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SOLAR POWER CONSTELLATIONS  
IMPLICATIONS FOR THE UNITED STATES AIR FORCE

by

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A Research Report Submitted to the Faculty

In Partial Fulfillment of the Graduation Requirements

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As the world population increases and natural resources used to produce energy decrease, alternative methods to produce sustainable, environmental cost effective energy are required. One proposed solution to the problem is solar power satellites. Solar power satellites are satellites, which collect the energy of the sun, convert it onto a beam, and beam that energy to a receiving antenna. The receiving antenna converts the beam into electricity and feeds the electricity into a power grid. The receiving antenna may be located on another satellite, or on Earth. Presented here are several solar power satellite proposals, architectures, incremental technology demonstrations and predictions as to when they will become commercially viable. Given the previous information, this paper analyzes the implications for the Air Force in relation to doctrine and future plans. The research method consisted of a search of scientific journals, published symposium papers, and research reports. The search focused on the current research on solar power satellites, and Air Force programs, which have power issues. Based on the research, the Air Force should plan to capitalize on the advantages of solar power satellite constellations. Solar power satellites can assist with implementing various plans (i.e., long endurance unmanned aerial vehicles, space-based radar, lasers, and small satellites), complying with public law, and reducing the logistics tail associated with an expeditionary force.

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## *Preface*

This paper covers the implications of solar power satellites for the United States Air Force. Solar power satellites are satellites, which collect the energy of the sun, convert it into a beam, and beam that energy to a receiving antenna. The receiving antenna converts the beam into electricity and feeds the electricity into a power grid. The receiving antenna may be located on another satellite, or on Earth. The first part of the paper provides background information on solar power satellites. It defines some common characteristics of all the different solar power satellite architectures. The background also discusses some of the barriers to implementation, technology demonstrations, and expectations for the first commercially viable systems. The second part of the paper is the analysis. It discusses various uses for solar power satellites in the Air Force. The final part of the paper consists of recommendations for future research.

I would like to thank Lieutenant Colonel Simpkins, who as my faculty advisor was enthusiastic, supportive, and critical all at the same time. In addition, none of this was possible without the dedicated support of the Air University library staff. In particular, Diana Simpson and Edith Williams both of whom opened a whole world of available research materials to me.

### *Abstract*

As the world population increases and natural resources used to produce energy decrease, alternative methods to produce sustainable, environmental cost effective energy are required. One proposed solution to the problem is solar power satellites. Solar power satellites are satellites, which collect the energy of the sun, convert it onto a beam, and beam that energy to a receiving antenna. The receiving antenna converts the beam into electricity and feeds the electricity into a power grid. The receiving antenna may be located on another satellite, or on Earth. Presented here are several solar power satellite proposals, architectures, incremental technology demonstrations and predictions as to when they will become commercially viable. Given the previous information, this paper analyzes the implications for the Air Force in relation to doctrine and future plans. The research method consisted of a search of scientific journals, published symposium papers, and research reports. The search focused on the current research on solar power satellites, and Air Force programs, which have power issues. Based on the research, the Air Force should plan to capitalize on the advantages of solar power satellite constellations. Solar power satellites can assist with implementing various plans (i.e., long endurance unmanned aerial vehicles, space-based radar, lasers, and small satellites), complying with public law, and reducing the logistics tail associated with an expeditionary force.

## **Part 1**

### **Introduction**

Currently the United States relies on fossil fuels to generate electrical power. The United States acquires fossil fuels from both domestic sources and imports. Scientific predictions indicate a “sharp decline in [fossil fuel] availability over the next 40 years.”<sup>1</sup> As the world population increases, and natural resources to produce energy decrease, alternative methods to produce sustainable, environmental friendly, cost effective energy are required. One solution to the lack of renewable energy resources is solar power satellites. A solar power satellite collects energy from the sun and beams that energy to a receiving antenna, which converts the energy into electricity. Peter Glaser first proposed solar power satellites in the late 60s. During the energy crises in the 70s, the government took a hard look at them. The studies generated by this inquiry essentially reported that solar power satellites were technologically possible but their cost and launch requirements were not. Fifteen years later NASA conducted a study to determine if anything had changed. The study concluded that costs were still high but they were not as high as originally predicted and that there were no technological showstoppers. Utility companies and many other nations are taking a close look at solar power satellites. Not only are they looking at them as sources of power on Earth but as sources of power for satellites to reduce their size and launch costs.

