg**; thrust-to-weight ratio = 20 (able to produce a similar power output to current medium-sized power stations)

Space Propulsion (Rocket Engine)

- effective specific impulse = 300 s; specific power = 60 kW/kg; thrust-to-weight ratio = **70,000** (producing accelerations capable of reaching orbital speeds in a few seconds)

Again, any of these examples of performance improvement by three orders of magnitude would intuitively suggest that a revolutionary breakthrough had been in achieved in propulsion technology.

4. Performance Metrics

4.1 Propulsion Mechanics

All forms of aerospace propulsion currently rely on accelerating some reaction mass to provide a propulsive thrust. For chemical rocket propulsion, the reaction mass is transported by the vehicle and contains the latent energy to heat and accelerate itself to generate thrust. These are Energy Limited propulsion systems. Other forms of rocket propulsion, such as electric propulsion, use reaction mass as a working fluid only, and add energy to the working fluid by electric heating from a solar or nuclear source. These are Power Limited propulsion systems. Aeronautical propulsion is somewhat similar in that most of the momentum flux in the exhaust of a gas turbine is from ambient air which has been compressed, heated by propellant carried by the aircraft, and then ejected to provide thrust. Here, the reaction mass is again a working fluid which is heated by some separate process.

For any propulsion system employing a reaction mass the so-called jet power can be written as

$$P = \frac{1}{2}\dot{m}v_e$$

where $\dot{m}$ is the flow rate of reaction mass and v_e is its exhaust speed. This is just the rate at which kinetic energy is generated by the flow of reaction mass from the propulsion system. Since the thrust generated by the propulsion system is given by

$$F = \dot{m}v_e \tag{4.2}$$

the jet power can also be written as

$$P = \frac{1}{2}Fv_e$$

The thrust-to-weight ratio of the vehicle will now be defined as N so that $F=NMg_o$, where M is the mass of the vehicle and g_o is the usual Earth gravitational acceleration (9.81 ms^{-2}). Note that in this context the value of g_o = 9.81 ms^{-2} is conventionally used for any given location. Using this definition, Eq. (4.3) can be written as

$$\frac{P}{M} = \frac{1}{2}v_e N g_o$$

where P/M is identified as the specific power of the vehicle. The specific power of the propulsion system alone can also be defined by considering the mass of the propulsion system separately from the total mass of the vehicle.

Lastly, the specific impulse of a conventional reaction propulsion system is defined as the momentum gained per unit weight of propellant used. Therefore, for an element of reaction mass δm, ejected with exhaust speed v_e the gain in momentum of the vehicle is $\delta m\ v_e$. Since the weight of the element of reaction mass is $g_o\delta m$, the specific impulse of the propulsion systems can be witten as

$$I_{sp} = \frac{v_e}{g_o} \tag{4.5}$$

A related definition of effective specific impulse, which can also be used to describe propellantless propulsion systems, will be discussed in section 4.2. Using the definition of specific impulse, Eq. (4.4) can now be illustrated as a contour plot, as shown in Fig. 4.1.

It can be seen from Fig 4.1 that conventional chemical propulsion provides rather poor specific impulse, although it can provide a large thrust-to-weight ratio for a short duration, suitable for launch vehicles. For comparison, current concepts for advanced fusion and anti-matter based propulsion for space applications are illustrated. Both of these provide significantly higher specific impulse than conventional chemical propulsion, resulting in extremely high performance for high energy applications, such as long duration, deep space missions.

The goal for advanced propulsion which exploits novel or exotic physics is usually cast in rather imprecise terms. The goal can now be defined as a breakthrough in effective specific impulse, specific power or thrust-to-weight ratio, as has already been defined in section 3.3. The performance of such high specific impulse and high specific power propulsion systems are labelled as High Coupling Physics in Fig 4.1. Such speculative devices would require a novel or exotic physical phenomena which is amenable to a high degree of practical exploitation and control to allow fabrication of a practical device.

However, it is perhaps more likely that any novel or exotic physical phenomena will, at least initially, be a somewhat weak effect. For example, speculative work on the relationship between gravity and electromagnetism may lead to some coupling between these two phenomena. It has been expected that the relatively advanced state of electromagnetic technology could then be exploited to initiate a high degree of control over gravitational forces. In practice, if such speculative work ever comes to fruition, it is likely that the practical coupling will be rather weak. A breakthrough in physics will not necessarily lead to a breakthrough in propulsion, or indeed transportation. These weak devices are labelled as Low Coupling Physics in Fig. 4.1.

