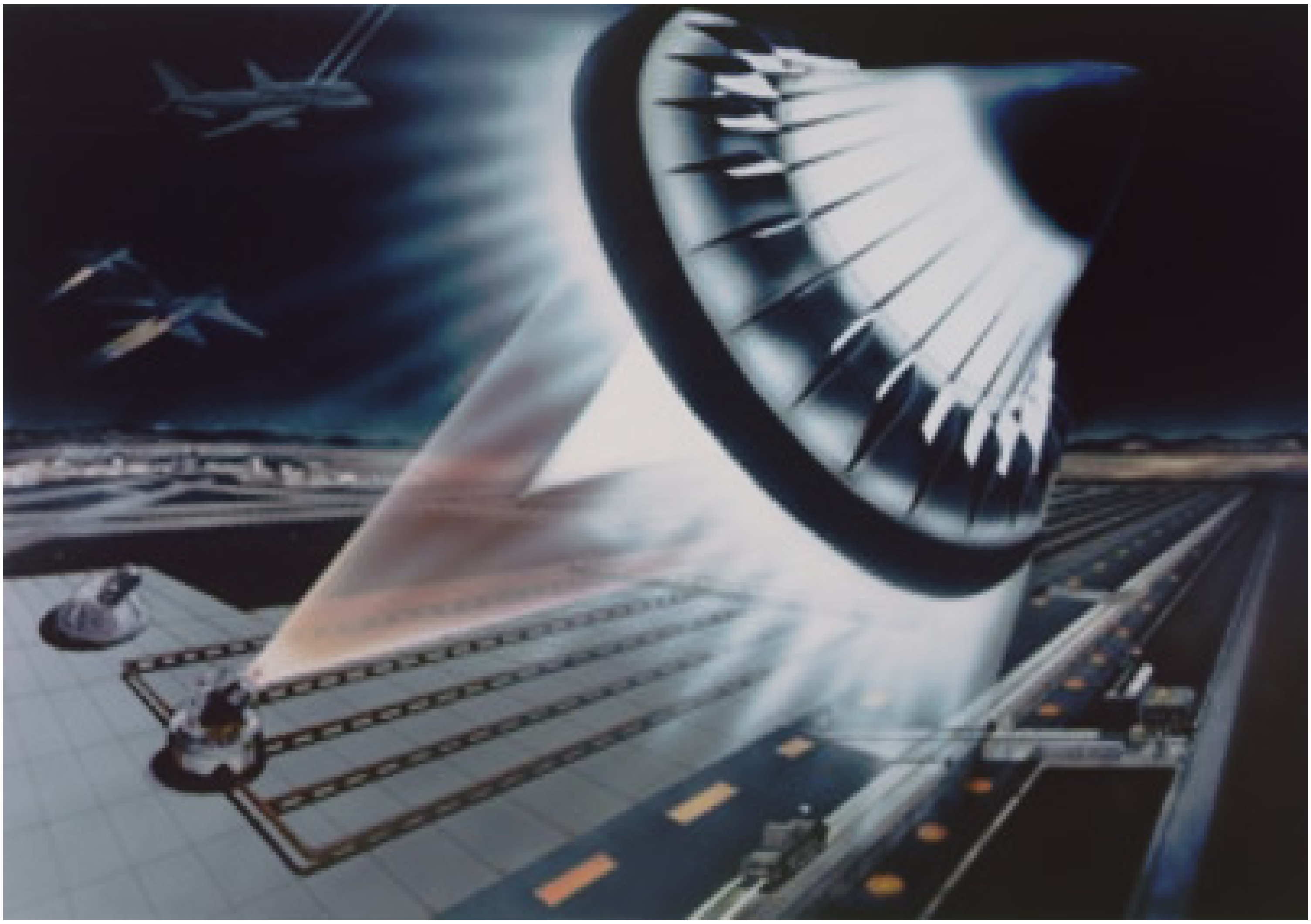

BEAMED ENERGY PROPULSION COMMERCIALIZATION ROADMAP

March 2018

The Report of the Workshop to Commercialize Directed Energy Systems for Low-Cost Space Launches, 11th High Power Laser Ablation/Directed Energy Conference, Santa Fe, New Mexico, April 7, 2016.

Project Details

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TABLE OF CONTENTS

In memory of Arthur Kantrowitz (1913-2008) and Jordin Kare (1956-2017)

WORKSHOP EXECUTIVE SUMMARY

Since Arthur Kantrowitz proposed in 1972 using microwave or laser beams to launch spacecraft into Earth orbit, beamed energy propulsion (BEP) has attracted many advocates – and a larger number of skeptics. Because new market opportunities and advances in key technologies may tilt BEP's future toward the advocates, the 11th High Power Laser Ablation/Directed Energy Conference hosted the Workshop to Commercialize Directed Energy Systems for Low-Cost Space Launches on April 7, 2016 to examine the current state of BEP development.

The workshop concluded there are no fundamental technological obstacles while the growing interest in small payloads, orbital propulsion, and orbital debris mitigation offer promising new markets. BEP promises to be the jet plane to the chemical rocket's propeller aircraft by

drastically improving the economics of space operations through sharply reducing the cost of reaching orbit.

Sharply lower launch costs will attract a range of new entrants into space exploration and business by greatly decreasing the financial barriers to entry. Lower launch costs will have cascading benefits, such as encouraging experimentation by lowering the cost of a failure. Reducing the pressure to maximize the yield per kilogram of payload should decrease the costs of satellites.

Three new market drivers may transform demand for BEP. Launching cubesats and supplying spools of filaments and other stock materials for additive manufacturing (3D printing) in space present opportunities for BEP's low-cost, high-throughput model. The small size and weight of these payloads reduce the energy needed to reach orbit and thus reduce the size and cost of a BEP system. Orbital debris mitigation provides another opportunity for BEP technologies to solve a growing threat to space operations. BEP may also prove able to shift satellites' orbits economically and quickly.