The purpose of this paper is to provide a detailed discussion of solar power satellites to include current technology capabilities and estimated implementation dates. This discussion will provide the foundation necessary to ascertain the terrestrial and space implications for the Air Force. Included in the analysis section are discussions on how solar power satellites are congruent with current doctrine and future studies.

### **Notes**

<sup>1</sup> Glaser, Peter E. and others. *Solar Power Satellites: A Space Energy System for Earth*. (New York: Wiley, 1998). 93.

## **Part 2**

### **Background**

Solar power satellites have the potential to supply the energy demands of the planet in a variety of situations. There are several different proposals currently under research for implementing solar power satellites. Some of the proposals place the satellites in low earth orbit, others place them in geosynchronous orbit. The destination of the solar power satellite beam also varies. The final destination of the beam may be earth, another satellite, or a relay station. One thing they all have in common is wireless power transmission. Wireless power transmission is one of the enabling technologies for solar power satellites. All of the solar power satellite architectures also share the same barriers to implementation. A few of the current barriers to realizing solar power satellites are solar cell inefficiencies, the high cost of launches and possible communication frequency interference. Currently Japan possesses the most robust plan for researching and developing proofs of concept for solar power satellites. As varied, as the proposals are to build a solar power satellite, there are just as many predictions as to when a system will become commercially viable. The next section defines solar power satellites, discusses Japan's successes, and presents expected implementation schedules.

### **Solar Power Satellites**

There are many different architectural designs for solar power satellites and solar power satellite constellations. Despite all the differences in design architecture and orbital locations,

they all have some common features. Essentially, all solar power satellites collect solar power, turn it into electricity, convert it into a beam, and beam it to a receiving antenna. Once received, the receiving antenna converts the beam back into electricity, and feeds the electricity into a power grid.<sup>1</sup>

A similar concept to the solar power satellite is the power relay satellite. It consists of a beam transmitted from earth to a satellite, which reflects the beam to a receiving site on earth that converts the beam back into electrical power.<sup>2</sup> Some designs call for multiple independently steerable reflectors so the satellite can transmit power to multiple locations.<sup>3</sup> Many consider power relay satellites an incremental step to a full solar power satellite.<sup>4</sup>

Some of the common elements of solar power satellites and power relay satellites are orbits, receiving methods, beaming methods, and barriers to implementation.

## **Orbits**

The versatility of the solar power satellite allows them to be located in any orbit; however, there are advantages and disadvantages to each orbit. Solar power satellites may be located in geosynchronous orbit. One advantage of the geosynchronous orbit is that the satellites are always in sunlight and can supply power almost continuously.<sup>5</sup> Another advantage offered by placing solar power satellites in geosynchronous orbit is that only a few of them are required to supply power to any place on earth. One disadvantage of geosynchronous orbit involves transmitting and receiving antennas. Solar power satellites placed in geosynchronous orbit will require large transmitting and receiving antennas due to their distance from the earth.

In direct contrast to solar power satellites in geosynchronous orbit, solar power satellites in low earth orbit pass in and out of sunlight regularly. The disadvantage of low earth orbit involves the number of satellites required to supply continuous power. Solar power satellite

constellation in low earth orbit requires many satellites in order to supply continuous power. The advantage over the geosynchronous location is that smaller satellites in low earth orbit require smaller transmitters and receivers.<sup>6</sup> Proposals to locate solar power satellites in all types of orbits exist.

### **Receiving Methods**

Receiving methods for the beam involve the use of a rectenna. The rectenna intercepts the beam of energy from the solar power satellite and converts it back into electricity.<sup>7</sup> The rectenna consists of long wires connected to rectifying diodes.<sup>8</sup> Rectifying diodes convert RF energy into electricity. Since the rectenna intercepts the beam and allows most sunlight to pass through, the land beneath the rectenna still has a variety of available uses. One concept proposes to use the land beneath the rectenna to grow crops or raise cattle.<sup>9</sup> A rectenna may be located on earth, another satellite, or on an aircraft.