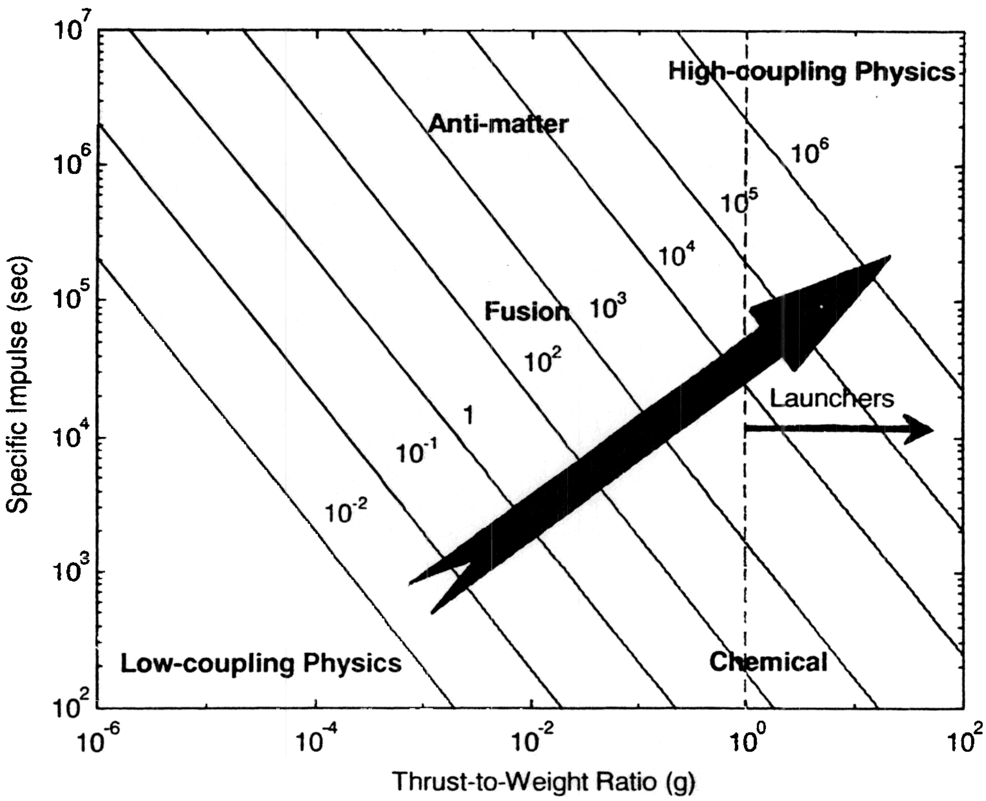


Figure 4.1. Propulsion System Performance Map with Contours of Specific Power (kW/kg)

4.2 Propellantless Propulsion

Since a hypothetical propellantless propulsion system will not expel reaction mass, the conventional definition of specific impulse, defined in section 4.1, is inappropriate. This conventional definition relates the change in momentum of the spacecraft to the weight of propellant expelled. Since a propellantless propulsion system does not expel propellant it will in principle have an infinite specific impulse. However, for a finite mission duration, only a finite total impulse will be delivered by the propulsion system. Infinite specific impulse is only available for an infinite mission duration. A propellantless propulsion system is not therefore necessarily superior to a conventional reaction propulsion system, with any trade-off being dependent on mission parameters.

In order to circumvent this difficulty with the conventional definition of specific impulse, an effective specific impulse will be defined as the total impulse delivered per unit weight of propulsion system

$$I_{sp} = \frac{1}{W}\int_0^T F dt$$

where F is the thrust delivered for mission duration T and W is the weight of the propulsion system. For a vehicle of total mass m_T and acceleration a_o the thrust is given by

$$F = m_T a_o$$

The weight of the propulsion system will now be defined by mass m_S so that

$$W = m_S g_o$$

where g_o is again by convention the usual Earth gravitational acceleration (9.81 ms^{-2}). The weight of the propulsion system can be written in a more useful form as

$$m_S = m_T(1-\kappa)$$

where κ ($0 \leq \kappa \leq 1$) is the payload mass fraction of the system. Therefore, the effective specific impulse of the propulsion system can now be written as

$$I_{sp} = \frac{1}{1-\kappa}\frac{a_o}{g_o}T$$

It can be seen that the effective specific impulse of the propulsion system increases linearly with mission duration. The longer the device is used for, the greater the total impulse which is extracted. In addition, $I_{sp} \to \infty$ as $\kappa \to 1$ since the weight of the propulsion system vanishes in this limit. For a propellantless propulsion system to be effective it can be seen that it must have a large payload mass fraction, and be used for a long duration. A propellantless propulsion system which has a large propulsion system mass and is used for a relatively short duration is unlikely to be competitive with conventional reaction propulsion.