TABLE 1 ESTIMATED TIME AND COST OF BEP DEVELOPMENT

Laser/microwave	Power	Time	Cost
System demonstration	n/a	1 year	$1-3M
1 km launch	1 MW	3 years	$10M
100 km suborbital launch	5 MW	6 years	$100M
Orbital launch (laser)	25-100 MW	10-12 years	$1-2B

Exciting ideas and promising technologies need resources and institutional support to turn them into practical realities. Partly because the concept of BEP is understandably alien to the conventional chemical rocket launch community on many levels, gaining legitimacy and attracting resources have proven difficult. Turning BEP's potential into commercial reality has not and will not automatically occur. Like other radical technologies, BEP has to be promoted, publicized, and find supporters.

Commercialization will succeed only by convincing the space community and other stakeholders that BEP will perform as promised. Given the current lack of high-level coordination of government and commercial efforts to develop the technologies needed for BEP, we recommend the creation of a national coordinating office to handle this task. With sustained financial support combined with the transfer of technologies from the directed energy weapons community, commercial BEP systems could appear by the mid- to late-2020s.

RECOMMENDATIONS

1. NASA, the commercial space industry, and academia should establish a public-private organization to coordinate with the BEP community and other actors the robust technology development program needed to move BEP from laboratory demonstrations to a practical system. A major early step is updating the technological, economic and operational models of BEP systems.

2. The BEP community should focus on creating systems to meet demand from the emerging market drivers of launching cubesats and other small spacecraft, orbital debris mitigation (ODM), and orbital maneuvering propulsion.

3. The directed energy weapons community should be encouraged to determine what military technologies can safely be transferred for commercial civilian dual use to accelerate BEP development.

4. To prepare the legal, institutional and regulatory infrastructure for BEP, the community should consult with major stakeholders, including the microsat/cubesat industry, the Air Force Laser Clearinghouse, federal lawmakers and regulators, and, especially for ODM, the space insurance industry.

5. Governments should explore international cooperation, especially for ODM.

6. The BEP community needs to promote and publicize BEP. One way is to initiate college student design competitions and industry X-Prize competitions to foster technological innovation and entrepreneurial start-up companies. This community also needs to engage venture capitalists and angel investors to raise the necessary start-up funding to commercialize BEP space launches.

INTRODUCTION

Beamed energy propulsion (BEP) promises to drastically improve the economics of space exploration and exploitation by greatly reducing the cost of reaching orbit. Our workshop did not find any fundamental technological obstacles to moving BEP from laboratory research to actual applications. New market drivers – cubesats and other small satellites as well as orbital debris mitigation and space-based 3D printing – provide opportunities for BEP's low-cost, high-throughput model. Commercialization, however, will succeed only by convincing the space community and other stakeholders that BEP will provide its promised benefits of low-cost access to and operations in space.

Given the current lack of high-level coordination of government and commercial efforts to develop the technologies needed for BEP, we recommend the establishment of a national coordinating organization to programmatically and strategically mature the relevant technologies. Such support fits firmly in the long tradition of federal support for transportation infrastructure, but will include partnership with the commercial space industry and academia. With sustained financial support and the transfer of dual-use technologies from the directed energy weapons sector, commercial BEP systems could appear by the mid- to late-2020s.

Significantly, our workshop included participants from the United States, Germany, Japan, and China. International cooperation offers great potential for accelerating the development and deployment of BEP.