### **Wireless Power Transmission**

One technology, which makes solar power satellites possible and possesses a great deal of potential for other applications, is wireless power transmission. Wireless power transmission is the method by which solar power satellites beam power to a rectenna. Wireless power transmission may occur with either a microwave or a laser beam. It involves transmitting electrical power from one location to another without the use of wires. Most of the studies focused on microwave wireless power transmission. Scientists have conducted several demonstrations of wireless power transmissions. The first demonstration was by William C. Brown. He proved the feasibility of the concept by powering a small helicopter with a microwave beam.<sup>10</sup> The next demonstration was by NASA in 1975. In this demonstration, they transmitted 30 kilowatts of power over a distance of one mile.<sup>11</sup> In 1987 the Canadians flew a

microwave-powered aircraft and concluded that a microwave beam could power it indefinitely.<sup>12</sup> Japanese researchers demonstrated the feasibility of powering a model airplane in 1992.<sup>13</sup> They also accomplished powering a satellite from a rocket in space in 1993, the ISY-METS experiment.<sup>14</sup>

## **Beam Technology**

Solar power satellites and their cousin power relay satellites both rely on wireless power transmission technology to transmit power from one location to another. The types of beams proposed use lasers or microwaves to transmit power from orbit to earth.

Lasers offer some disadvantages and advantages as compared to microwaves. Lasers are more hazardous than microwaves and require safety measures such as physical barriers, surveillance, sensors to detect imminent collisions and a pilot safety signal to prevent the beam from wandering.<sup>15</sup> The pilot safety signal allows the transmission beam to operate, without the signal there is no transmission. In addition to the hazards, another disadvantage associated with lasers involves the atmosphere. The atmosphere tends to absorb lasers especially during wet weather.<sup>16</sup> Lasers provide advantages over microwaves such as reducing the size of the transmitting and receiving antennas.<sup>17</sup>

Microwaves on the other hand require larger transmitting and receiving antennas. However, the atmosphere does not absorb microwave beams in the 2.45-megahertz frequency range.<sup>18</sup> The microwave beam is also not hazardous to the environment, humans, or animals. Microwaves are not hazardous because the energy contained in the beam is less than ten times the allowed leakage from the door of a microwave oven.<sup>19</sup> The only effect on someone or something in the middle of the beam would be warmth.<sup>20</sup>

## **Barriers to Implementation**

Current barriers to implementation are the cost for the system, the high cost of launch services, solar cell inefficiencies, and possible communication frequency interference. The type of solar power satellite architecture proposed has a lot to do with cost. Regardless of the architecture all the designs are on an order of several billions of dollars. This price tag has a tendency to scare away potential investors. The high cost of launches contributes to that estimate. Until the price per pound to put a payload in orbit comes down, this will continue to be a barrier.

In addition to cost, the inefficiencies of solar cells are also a barrier to implementation. Solar cells, the main method for harnessing solar power currently have efficiencies in the range of 20%. This means that the solar arrays must be kilometers in size to generate enough power worth beaming back to earth.

The final barrier to implementation is frequency interference. In the arena of communications, before scientists conducted experiments, many supposed that there was a potential for interference from the beam on communications systems, radar, and aircraft communications in the geographic area of the beam.<sup>21</sup> A Japanese study conducted in 1993 demonstrated that a high power microwave beam would not be strong enough to interfere with telecommunications.<sup>22</sup> However, most of the articles and research supporting solar power satellites still list frequency or communications interference as an issue to resolve.

## **Japan's Solar Power Satellite Successes**

Japan is the leader in solar power satellite technology today. They are working on several proofs of concept for solar power satellites. The three main projects are the space flyer unit, ISY-METS, and solar power satellite 2000 (SPS2000). The space flyer unit deployed on the

shuttle and tested various solar power to electricity generating schemes.<sup>23</sup> The ISY-METS, mentioned earlier, proved that one spacecraft could supply power to another in space using wireless power transmission. The SPS2000 experiment has two parts. The first part demonstrated a solar power satellite, suspended several feet off the ground, which beamed 4 watts of power to a rectenna. The rectenna powered a water pump, fan, and lights.<sup>24</sup> The second part will be a small solar power satellite in orbit beaming power to five locations.<sup>25</sup>