4.3 Reaction Propulsion

A similar analysis can now be performed for a power-limited reaction propulsion system using the definition of effective specific impulse from Eq. (4.6). For a propulsion system with mass flow rate $\dot{m}$ and exhaust speed v_e the jet power P is again defined as

$$P = \frac{1}{2}\dot{m}v_e$$

Therefore, since the thrust $F = \dot{m}v_e$ it can be seen that

$$F = \sqrt{2P\dot{m}} \tag{4.12}$$

For a power system of mass m_{ps}, the jet power may be written as

$$P = Cm_{PS} \tag{4.13}$$

where C is the specific power of the power system (W/kg). The total weight of the propulsion system W_{ps} can now be defined as the weight of the power system and the weight of reaction mass. Therefore, for a mission of duration T, the propulsion system weight is given by

$$W_{ps} = (m_{ps} + \dot{m}T)g_o \tag{4.14}$$

The effective specific impulse of the reaction propulsion system can now be written as

$$I_{sp} = \frac{\sqrt{2Cm_{ps}\dot{m}}}{(m_{ps} + \dot{m}T)g_o} \tag{4.15}$$

In order to maximise the effective specific impulse, the power system and propellant mass must be optimised. It can be shown from Eq. (4.15) that the effective specific impulse is maximised if

$$m_{ps} = \dot{m}T \tag{4.16}$$

so that the power system mass is equal to the propellant mass. In this case the effective specific impulse may be written as

$$I_{sp} = \frac{1}{g_o}\sqrt{\frac{CT}{2}} \tag{4.17}$$

It is seen that while the effective specific impulse of the propellantless propulsion system increases linearly with mission duration, the increase is only to the one half power for a power-limited reaction propulsion system. Therefore, in principle any propellantless propulsion system will always out perform a reaction propulsion system, given sufficient time. This is to be expected since the propellantless propulsion system does not require reaction mass. However, this analysis also shows that the benefit of propellantless propulsion is a function of the mission duration. Propellantless propulsion will only be of significant benefit for long duration and/or high energy missions and if a practical device can be fabricated that has a low enough mass to allow a reasonable vehicle acceleration.

4.4 Comparison of Modes

It can be seen that while the use of effective specific impulse provides only a broad comparison of propellantless and reaction propulsion, it can be used to provide some useful scaling laws. Firstly, it has been shown that the effective specific impulse for propellantless propulsion will increase linearly with mission duration. However for conventional reaction propulsion, the effective specific impulse increases only as the one half power of mission duration. Therefore, propellantless propulsion has a beneficial scaling compared to reaction propulsion for longer mission duration.

To provide an example for comparison, a low thrust spacecraft propulsion system will be considered. Firstly, a propellantless propulsion system which produces a small spacecraft acceleration of 0.25 – 3 mms^{-2} will be compared with a solar electric propulsion system with a specific power of 25 – 200 W/kg. Clearly, the acceleration produced by some speculative propellantless propulsion system is highly uncertain, however, these low accelerations are suitable for deep space missions. A reaction propulsion system with a specific power of 25 W/kg is typical of solar electric propulsion technologies currently in use, while 200 W/kg is typical of a future nuclear electric propulsion system.

The relationship between effective specific impulse and mission duration is shown in Fig 4.2. It can be seen that the propellantless propulsion system is only competitive with the conventional reaction propulsion system for long duration missions if the induced acceleration is small. However, for a high acceleration (of order 3 mms^{-2}), the propellantless propulsion system will quickly out perform even an advanced nuclear electric reaction propulsion system.