THE PROMISE OF BEAMED ENERGY PROPULSION

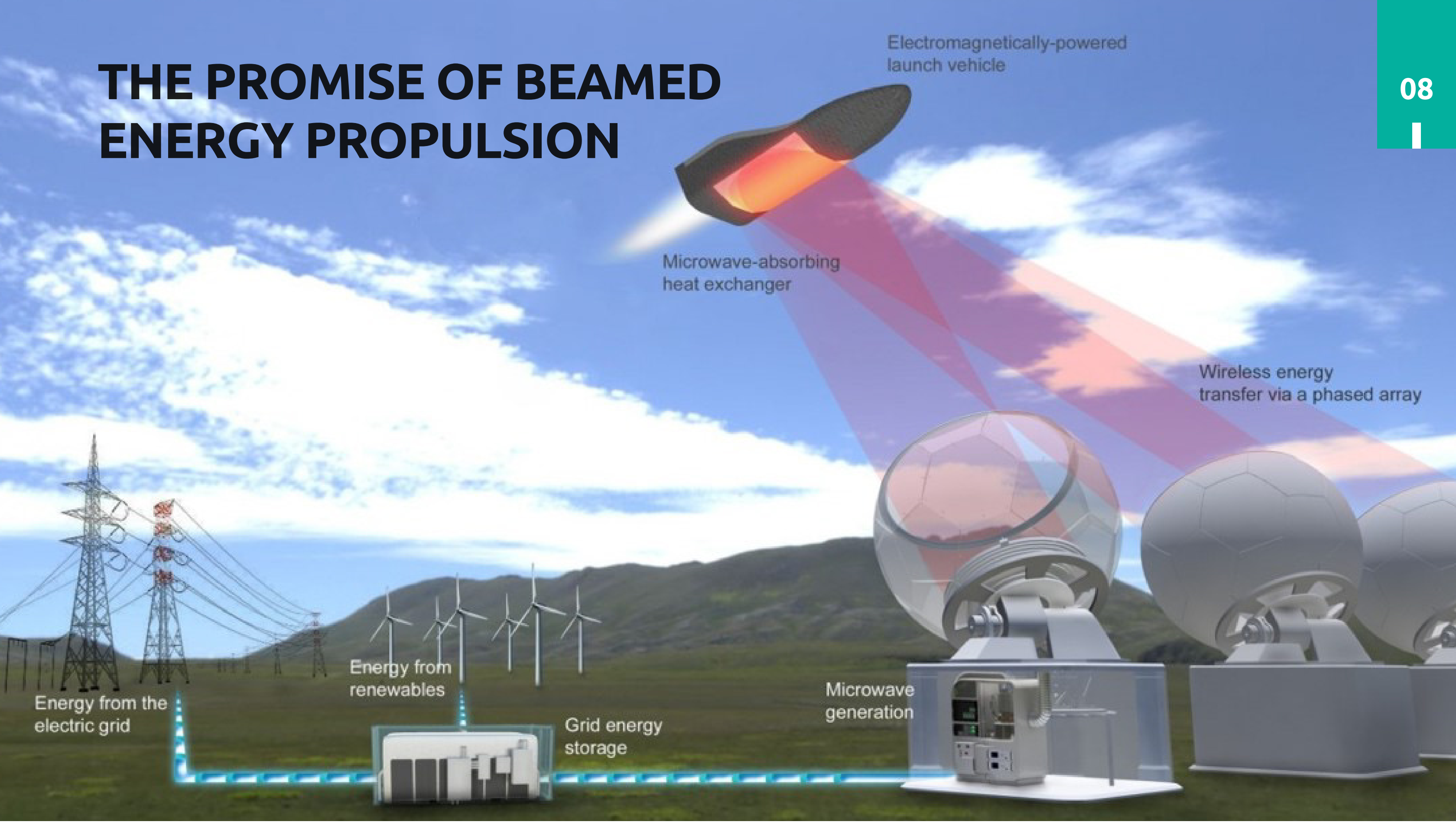

Figure 1

Beamed energy propulsion (also known as directed energy propulsion), employs laser or microwave energy to transmit propulsive power at a distance. Unlike conventional rockets, most of the BEP system remains on the ground ready for rapid reuse, thus significantly reducing the cost and effort of reaching orbit.

BEP promises to transform the existing paradigm of a few launches per year to hundreds or thousands of inexpensive launches, creating a pipeline to space of small payloads. The key metric is throughput, not the capacity of a single launch. High throughput will reduce launch costs by amortizing the capital costs of the ground-based BEP system over many launches.

Our workshop focused on three potential applications: launching payloads from Earth to low earth orbit (LEO), orbital debris mitigation, and orbit-changing maneuvers.

The excitement over BEP is fourfold:

1. Rapid, reliable, all-azimuth launch, and inexpensive access to orbit for cubesats, nanosats and other small payloads
2. Ability to ship thousands of tons into space annually at costs as low as $200 per kilogram of payload mass
3. Flexible, inexpensive mitigation of orbital debris hazards via kinetic "nudges" delivered from ground-based lasers.
4. Low-cost propulsion from LEO to higher orbits and power beaming to transmit energy to satellites

Lower launch costs will transform space exploration and exploitation. Sharply reducing launch costs from the current $20,000 to $200 per kilogram means orbiting the components for a 1-GW, 3,000-ton solar power station (the base model for the 2007 DoD National Space Security Office study) will cost $600 million instead of $60 billion. More immediately, the ability to launch cubesats and other microsats rapidly and inexpensively should greatly increase their attractiveness. Sharply lower launch costs will attract a range of new entrants into space exploration and commercial space business by greatly decreasing the financial barriers to entry. Lower launch costs will have cascading benefits, such as encouraging experimentation by lowering the cost of a failure. Reducing the pressure to maximize the yield per kilogram of payload mass should decrease the cost of satellites.

BEP currently is a set of promising technologies that will need significant development but offer a paradigm-shifting return on investment. To realize the great potential of BEP, our workshop strongly recommends a more organized, focused approach to commercialize BEP. Given adequate support, BEP development could yield operational systems by the mid-to-late 2020's.

Public and Private Motivations to Develop BEP

Why should governments, industry, academic institutions, foundations, and individuals invest in BEP? After all, conventional rockets work well and their economics are improving as SpaceX and Blue Origin are demonstrating. Indeed, the entire space age – including careers, institutions, and routine operations – revolves around conventional chemical rockets.

Yet the price, complexity, reliability and inherent limits of chemical rockets limit the future of space exploration and exploitation. Currently, sending a kilogram of payload into orbit costs $10,000-20,000 with higher costs for smaller payloads. Even the order of magnitude decrease promised by the SpaceX Falcon Heavy means that launching satellites, space probes and other payloads will remain expensive. After nearly six decades of space launches, rockets lifted only about 330 tons of payload to orbit in 2015, not even the equivalent of three 747 cargo flights [1].

High insurance rates indicate continued challenges with the reliability of conventional chemical rockets. Beamed energy thermal rocket and Lightcraft launch vehicles should be safer than chemical rockets because they cannot explode and do not discard rocket stages as they fly to orbit. They are also smaller and lighter because most of the BEP system remains on the ground, which makes launch vehicles easier and cheaper to launch.

Finally, chemical rockets will encounter inherent limits to reductions in cost. Conventional chemical rocket propulsion systems are limited by the amount of energy stored in the propellant, but BEP systems can add more energy externally by using a ground-based directed energy system. That means a greater percentage of the BEP launch vehicle is actually useful payload. Only 2-5% of the launch mass of a chemical rocket is actual payload. By contrast, the payload can comprise 15-20% of a BEP thermal rocket launch and potentially over 50% of a BEP Lightcraft launch [2-6]. NASA's 2012 study concluded that using BEP to propel vehicles into space is technically feasible if a commitment to develop new technologies and large investments can be made over long periods of time [2].

A historical analogy is the replacement of propeller aircraft by jet aircraft: propellers dominated the first four decades of aviation, making great strides from the Wright Flyer to the Lockheed Constellation, but propellers could not provide the greater range, speed, and economics of jet aircraft that transformed flying to finally became a means of travel for the many and not just the few. BEP promises to be the jet plane to the chemical rocket's propeller aircraft, but needs an organized program of implementation, ideally without a world war pushing its development.

WHAT HAS CHANGED?