### **Expected Implementation**

Current predictions as to when solar power satellites will be available vary somewhat. An article in *Space Business News* indicated that they expected solar power satellite demonstrations by 2006, and expected functioning capital earning models by 2010.<sup>26</sup> Ralph Nansen, who worked on the first government sponsored solar power satellite studies, and is the author of *Sun Power: The Global Solution for the Coming Energy Crisis*, also expects the first units in 2006.<sup>27</sup> However, Peter Glaser the founding father of solar power satellites believes that it will take 15 to 20 years once investors make the commitment to build solar power satellites before they become a reality.<sup>28</sup>

### **Summary**

Solar power satellites harness the energy of the sun, convert that energy into electricity, and beam the electricity to a rectenna. The beam may be a laser or a microwave. The rectenna may be located on earth, on another satellite, or on an aircraft. A power relay satellite receives a beam of energy from earth and reflects it to another location on the planet. A rectenna receives the beam, from either a solar power satellite or a power relay satellite, converts it back into electricity and feeds it into the local power grid. Solar power satellites possess the potential to

continuously supply much of the world's current and future energy needs with power that is environmentally benign and renewable. The main feature of solar power satellites is wireless power transmission. Several engineers in different parts of the world have demonstrated this concept as technologically feasible and it only requires implementation. Lasers and microwaves are the contenders for use in the beam. Most of the studies thus far focused on the microwave as the means to propagate the beam because they attenuate less in the atmosphere and are less hazardous than lasers. The cost is the main barrier to implementation. Although engineers in Europe, the Ukraine, and the United States research solar power satellites, engineers in Japan possess the most robust program with the supporting technological demonstrations. Several predictions to when solar power satellites will become commercially available exist. They range anywhere from the next decade to mid-century.

### Notes

<sup>1</sup> *Space Based Solar Energy: A Brief Review and Analysis*. National Power Research Institute, Inc. 1998. Available on-line [www.nspri.org](http://www.nspri.org). 6.

<sup>2</sup> Glaser, Peter E. "A Global Perspective on Renewable and Solar Energy." *The Journal of Social, Political and Economic Studies* 19, no 1 (Spring 1994). 5.

<sup>3</sup> Bekey, Ivan and Richard Boudreault. "An Economically Viable Space Power Relay System." *Space Energy and Transportation* 3, no. 3 (1998). 159.

<sup>4</sup> *Ibid.*, 158.

<sup>5</sup> Glaser, Peter E. and others. *Solar Power Satellites: A Space Energy System for Earth*. (New York: Wiley, 1998). 5.

<sup>6</sup> Hoffert, Martin I. and Seth D. Potter. "Energy and Information from Orbit: Technologies for the Greenhouse Century." *Ad Astra* (Jan/Feb 1998). 36.

<sup>7</sup> Nansen, Ralph. *Sun Power: The Global Solution for the Coming Energy Crisis*. (Canada: Ocean Press, 1995) 206.

<sup>8</sup> *Ibid.*, 206.

<sup>9</sup> Glaser, Peter E. and others. *Solar Power Satellites: A Space Energy System for Earth*. (New York: Wiley, 1998). 176.

<sup>10</sup> Glaser, Peter E. and others. *Solar Power Satellites: A Space Energy System for Earth*. (New York: Wiley, 1998). 58.

<sup>11</sup> Glaser, Peter E. "A Global Perspective on Renewable and Solar Energy." *The Journal of Social, Political and Economic Studies* 19, no 1 (Spring 1994). 4.

<sup>12</sup> *Ibid.*, 5.

<sup>13</sup> Kaya, Nobuyuki. "Japan's Solar Systems." *Ad Astra* (Jan/Feb 98). 41.

## Notes

<sup>14</sup> Glaser, Peter E. "A Global Perspective on Renewable and Solar Energy." *The Journal of Social, Political and Economic Studies* 19, no 1 (Spring 1994). 5.

<sup>15</sup> Dickinson, Richard M. "Lasers that Beam Power to Earth." *Aerospace America* (July 1999): 52.

<sup>16</sup> Glaser, Peter E. and others. *Solar Power Satellites: A Space Energy System for Earth*. (New York: Wiley, 1998). 9.

<sup>17</sup> Dickinson, Richard M. "Lasers that Beam Power to Earth." *Aerospace America* (July 1999): 50.

<sup>18</sup> Nansen, Ralph. *Sun Power: The Global Solution for the Coming Energy Crisis*. (Canada: Ocean Press, 1995) 200.

<sup>19</sup> Ibid. 111.

<sup>20</sup> Ibid. 111.