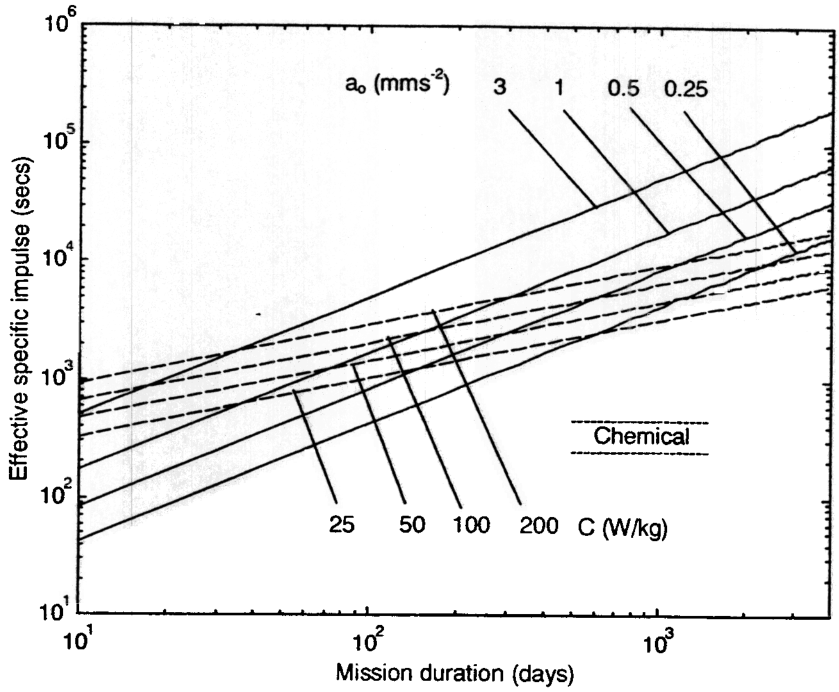


Figure 4.2 Effective specific impulse for a range of reaction and reactionless propulsion system performances

5. Taxonomy for Advanced Propulsion

The taxonomy aims to classify current and proposed propulsion systems into groups which share similar properties. By creating a classification the taxonomy exposes areas that are underdeveloped and may, thereby, possibly stimulate new research. Furthermore, the taxonomy can be used in part to determine if a newly proposed propulsion concept is truly original. As shown in the appendix, seven hierarchies have been developed for propulsion which end in an example.

The hierarchy begins with the fundamental principle behind a propulsion system which for all current designs is based on reaction. In order to achieve a motive force, Newton's 3rd law has to be satisfied and it remains to be seen whether a reactionless propulsion system is theoretically, or even practically, possible. Propulsion systems can be split into those that utilise a force directly and those that convert a torque into a propulsive force. The third hierarchy establishes whether the motive force or torque is generated by the propulsion system internally, whether the motive force or torque is imparted on the system by an external source, or a mixture of the two. The location of the energy source, which powers the motive force or torque, forms the subsequent hierarchy followed by the fundamental force that governs the energy source. At present, the four known fundamental forces of nature are gravitational, electromagnetic, weak, and strong force. A fifth classification has been added to identify energy sources that use a combination of the fundamental forces and to indicate the possibility of perhaps another fundamental force being discovered. The last two hierarchies develop the manifestation of the energy source in more detail, and its underlying fundamental force, before yielding a specific example.

Propulsion systems that generate a motive torque require a medium to convert the torque into a propulsive force. Generally, a method of transport, or a transportation infrastructure, is required to achieve the conversion. The internal combustion engine is a good example, e.g. as applied to cars, trains, boats and propeller driven aircraft. The fact that a medium and a conversion is necessary to exploit a motive torque implies the requirement of mechanical machinery and frictional losses which result in a lower efficiency. Thus, it seems justifiable to assume that a breakthrough in propulsion will probably involve a directly generated motive force.

A propulsion system generating an internal motive force with an internal energy source can operate independently of the environment and is thus defined as an active propulsion system. In contrast, systems on which an external motive force acts with an external energy source are defined as passive, and are thus at the mercy of the given environmental conditions. However, passive systems must consequently lead to a mass saving, as they do not incorporate an engine and fuel, and so it is therefore not surprising to see that such propulsion techniques are being considered for in-Space propulsion, such as beamed power propulsion. By making the distinction between internal and external motive force and energy it is interesting to see that, say, microwave radiation is found on two separate branches, whereas it might only be found under one entry in conventional taxonomies. In the first case the radiation is emitted from the payload to generate thrust and in the second case the radiation is beamed to the payload to transfer momentum.