Since Arthur Kantrowitz proposed in 1972 using microwave or laser beams to launch spacecraft into Earth orbit, BEP has attracted many advocates – and a larger number of skeptics. New market opportunities and advances in key directed energy technologies may tilt BEP's future toward the advocates.

Leik Myrabo (then at the Rensselaer Polytechnic Institute) and Frank Mead (then at the Air Force Research Laboratory) launched an outdoor free-flying laser Lightcraft to an altitude of 72 meters at the High Energy Laser Systems Test Facility (HELSTF), White Sands Missile Range, New Mexico on October 2, 2000 [4]. Nearly two decades later, that record still stands, a sign of a lack of progress and the lack of funding to enable that progress.

The first outdoor free-flying microwave thermal rocket launch occurred at Kirtland Air Force Base conducted by Kevin Parkin (then at Carnegie Mellon University) and collaborators on February 25, 2014 and achieved an altitude of 10 meters [7]. Both laser and microwave flight test vehicles were similar in their small size and mass to Robert Goddard's first free-flying liquid fueled test rockets.


Figure 2a


Figure 2b

BEP is a classic example of technology push dominating market pull as the BEP researchers and not the potential users remain the major actors. For commercialization, users must become involved in advancing BEP, which means BEP must offer significant advantages over chemical rockets. Those advantages increasingly exist due to significant changes in both the demand and supply sides of BEP in recent years.

Demand

Three new market drivers may provide the initial operational opportunities for BEP. Launching cubesats and other small payloads is the first new application. A rapidly growing market that did not exist until 2003, cubesats are a promising BEP launch market because their size and weight are small, reducing the energy needed to reach orbit and thus reducing the size and cost of a BEP system.

Cubesats today are delivered to orbit whenever the big commercial launch vehicles have room for the extra payload or they are transported to the International Space Station for deployment. Both approaches restrict their timing for launch and orbital insertion options. Dedicated small rocket launchers remain in the research stage, but several small rocket launch service companies are now emerging due primarily to very limited funding from NASA and DARPA with most of their funding coming from venture capital firms and angel investors.

These dedicated launchers cost from $20,000 to $55,000 per kilogram of payload mass [8-10]. As the recent British Interplanetary Society Nanosat Launch Vehicle Feasibility Study noted, these projects "appear to have all foundered on what might be called 'economies of scale', or scaling effects, thus it seems that smaller launch vehicles for smaller payloads don't have proportionately lower launch costs" [11]. By starting small and scaling up, BEP promises to provide at least a tenfold decrease in launch costs, a drop that will further spur the smallsat industry.

Another, still nascent market unimaginable even two decades ago is supplying spools of filaments and other materials for additive manufacturing (3D printing) in space. BEP's ability to launch large numbers of small payloads may provide a low-cost method of supplying specific materials for orbital 3D printers, greatly reducing the cost of manufacturing in space.

The second new market is orbital debris mitigation/reduction/removal (ODM). Over the past decade, awareness of the serious danger posed by debris ranging from dead satellites and rocket stages to fragments less than a centimeter has grown.

ODM comes in several varieties. Laser light pressure or ablation can nudge debris off potential collision courses or destroy or deorbit debris. For large objects, nudging may be easier and less expensive than deorbiting. While several solutions have been offered, including tethers and de-accelerators as well as lasers, none have been tested in space, although a 2015 proposal to test a laser ODM at the International Space Station may change that [12, 13]. If scaled up, a laser ODM could assist in deorbiting dead satellites [14].

Finally, in-orbit boosting of satellites offers the potential for faster transit times from LEO to GEO and beyond as well as spacecraft that carry less fuel. The competition of chemical and electric thrusters is well established but demand large amounts of onboard propellant and long flight times respectively. BEP offers significant savings in system complexity, weight and time. Laser-ablative microthrusters on a satellite and BEP from another satellite, Earth, or the moon may provide unprecedented capabilities of flexibility, maneuverability, and thrust, especially for missions beyond GEO and the moon.

Supply

Advances in a multitude of technologies have increased the efficiency and decreased the projected cost of BEP systems. The estimated energy cost of launch for a BEP system is only $2 per kg of launch vehicle mass, based on $0.10/kWh of electricity, in contrast to the < $100 per kg for a conventional chemical rocket. The full cost to launch a payload by BEP or chemical rocket, is much higher.

The goal for producing BEP high-power microwave or laser beams is $1 per watt of beam power, so a 1 kW system would cost $1,000 and a 1 MW system would cost $1 million. This price point for microwave BEP has already been reached: Basic 1 MW gyrotrons are now commercially available for about $1M, or $1 per watt. Known military laser weapons cost $1,000-3,000 per watt of beam power, which includes the full supporting infrastructure (such as the modified Boeing 747 for the Air Force's chemical Airborne Laser and the waste heat removal system for the Navy solid-state Laser Weapon System, LaWS). Civilian lasers, built without military requirements, are significantly less expensive. High-quality near-IR laser light from an industrial high-power fiber laser has dropped from several hundred dollars per watt in the early 2000s to approximately $20 per watt in 2016, and is likely to drop below $10 per watt by 2025 even without the BEP market.

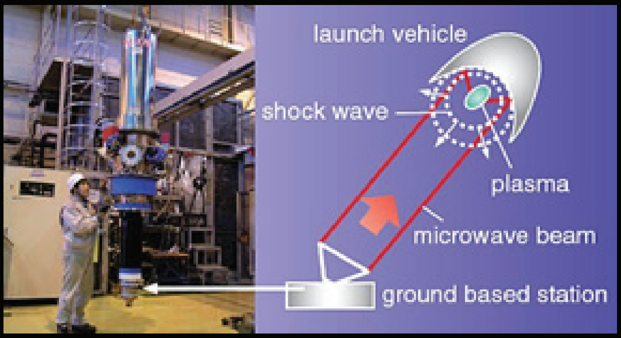

Figure 3

A 2005 study of BEP for the Air Force Research Laboratory predicted a launch cost of $20-3,000 per kilogram of payload mass using a megawatt-class solid-state slab laser. The higher figure includes the full cost of launch operations and the lower figure includes only the cost of producing the laser beam and empty Lightcraft structure [4, 5]. One immediate task is to update the 2005 and 2012 payload launch cost studies and include other laser and microwave technologies.