<sup>21</sup> Glaser, Peter E. and others. *Solar Power Satellites: A Space Energy System for Earth*. (New York: Wiley, 1998). 15.

<sup>22</sup> Kaya, Nobuyuki. "Japan's Solar Systems." *Ad Astra* (Jan/Feb 98). 43.

<sup>23</sup> Glaser, Peter E. and others. *Solar Power Satellites: A Space Energy System for Earth*. (New York: Wiley, 1998). 280.

<sup>24</sup> Ibid., 287.

<sup>25</sup> Ibid., 281.

<sup>26</sup> "Emerging Space Industries for the Next Century." *Space Business News* 17, no. 7 (31 March 99): 4.

<sup>27</sup> Nansen, Ralph. *Sun Power: The Global Solution for the Coming Energy Crisis*. (Canada: Ocean Press, 1995) 225.

<sup>28</sup> Glaser, Peter E. and others. *Solar Power Satellites: A Space Energy System for Earth*. (New York: Wiley, 1998). 13.

## **Part 3**

### **Analysis**

Solar power satellites have definite applications in the private sector, generating power cheaper and cleaner than fossil fuels and other renewable energy sources such as hydroelectric, wind, and terrestrial solar power. Solar power satellites may also supply power where traditional electrical power grids are prohibitively expensive to install. Solar power satellites also enhance the national security of a country that chooses to adopt them as a form of power generation by reducing reliance on the import of fossil fuels.

The implications for the Air Force are just as significant. Solar power satellites are an enabler for many of the applications discussed in such studies as *Spacecast 2020* and *New World Vistas: Air and Space Power for the 21<sup>st</sup> Century*. *Spacecast 2020* was a study conducted by Air University to identify capabilities for 2020 and beyond and the technologies to support them to preserve the security of the United States.<sup>1</sup> *New World Vistas* was a similar study conducted by the Air Force Scientific Advisory Board that focused on the next 10 to 30 years. They looked at improved Air Force capabilities, lower costs, and commercial dual use technology.<sup>2</sup> Based on the information in the above studies, solar power satellites have the potential to effect Air Force operations terrestrially and in space.

## **Terrestrial Implications**

Solar power satellites may affect terrestrial Air Force operations. One terrestrial application for solar power satellites, or the technologies associated with them, involves unmanned aerial vehicles. Unmanned aerial vehicles are used during contingencies to supplement satellite and piloted (manned) aerial reconnaissance coverage. The unmanned aerial vehicle may be powered by a wireless power transmission, which would increase its endurance. In another area, one of the core competencies of the Air Force is agile combat support, which involves reducing the footprint of deployed forces. The use of solar power satellites to supply the power at deployed locations would reduce the logistics tail by eliminating generators and the support equipment and supplies associated with them. The third area concerns public law. Public law requires the Department of Defense to develop and encourage alternative sources of energy for installations. As an alternative to electricity generated from fossil fuels, solar power satellites fit the bill admirably. Terrestrially, solar power satellites or the technology associated with them enable long duration unmanned aerial vehicles, which receive power through wireless power transmissions, allow for logistical improvements, and assist the Air Force in complying with public law.

### **Unmanned Aerial Vehicles**

Unmanned aerial vehicles help achieve information superiority. Both joint and Air Force service visions define information superiority as vital. *Joint Vision 2010* calls information superiority a technological innovation to enable dominant maneuver, precision engagement, focused logistics, and full-dimensional protection. It defines information superiority as “the capability to collect, process, and disseminate an uninterrupted flow of information while exploiting or denying an adversary’s ability to do the same.”<sup>3</sup>

*Global Engagement: A Vision for the 21<sup>st</sup> Century Air Force* expresses the Air Force's vision for the future and defines its core competencies. One of the Air Force Core Competencies it describes is information superiority. It goes on to endorse the use of unmanned aerial vehicles to "explore their potential uses over a full range of combat missions" <sup>4</sup> to achieve information superiority.