Generally, the taxonomy demonstrates that the overwhelming majority of propulsion systems are ultimately reliant on the electromagnetic force either directly, or through chemical binding energy. The strong force is the next foundation of other propulsion systems followed by the gravitational force which up to now has only been exploited in Space by gravity assists. The weak force remains unused in current propulsion. The strong force is regarded as the most powerful force in nature, followed in descending order by the electromagnetic, weak, and gravitational force. Despite its strength, the strong force does not manifest itself in the macroscopic universe and thus it is not surprising to find the majority of propulsion systems are based on the electromagnetic force. Given these facts, the taxonomy suggests that a breakthrough in propulsion is unlikely to involve the gravitational force directly or indirectly. Finally, the taxonomy shows that current propulsion used conventionally by humans is, apart from air breathing jet propulsion, based on propulsion systems utilising a torque.

6. Evaluation Criteria

There is a plethora of concepts for advanced propulsion which rely on speculative or exotic physics. Many of these concepts have been proposed by individuals or fringe groups with no formal background in the physical sciences, or indeed mathematics. Similarly, there exists a range of devices which have been invented that claim to show reactionless propulsion. In addition to these fringe efforts however, there are speculative concepts emerging from credible individuals in the physics community that offer the possibility of new advances in propulsion. In order to filter these concepts a set of criteria must be adopted which eliminates the dubious and critically evaluates the potential of serious, but speculative ideas in a rigorous manner:

- **New concepts must have a link to internationally recognised, peer reviewed literature**. Science is a necessarily conservative endeavour that relies on the community peer reviewing new ideas, usually through critical evaluation of journal publications. The peer review process ensures the rigour and quality of new science and provides an exacting test for new ideas. Any speculative physics must have some connection to peer reviewed ideas to demonstrate a link to the current body of scientific knowledge.

The new concept must be testable, measurable, demonstrable, repeatable and explicable in any controlled laboratory-scale experiments. As a step to practical exploitation any new concept must be testable and be able to repeat the claimed phenomena consistently in a controlled laboratory supervised by credible experimenters. In addition, the concepts must be testable on a laboratory scale. New physical phenomena related to large-scale cosmology are unlikely to be exploitable for propulsion.

- **Where does the concept sit in the set of performance metrics?** The likely performance of the device must be assessed using the performance metrics proposed in sections 3 and 4 and compared to competing concepts for advanced propulsion, whether using new physics or not. Only if the device leads to a breakthrough in these metrics can it be deemed a breakthrough in propulsion. Again, new physical phenomena may be weak and difficult to exploit for practical purposes.

  Any new concept must be engineered into a practical device. Speculative physical phenomena may emerge which appear to offer significant benefits. However, any phenomenon must be capable of exploitation and a practical device must be engineered using currently available technologies. Recent apparently consistent solutions to the field equations of general relativity demonstrate the principle of faster-than-light transportation, but the equivalent of several solar masses of energy are required to engineer a practical device.

7. Conclusions

7.1 Review of Advanced Propulsion Activity

High risk breakthrough propulsion research can be defended as a reasonable activity to pursue given the potential future pay-off through practical exploitation. Although historical arguments can be made that the performance of current propulsion systems has reached a plateau, and that a breakthrough in propulsion physics is near, these arguments are somewhat spurious. History in fact shows that advances in propulsion are made by more efficient thermodynamic cycles, representing development of existing propulsion physics. Progress from the steam engine to the gas turbine represents an improvement in thermodynamic efficiency in burning carbon-based fuels and did not rely on new physics. Propulsion based on new physics is somewhat rare, with the linear induction motor and nuclear thermal propulsion being the most visible, but with limited practical application for propulsion. Nuclear thermal propulsion in particular has been limited to military submarines. It is also unlikely that any future breakthrough in propulsion physics will be an all encompassing propulsion device, but will be limited to some particular operating domain.

Section 2 of this report shows that advanced propulsion based on speculative physics is an activity which has seen modest investment by NASA and other centres in the US. The focus for US efforts is the NASA Breakthrough Propulsion Project which has taken a rigorous approach to its activities by using the traditional peer review system to evaluate proposals for new research. At present there is no co-ordination of what little activity occurs in Europe. Advanced propulsion in the European Space Agency has been limited to the development of chemical and electric propulsion systems for future deep space missions. Since the European Space Agency is considerably smaller than NASA, the technology activities of the agency have been mission focused, without the luxury of more speculative activities. Any co-ordination of UK and European activity must be through credible individuals and research centres which can provide reasoned, but speculative debate, and can provide critical evaluation of new concepts.