Advances in technology will reduce the estimated 2005 cost. The promise of the BEP market and a dedicated R&D program should accelerate the scaling up of both pump-diode laser manufacturing and extensive automation of assembly, alignment, and testing of complete bulk slab, high-power fiber, thin-disk, edge-pumped disk, or planar waveguide lasers, and free-electron lasers.

Like many other technologies, military R&D has outpaced civilian BEP development. Some of the most important technical advances, such as high-energy lasers and high-power RF/microwave generators and their beam directors, have resulted from the R&D on directed energy weapon systems. Transferring these technologies into the civilian sector could significantly advance the overall technological infrastructure needed for commercial BEP operations. The Navy's LaWS is based on industrial high-power fiber laser welding technology and has actually been deployed since 2014 in the Persian Gulf. Two historical American analogies are the decision by the Signal Corps not to classify the transistor but encourage its diffusion to the private sector and the deliberate effort to transfer technologies from the military-funded ARPANET to unclassified civilian applications, thus accelerating the development and diffusion of the world-wide Internet.

TECHNICAL MILESTONES AND CHALLENGES

BEP requires advances in many technologies to reach the necessary levels of operational efficiency, reliability, and commercial feasibility (see Appendix 1). None are showstoppers. Our report tries to be as technology-neutral as possible because multiple engineering design options and tradeoffs exist for most technologies.

Some choices are at the mission level (should ODM focus on nudging spent rocket stages off potential collision paths or on removing particles), some at the strategic level (ground- or space-based ODM tracking), some at the technology level (microwave or laser; continuous or pulsed beaming), and some at the subsystems level (laser amplifiers, beam directors, waste heat removal, power systems).

Technological maturity can be judged in several ways. Two of the simplest are the Technology Readiness Level (TRL) and specific milestones. The TRL of key BEP components ranges from 3 to 9. Commercialization demands a TRL of 7-9. As important as reaching these levels of technological capability is demonstrating that BEP will perform as promised.

This report emphasizes key demonstrations because historically they have been essential to the development of radical technologies by showing sponsors and potential customers that the system actually works. Thomas Edison's demonstration of the incandescent electric light bulb in 1878 to Wall Street investors gave them the proof to invest the tens of millions of dollars that created the industrial manufacturing base and infrastructure needed to establish electrical lighting throughout America. BEP will need similar demonstrations to dispel doubt and generate excitement to develop a commercial BEP market.

Demonstrating proof-of-concept is an important milestone. However, turning an experimental system into a practical system that can economically provide the durability and reliability demanded by daily launch operations is the last set of challenges. The main components of the BEP facility should last for well over 10,000 hours of operation, typical of high-power directed energy hardware, so the total cost savings can more than repay the initial facility investment cost. This is industrial engineering at its most basic.

The three near-term opportunities - launch to LEO, ODM, and inter-orbit transit - involve similar concepts and common technologies but also have application-specific differences. Acquiring, tracking, nudging, and removing space debris, for example, require different types of laser operations from a laser used for launch to LEO.

Launch to LEO

The two main proposed approaches are the thermal rocket and Lightcraft. Microwave or laser beam power can propel both options. In a thermal system, a microwave or laser beam focuses onto a heat exchanger on the launch vehicle to heat a liquid monopropellant or ablates a solid propellant. A Lightcraft operates in air breathing mode to Mach 5 and 30 km altitude and then in thermal rocket ablation mode into space. The major differences are that the thermal rocket uses continuous wave lasers while Lightcraft and ablation require pulsed power which currently is more costly though a higher percentage of the Lightcraft mass is payload.

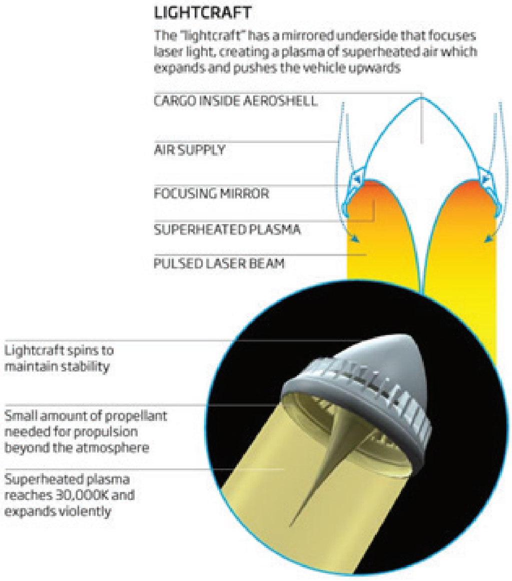

Figure 4

A first-generation laser BEP launch system would require 10-25 MW of total beam power to send a 10-25 kg satellite into orbit. The beam power per kilogram of vehicle mass launched from Earth is an appropriate metric. While estimates range from 0.1-1 MW per kg of vehicle mass, this report uses 1 MW per kg as a simple rule-of-thumb figure. Orbital maneuvering needs only from 0.1 kW per kg for minor maneuvers or station-keeping to 1 kW per kg for orbital transfers.

The set of demonstration milestones for laser and microwave BEP is:

- laboratory demonstration of components and integrated BEP systems (completed)
- sounding rocket (1-2 km altitude)
- suborbital demonstration (100 km)
- orbit (400 km)

Reaching orbit (400 kilometers for the ISS) requires an order of magnitude more energy than reaching 100 kilometers, the official definition where space begins and the goal of Virgin Galactic's Spaceship Two.