Supported by the highest levels of the Department of Defense, the use of unmanned aerial vehicles to achieve information superiority in regional conflicts is increasing. High altitude and long endurance vehicles are in development for monitoring the atmosphere, environmental impact studies, and more important to the Air Force, for communications relays, surveillance, and missile defense. <sup>5</sup> Other military uses for such vehicles are reconnaissance, targeting, target designation, and battle damage assessment. <sup>6</sup>

One of the requirements for these vehicles is that they must have long endurance, <sup>7</sup> which currently is not possible. Using a microwave beam for powered flight and to power on-board instrumentation increases the endurance of the vehicle. Theoretically, by powering the craft with a beam it would possess unlimited endurance. <sup>8</sup> The power transmitted to the unmanned vehicle could come from a solar power satellite in space or from a ground station. These vehicles would be part of a war fighting commander-in-chief's arsenal. Unmanned aerial vehicles with various detection modules would serve as near earth satellites for regional coverage of events. This is especially important in areas where satellites are not available for coverage, the revisit time of a satellite is too long, or due to limited assets, sharing of satellite time takes place.

## **Logistics**

In addition to information superiority, one of the emerging operational concepts expressed in *Joint Vision 2010* is focused logistics.

Focused logistics will be the fusion of information, logistics, and transportation technologies to provide rapid crises response, to track and shift assets even while enroute, and to deliver tailored logistics packages and sustainment directly at the strategic, and tactical level of operations.<sup>9</sup>

It goes on to say, that focused logistics will accomplish “lightened deployment loads” and “a smaller logistics footprint.”<sup>10</sup>

In addition to *Joint Vision 2010*, Air Force doctrine also describes logistics as an important part of agile combat support, one of its core competencies. One of the objectives of agile combat support is to “reduce the overall “footprint” of forward-deployed support elements.”<sup>11</sup>

Power relay satellites, a stepping stone to full solar power satellites, could supply power to deployed locations and be part of focused logistics and agile combat support. Part of the deployment planning process would be identifying the nearest power relay satellite, the coordinates for the reflecting dish, and the amount of power required by the site. The next step, after demonstrating sites powered by a relay satellite, would be employing solar power satellites instead of relaying electricity across the globe.

Using power beamed from a relay station or a solar power satellite could eliminate the power generating part of a deployment and reduce airlift. Incorporating the rectenna or the receiving part of the beam into camouflage netting or into tent tarps creates no additional infrastructure. For example, a typical joint task force communications unit for a bare base deployment requires the generators in Table 1 to supply power for the communications equipment and site. According to the Computer Aided Load Manifest software, used by logistics planners, to bring the generators into theater requires one C-17 or two C-141s.

**Table 1. Communications equipment generator requirements for deployment**

<b>Equipment</b>	<b>Generator</b>	<b>Size</b>	<b>Short Tons</b>
SHF Satellite Spoke	10 kW	150L X 84W X 69H	2.1
SHF Satellite Hub	15 kW	204L X 96W X 86H	3.87
Automatic Circuit Switch Voice	30 kW	207L X 95W X 80H	4.6
Automatic Circuit Switch Message	30 kW	207L X 95W X 80H	4.6
Site Power *	100 kW	194L X 99W X 85H	4.9

\* two are required

**Source:** Joint Communications Support Element. *C4I Planner's Guide*. Macdill AFB, FL 1998.

A Kenney Battlelab initiative on replacing aerospace ground equipment recommended alternative sources of power for airfield operations. In the report, it states power producing equipment “is repeatedly singled-out through after action reports ... as the number one airlift intensive requirement for Air Expeditionary Force deployment.”<sup>12</sup> The report recommends adopting fuel cell technology to solve the problem, however, solar power satellites or power relay satellites are also viable options.

In addition to reducing airlift, using power from a satellite would reduce the fuel required for generators, minimize hazardous emissions and waste, reduce heat signatures, and eliminate a plethora of support equipment, war readiness spares kits, tools, and spillage clean up kits.<sup>13</sup>

### **Public Law**

Several studies were conducted by the Department of Energy and the Department of Defense to research methods to comply with public law 101-510-November 5, 1990, which is reflected in Title 10, Subtitle A, Part IV, Chapter 172, section 2901 of U.S. Code. The law provides for the establishment of the Strategic Environmental Research and Development Program. The purpose of the program is to ensure that the Department of Energy and the Department of Defense “will identify and develop technology to enhance the capability of the Department of Defense and the Department of Energy to meet their environmental

obligations.”<sup>14</sup> It also requires the Department of Defense and Department of Energy to “identify technologies developed by the private sector that are useful for ... defense activities.”<sup>15</sup>

During a program developed in support of public law 101-510, Sandia National Laboratories conducted an experiment at Fort Huachuca, Arizona where they put a solar power collector to generate electricity.<sup>16</sup> Although the demonstrated collector could not power the entire site, it demonstrated the potential for solar power use on military installations. A solar power satellite could potentially beam enough power to a base to provide enough power for all its needs. Solar power satellites could provide electricity that is independent from the local power grid, secure, environmentally friendly, and complies with public law for military installations.