7.2 Objectives and Metrics

While speculative physics can appear to lead to significant advances in propulsion, a true breakthrough must be measured in precise terms. A clear definition of breakthrough has been provided for both transportation and propulsion. Used effectively this definition, and the associated key parameters, can provide an indication of the value of any future propulsion device and its effect on the transportation system within which it is utilised. For propulsion systems, key performance metrics have been defined which allow comparison of new concepts with existing propulsion concepts. These metrics enable an engineering evaluation of the potential benefit of speculative concepts which may have limited utility in practice. The demonstration of an exotic phenomenon in gravitational physics can only lead to a breakthrough in propulsion if the phenomenon allows strong coupling and is amenable to manipulation with existing technologies to provide, for example, a breakthrough in specific impulse or specific power.

7.3 Objections to Advanced Propulsion

Although some speculative physical phenomena appear to offer significant advantages for advanced propulsion, some caution is required. For example, the practical exploitation of reduction in inertial mass though ZPF effects, as discussed in section 2.2, appears difficult. The following thought experiment provides some indication of the hazards involved.

For rocket propulsion, where the vehicle must transport its own reaction mass (propellant), the inertial mass of the vehicle (its structure and payload) could in principle be reduced by the manipulation of the ZPF by some hypothetical device. If it is assumed that the device is transported by the vehicle, to provide a continual reduction in inertial mass, the inertial mass of the propellant will also be reduced by the same processes that reduces the inertial mass of the vehicle structure and payload. However, since the thrust provided by the propulsion system is a function of the rate at which linear momentum is being transported away by the propellant, the reduction in the inertial mass of the propellant will lead to a reduction in thrust. This reduction in thrust will be exactly the same as the reduction in the vehicle mass, so that the vehicle acceleration will be left unchanged by the action of the hypothetical ZPF device. Similar difficulties exist with the application of inertia modification to spacecraft, since orbital mechanics is essentially independent of the spacecraft mass.

Similar objections arise to other proposed devices. Reactionless propulsion based on rotating mechanisms require that the properties of space are not isotropic. The isotropy of space is a deeper principle than a law of physics (such as Newton's third law) and is more akin to a fundamental postulate of nature. The violation of such fundamental postulates are unlikely to be encountered in a mechanical reactionless propulsion device. Similarly, a gravity shielding device would violate the equivalence principle of general relativity. Such extraordinary claims require unequivocal supporting evidence, which is not available at present. In any device which appears to demonstrate a violation of fundamental physics, Occam's razor must be invoked to decide if a violation is taking place, or whether vibration, standing wave modes or non-linear (but Newtonian) mechanical effects have lead to spurious, but entirely explicable results.

8. Recommendations

8.1 External Perceptions of Project Greenglow

As the only co-ordinated and credible advanced propulsion activity in the UK pursuing concepts in speculative physics, Project Greenglow attracts significant attention. A search of the internet for these key words will yield many links to sites which have some comment on the project. Unfortunately, many of these links are to fringe groups, conspiracy theorists and the plainly mad. There is even a Greenglow e-group which discusses the project and its activities, amongst other topics. The name Greenglow provides all of the connotations which these individuals and groups need to take an interest in the project. This interest is unwelcome. (**http://www.egroups.co.uk/group/greenglow**)

It is recommended the project be re-named and a clear statement of its objectives, as adopted from this report, be produced.

The project web site (**www.greenglow.co.uk**) also provides a missed opportunity to clarify the aims of the project. The web site provides links to a small number of other sites, one of which (**www.electrogravity.com**) has direct links to UFO and para-science sites. The close (in a virtual sense) proximity of the project to these groups is also unwelcome.

- **It is recommended that the current web site be suspended until a complete presentation is available which addresses the above issues.**

8.2 Management of Project Greenglow

In order to ensure the highest quality science and a continual influx of new ideas, the manner in which Project Greenglow is managed should be revised.

- **It is recommended that the progress of the project is subject to annual peer review in order that future activity is conducted in a rigorous manner**

The NASA Breakthrough Propulsion Project, and indeed CIPA (section 2.2), has utilised the services of the physics community to review proposals for new research activity and to evaluate completed or on-going research. This peer review ensures the quality of the science being pursued and acts as a filter for dubious research.

While scientific rigour is essential, equally essential is a spirit of open, but sceptical thought. The project will only advance by catalysing new ideas and subjecting them to evaluation. Such new ideas can be sought in an informal manner from the physics community.