A rough estimate (with unknown uncertainty bars for cost and time) for laser launch to LEO is a decade and $1-2 billion, although LOLCAT (Liquid-Oxygen/Laser-Cracked Ammonia Thruster) proponents think that their approach could reach operational maturity for only
$250-500 million [15].

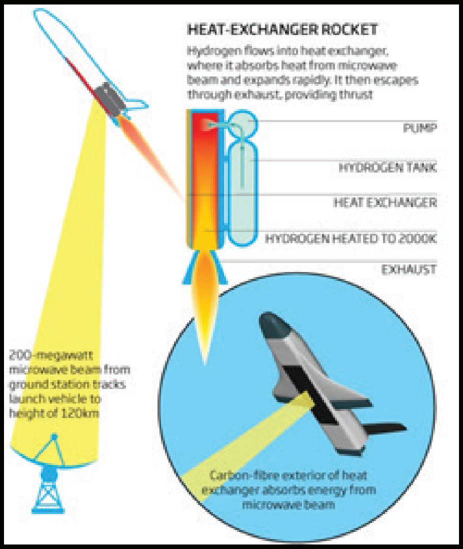

Figure 5

TABLE 2 LASER BEP TIMETABLE

Laser/microwave	Power	Time	Cost
System demonstration	n/a	1 year	$1-3M
1 km launch	1 MW	3 years	$10M
100 km suborbital launch	5 MW	6 years	$100M
Orbital launch (laser)	25-100 MW	10-12 years	$1-2B

ODM

The demonstration milestones for ODM are nudging orbital debris to alter its orbit and removing debris by pushing it to reenter Earth's atmosphere and burn up. Given adequate support, researchers in the field considered nudging possible by 2022 and removal by 2033 (plus or minus a few years).

Orbital maneuvering and propulsion

The three major approaches for orbit-changing propulsion are a ground-based system beaming power to the satellite, onboard laser-ablative micropropulsion, generating micro- to milli-newtons of thrust, and Young K. Bae's Photonic Laser Thruster, which amplifies an onboard laser's thrust by exploiting an active resonant optical cavity between two mirrors on paired spacecraft [16].

TABLE 3 LASER ABLATIVE MICROPROPULSION TIMETABLE

	10% probability	50% probability	90%[e1] probability
in-space proof of principle	2019	2020	2022
in-space system testing	2019	2022	2024
orbital operations	2020	2023	2025

TABLE 4 PHOTONIC LASER THRUSTER (PLT) TIMETABLE

	Photon Thrust	Pump Diode Laser Power	Time	Cost Estimate (w/o launch cost)	Orbit
Space qualifiable PLT development	1 mN	300 W	1.5 Year	$1M	Ground
Space qualified PLT construction and testing	1 mN	200 W	1.5 Year	$2M	Ground
PLT and cubesat integration and flight demonstration at ISS	1 mN	200 W	2 Years	$5M	LEO
Two spacecraft PLT flight demonstration for a virtual telescope	1-3 mN	150 - 500 W	3 Years	$10M	LEO-MEO
Multi-spacecraft PLT flight demonstration for propellant-free stationkeeping mission	5 - 10 mN	1-2 kW pulsed operation	5 Years	$20M	LEO-GEO
Multi-spacecraft PLT flight demonstration for orbit changing	10-100 mN	2-20 kW pulsed operation	5 Years	$50M	LEO-GEO
PLT propulsion demonstration for propellant-free transit concept	100-5000 mN	20-750 kW pulsed operation	5 Years	$100M	GEO, Lagrange Points

NEXT STEPS

Exciting ideas and promising technologies need resources and institutional support to turn them into practical realities. Partly because the concept of BEP is understandably alien to the conventional chemical rocket launch community on many levels, gaining legitimacy and attracting resources have proven difficult. Turning BEP's potential into commercial reality has not and will not automatically occur. Like other radical technologies, BEP has to be promoted, publicized, and find supporters.

New Funding and Organizational Support

Early demonstration projects and development will cost a few million dollars, a level that foundations, philanthropists, and governments could easily fund for the next few years. The recent $100 million Breakthrough Starshot initiative to send nanoprobes to Alpha Centauri by laser sail propulsion may offer the opportunity for early-stage funding [17]. BEP may be able to reach Earth orbit by hitching its wagon to the stars.

The BEP community is currently a collection of individual researchers and groups scattered across the globe in universities and government laboratories. For BEP to succeed, it needs an organization to coordinate and support its development. Establishing an industry-academic-government collaborative partnership BEP program office at NASA, a university or other supportive organization is the logical next step in advancing BEP.

In the United States, the federal government has historically played a major role in promoting and funding national infrastructure development including canals, railroads, waterways, highways, and aviation. The billions of dollars invested by the U.S. military on rocket development in the 1940s-50s laid the foundations for the NASA and commercial rockets of the 1960s. Investing in BEP would continue that historic and essential role. However, today it will be necessary to establish investment and development partnerships with academia and industry in light of ongoing government fiscal constraints.

The United States government expects to spend over $600 million per month for space launch activities from FY2014 to FY2018. Developing the Space Launch System will cost at least $41 billion through 2025 with a low-ball estimated launch cost of $500 million compared to a launch cost of $1.4 billion (in FY2014 dollars) for the Saturn V [18]. Tapping a small amount of that spending for BEP development could pay big dividends.

Another possible source of federal funding is the Department of Energy, which expects to spend $100 billion to dispose of 50,000 tons of high-level nuclear waste, or approximately $1,000 per kg. A BEP launch system to transport radioactive waste payloads out of the solar system could provide a significantly less expensive, more permanent and politically feasible alternative than underground disposal. Certainly, some exploratory research might prove a wise investment [19-21].

Of course, the emergence of a visionary entrepreneur like Elon Musk or Jeff Bezos willing to support BEP at an early stage could propel BEP development much faster. Yuri Milner, the Russian entrepreneur, venture capitalist and physicist who founded investment firms Mail.ru Group and DST Global, and his wife Julia established the Breakthrough Initiatives program in 2015. They have provided the Breakthrough Starshot project with $100 million in funding. It would be desirable to recruit such angel investors in collaboration with federal funding to support the development of low-cost commercialized BEP space launches.