- **It is recommended that an annual retreat be organised with invited participants from academia and industry.**

In order to attract high calibre individuals from the physics community, it essential that such retreats take place anonymously, with absolutely no press contact and with no formal documentation. New ideas can also be sought from the wider physics community through the traditional route of solicited proposals, if funding for such activity becomes available.

- **It is recommended that if the project has significant resources available in future, an open call for proposals should be made in addition to directed programmes of research.**

It should be remembered however, that a true breakthrough in propulsion is unlikely to be obtained either cheaply or quickly.

It is recommended that selected project activities should be adequately funded to ensure progress instead of low level funding of a large number of activities which will lead to stagnation.

The present portfolio of research activity supported by the project is somewhat diverse. If a true breakthrough is to be sought, it is recommended that future activity centres on the investigation and experimental testing of truly novel or exotic physics. While any programme of speculative research must be broad to ensure new concepts are uncovered, a weighting of activities is recommended to ensure some progress in more promising fields. As will be discussed in section 8.3, exploitation of the zero point field (ZPF) holds some promise due to the experimental confirmation of the Casimir force, a key prediction of ZPF theories.

It is recommended that ZPF physics and laboratory experimentation be a key topic in future project activity.

Speculative gravitational physics is also a promising field, but is somewhat difficult to investigate through laboratory scale experiments. For these reasons it is recommended that future funding be directed through a weighting of approximately 50% to ZPF, 20% to gravitational physics and 30% through a responsive mode to a range of concepts or tests. Funding weightings and programme direction should be subject to annual peer review, as discussed above.

While it is recommended that ZPF be a major theme of future project activities, so-called DC-motion devices (gyroscopes, unbalanced oscillating mechanisms) should not. These devices are an illusion with similar status to perpetual motion machines.

- **It is recommended that DC motion devices are not pursued further within the project**

As discussed in section 7.3, the perceived advantages of practical exploitation of speculative physics for propulsion can hide fundamental issues. ZPF induced inertia modification appears to hold significant promise, but basic reaction propulsion mechanics contradicts this. Similar problems are likely to be lurking elsewhere.

- **It is recommended that a study be initiated to investigate the effect of speculative physics (inertia modification, gravity shielding) on the fundamental mechanics of propulsion.**

Finally, if future activity does lead to speculative advanced propulsion devices, these devices must be tested in a controlled laboratory setting. This criteria for evaluation is noted in section 6. In order to provide consistency, a set of simple but carefully designed laboratory tests are required to discriminate new propulsion from spurious mechanical effects.

It is recommended that a study be initiated to design a set of tests, and their realisation as laboratory experiments, which will provide definitive proof of propulsion based on new or exotic physics.