Scaling up to operational systems will cost hundreds of millions of dollars, depending on the type of mission. That demands commitment at the national and international levels, a commitment that should not be given until BEP demonstrates its feasibility.

TECHNOLOGY TRANSFER

BEP is a civilian application based on dual-use directed energy technologies created for national security. So too were the peaceful exploration and exploitation of space built on the German, Russian, and American military rockets of the 1920s-50s. Just like the United States Signal Corps had encouraged the diffusion of knowledge about the transistor instead of classifying it in the late 1940s, technology transfer from the military to civilian BEP applications should be encouraged. The military will benefit from a larger market and quicker development which should reduce its costs as well as wider distribution of knowledge, just like the transistor in the 1950s.

PROMOTION

Producing this roadmap will not result in its implementation. BEP needs to be promoted and publicized. As well as acting individually, the BEP community needs to create a forum, committee, or other institutional arrangements to promote, publicize and encourage the development of BEP.

BEP promoters need to spread their enthusiasm into the broader aerospace and engineering communities as well as into the academic and public arena. One way is to create a BEP X-Prize based on the Ansari and Google-X models. These monetary awards are less important than the legitimacy conferred on the goal, the high national and international profile, and the excitement (and investment) that the awards created.

A second way is to encourage student interest by working with the IEEE Student Design Contest, AIAA Student Design Competition, Student Aerospace Challenge for European Students, International Space University Team Project, and other entities to create competitions to design a BEP system. Teaming with students in business, communications, and advertising to create campaigns to promote BEP should also be considered.

Also needed is a campaign to educate the public, space industry, and public policy decision makers, and other stakeholders about the benefits of BEP. A lesser goal should emphasize that BEP is not a James Bond death ray weapon or a Star Wars weapon of mass destruction but an industrial tool that will be properly regulated and used for the benefit of humanity.

The BEP community should search for other markets that could employ BEP technologies and encourage their development, deployment and diffusion. This will reduce technical risk and cost while increasing industry capability and creating the cadres of educated and trained people needed to make BEP a reality.

INSTITUTIONAL INFRASTRUCTURE

Not all support is financial. BEP development will also depend on the creation of institutional support for BEP applications. One key area is establishing "rules of the road" for high-power laser and microwave operations through the atmosphere and in space to ensure non-interference with existing orbital spacecraft. Discussions with the Laser Clearinghouse at the Air Force Research Laboratory (AFRL) Directed Energy Directorate Satellite Assessment Center (SatAC) and the Center for Advanced Aviation System Development (operated for the Federal Aviation Administration) are essential to understand the challenges of operating in space.

Another key stakeholder in ODM is the commercial space insurance industry. Discussions with the insurance industry should begin now to understand its needs and concerns about ODM and make the industry a partner and not a potential obstacle.

INTERNATIONAL COOPERATION

Significantly, 35% of the workshop participants were not Americans, reflective of the worldwide scope of BEP research. BEP development and commercialization should be viewed similarly. Indeed, a combination of international cooperation leavened with national competition may prove the best of all worlds.

ODM in particular needs an international framework because 12 nations and ESA have launched satellites and over 70 countries have satellites in orbit. There are still satellites and launch vehicle components remaining in orbit from the dawn of the space age. The physics of debris does not respect national boundaries. NASA should lead the way in discussing with ESA, RSA, JAXA, India, and China ways of cooperating, coordinating and consenting, possibly via the International Astronautical Federation.

CONCLUSION

BEP offers a path to expand radically the exploration and exploitation of space by greatly reducing the cost of reaching orbit. Like the Erie and Suez canals, turning these visions into commercial reality will demand development of technologies and investment but, as important, the acceptance and advocacy of BEP by the aerospace community and public will be necessary.

The vision of scores of daily launches of cubesats and micro-/nano-sat payloads by industries, businesses, schools, universities, and governments for business, education, science experiments, weather monitoring and remote sensing, global telecommunications and navigation, ham radio communication, and engineering tests contrasts sharply with the current reality of waiting for a chance to share a ride with a large satellite on a large chemical rocket. BEP can turn that vision into a reality.

Longer term, BEP has the potential to transform manufacturing in space and otherwise truly make space a "normal" place to work in as well as explore, indeed even reach Alpha Centauri. Such a journey begins with the steps outlined in this roadmap.

APPENDIX 1. TECHNICAL GOALS

Regardless of the application, further advances in several supporting technologies are universally needed. Key technologies include high-energy laser and high-power RF/microwave technologies, target acquisition and tracking, beam control, launch vehicle (thermal rocket or Lightcraft), and miniaturized thrusters for spacecraft attitude and orbital station-keeping control. Other major supporting technologies include pulsed or continuous power supply, energy storage, thermal management, laser and RF/microwave components, adaptive optics, and phased arrays.

Different approaches will demand different technologies. For example, laser thermal (and to some extent laser ablative) launch can be done without combining separate beams or using incoherent polarization or wavelength combining to reduce the number of separate beams. Lightcraft have tighter beam requirements but may be able to use similar schemes. In contrast, microwave requires large-scale beam combining because the apertures are so large that incoherent wavelength combining may not work. However, beam combining will be necessary in order to scale up the beam power needed to launch heavier payloads.

Launch to LEO

Lightcraft operate in two propulsion modes: airbreathing (pulsed detonation wave) and rocket ablation. The Lightcraft operates in air breathing mode to Mach 5 and 30 km altitude and then in thermal rocket mode into space using liquid, gaseous, or solid ablation propellant. In this two-mode propulsion concept, a forebody aeroshell acts as an external compression surface for the airbreathing engine inlet. A parabolic-shaped afterbody mirror on the bottom of the craft serves as both the primary receptive optic for the RF/microwave or laser beam and as an external plug nozzle expansion surface.

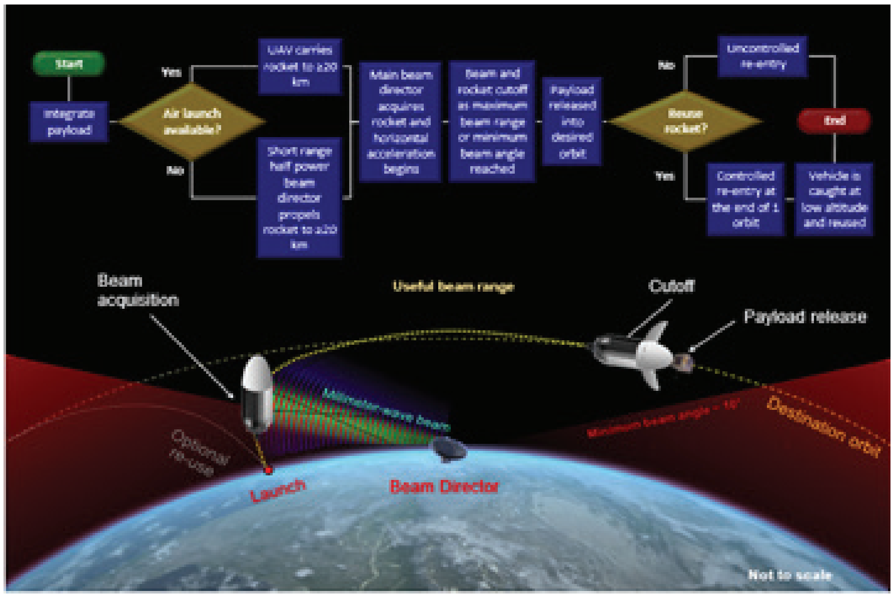

Figure 6

The primary thrust structure is a centrally located annular shroud, which provides air through the inlet and also acts as an annular focused energy "absorption/propulsion" chamber for plasma formation. The air inlet is closed when the Lightcraft operates in the rocket mode. The intensity of the focused pulsed radiation is sufficiently high that atmospheric breakdown occurs in the annular shroud causing inlet air to momentarily burst into highly luminous plasma, thereby producing an expanding superheated plasma shock wave that produces downward thrust. Variations of this design include the Japanese Laser-driven In-Tube Accelerator and the German parabolic bell thruster [22, 23].

Another type of microwave and laser thermal rocket uses a high-strength, high-temperature heat exchanger, integrated into a small section of the outside wall of a rocket, to capture the beamed energy and heat up a flow of gaseous or liquid monopropellant to produce thrust through a rocket nozzle.

While gas dynamic and chemical lasers pioneered early research in BEP, commercial requirements of low operating costs and environmental sustainability encourage solid state and free-electron lasers. Specific technologies required for laser propulsion are:

1. Laser Lightcraft: high-power laser system (fiber, thin-disk, planar waveguide, edge-pumped disk, bulk slab, free-electron; diode laser pump); power source and energy storage; thermal management system; beam director with multiple beam combining and adaptive optics; Lightcraft vehicle with onboard telemetry system and FEEP thrusters; and thermoplastic ablation material for space propulsion.
2. Laser Thermal Rocket: high-power laser system (fiber, thin-disk, planar waveguide, edge-pumped disk, bulk slab, free-electron; diode laser pump); power source and energy storage; thermal management system; beam director with multiple beam combining and adaptive optics; rocket structure; monopropellant fuel; and thermal heat exchanger.

Specific technologies required for microwave propulsion are:

1. RF/Microwave Lightcraft: high-power RF/microwave system (gyrotrons); power source and energy storage; thermal management; beam director with multiple beam combining; Lightcraft vehicle with onboard telemetry system and FEEP thrusters; and superconductors with cryogenic system.
2. RF/Microwave Thermal Rocket: high-power RF/microwave system (gyrotrons); power source and energy storage; thermal management; beam director with multiple beam combining; rocket structure; monopropellant fuel; and thermal heat exchanger.

ODM

Specific technologies required for ODM, regardless of the remediation method, are: better debris tracking, especially of very small debris, better predictive analyses, and a ground and/or orbiting high-energy laser system. Small objects are much harder to track but demand much less energy to move or ablate than the large objects.

Orbital maneuvering and propulsion

Specific technologies required for orbit-changing propulsion are: ground-based or space-based high-power RF/microwave and/or high-energy laser systems with all of the requisite subsystem components. Laser-ablative micropropulsion, generating micro- to milli-newtons of thrust,

Young K. Bae's Photonic Laser Thruster amplifies photon thrust, produced by a diode laser-pumped solid-state laser, by orders of magnitude by exploiting an active resonant optical cavity formed between two mirrors on paired spacecraft. The PLT can be used for spacecraft formation flying in orbit, orbital maneuvers, spacecraft station-keeping, and spacecraft transit to the Moon and the planets.

Finding other markets for BEP technologies

Obvious examples include high-power fiber lasers, thin-disk lasers, planar waveguide lasers, bulk slab lasers, edge-pumped disk lasers, free-electron lasers, and RF/microwave beam generators. Are there similar opportunities for beam director and related advanced optics, thermal heat exchangers, power systems and energy storage, waste heat removal, or other key technologies?

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PHOTO CREDITS

Cover Photo

- Lightcraft Program, Advanced Concepts Office, AFRL, Edwards AFB, CA

Figure 1

Kevin Parkin

Figure 2a

Lightcraft Program, Advanced Concepts Office, AFRL, Edwards AFB, CA.,

Figure 2b

Leik Myrabo with Lightsat

Figure 3

Kevin Parkin

Figure 4

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Figure 5

Microwave Rocket Team, Komurasaki Lab, Univ. of Tokyo, Japan.

Figure 6

Kevin L.G. Parkin and Thomas Lambot, Microwave Thermal Propulsion NASA/TP-2017-219555