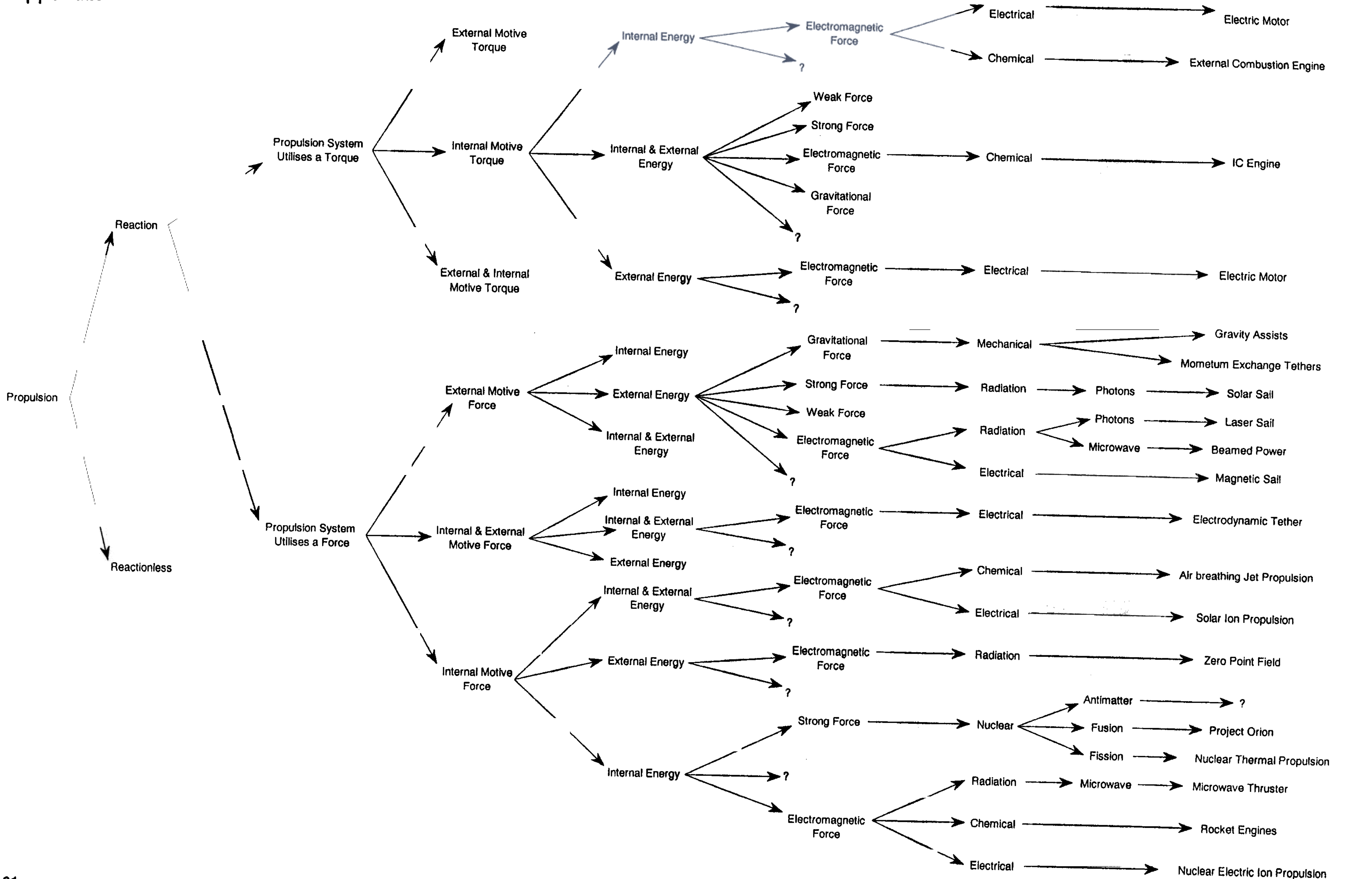
8.3 Future Directions in Advanced Propulsion

From the survey of international activity undertaken as part of this study, the most likely area for a breakthrough in propulsion is believed to be exploitation of the zero point field. Aside from speculative inertia modification effects, the ZPF represents a potential source of energy which may be available for exploitation. The lead which ZPF has over other concepts is the accurate laboratory measurement of the Casimir force, an effect long predicted by ZPF physics. This laboratory scale investigation demonstrates that ZPF is an effect which is amenable to further experimentation. This is unlike other speculative concepts, many of which do not have a clear route to experimental investigation. In addition, the length scales associated with the ZPF are such that micro-machined devices (MEMS technology) can be exploited as an experimental tool. MEMS is a technology undergoing rapid growth for commercial applications and can be exploited for ZPF studies.

The practical extraction of energy from the ZPF will require a thermodynamic cycle to pump energy from the ZPF to macroscopic scales. Although the Casimir force appears to be conservative, there may be practical routes to energy extraction which remain to be discovered. If energy extraction from the ZPF is ultimately practical, a ZPF device can be used to provide a breakthrough in reaction propulsion for aerospace applications by heating some working fluid. From the performance metrics in section 4, ZPF exploitation is a breakthrough in specific power.

The use of a new energy source to drive a somewhat conventional propulsion system has some heritage in aerospace engineering. Between 1957 and 1964 the US Air Force sponsored the development of a cruise missile which used a compact, high temperature fission reactor to heat air as a working fluid in a conventional ramjet type system. The missile was configured to cruise Soviet airspace with a payload of nuclear weapons, moving at Mach 3 at almost tree-top level. Since the reactor had a long life with only a modest load of fissile material, the missile could cruise almost indefinitely. This is a rare, but somewhat extreme, example of new physics (the exploitation of nuclear binding energy) being exploited for practical advanced propulsion. (**http://www.merkle.com/pluto/pluto.html**)

Using a future ZPF device to heat air in a conventional reaction propulsion mode is perhaps a useful vision for propellantless (although not reactionless) propulsion. Such a device could lead to a true breakthrough in civil and military air transportation, enabling rapid long haul air transport with no fuel costs and with no emissions. Such a vision requires the exploitation of speculative physics, but it is not required to defy Newton's third law.



Taxonomy for Propulsion