## Space

In addition to the terrestrial implications of solar power satellites for the Air Force, there are also implications for space operations. The power required for spacecraft operations is increasing. In order to meet this increase, engineers are looking at standardized solar cells, new gallium/aluminum solar cells and paying close attention to solar power satellite developments.<sup>17</sup> The problems associated with increasing the size of solar arrays on satellites to meet the increasing power demands are deterioration of structure dynamic performance, complications of orientation and stabilization, placing solar arrays under the launcher fairing, deploying solar arrays in orbit, buffer elements for periods without sunlight and discrepancies between the orientation of devices and solar arrays.<sup>18</sup> Engineers from the Ukraine recommend solving these problems with solar power satellites using wireless power transmission or a cable.<sup>19</sup> The authors of *New World Vistas* also recommended this approach. They advocated using space solar power satellites to power other satellites in space and predicted that “power beaming will become a major element of spacecraft operations.”<sup>20</sup> Solar power satellites would provide improvements

in the areas of reconstitution, maneuver, force application, space-based radar, and communication satellites which produce power as well as transfer data.

## **Reconstitution**

As outlined in Air University study *Spacecast 2020*, the rapid launch and deployment of satellites is required to comply with the United States National Military Strategy concept of reconstitution. Reconstitution for space is the ability to launch satellites for “unanticipated system failures ... [due to hostile actions] and multiple area coverage requirements, [which] ... require the immediate placement of satellites into orbit.”<sup>21</sup> Solar power satellites enable reconstitution with unmanned aerial vehicles performing the same functions as satellites, as mentioned previously, and through enabling smaller satellites. One of the difficulties in achieving small satellites is the fact that power generation takes up about 25% of the weight of a satellite.<sup>22</sup> Satellites launched without onboard power generation would be smaller and receive power on orbit from a solar power satellite. Solar power satellites enable reconstitution with unmanned aerial vehicles with unlimited loiter time for immediate deployment for a warfighter, and by reducing the size of satellites which facilitates rapid launches.

## **Small Satellites**

Small satellites not only fulfill the reconstitution requirement but also meet other requirements for smaller, faster, and cheaper satellites. Typically weighing less than 250 kg, and designed for one mission, “quick checkout and rapid launch,” small satellites offer advantages over larger satellites, which are more expensive, cost more to put in orbit, and take longer to build.<sup>23</sup> Small satellites are good candidates for imagery, and some types of communications.<sup>24</sup> Constellations of small satellites serve another purpose. They have reduced vulnerability and

increased survivability compared to single satellites. Powering small satellites with energy beamed from a solar power satellite further reduces their size, cost, and launch requirements.

### **Maneuver**

One of the vulnerabilities of satellites is that they lack maneuverability. Orbit changes are possible but the amount of station keeping fuel limits these maneuvers. Unscheduled orbital maneuvers for, supported warfighters, on-orbit station keeping, or avoiding an anti-satellite weapon, reduce the life expectancy of satellites. The *New World Vistas* study concluded, “technologies to substantially enhance survivability are ...maneuvering technologies...enabled by the technologies of high generation power in space.”<sup>25</sup> Moreover, the report stated that electrical propulsion and solar power satellites would enable maneuvering for survivability, station keeping, and repositioning to meet warfighter requirements.<sup>26</sup>

### **Force Application**

United States Space Command developed four operational concepts to guide their vision. One of those operational concepts is global engagement. The *USSPACECOM Long Range Plan* defines global engagement as an “integrated focused surveillance and missile defense with a potential ability to apply force from space.”<sup>27</sup> This application of force from space involves holding at risk earth targets with force from space.<sup>28</sup> *New World Vistas* identifies several force application technologies. One of the technological issues associated with developing these space force application technologies is that they all require large amounts of power generation. A solar power satellite can supply the required power. Two technologies in particular would benefit from integration with a solar power satellite, directed energy weapons, such as lasers, and jamming devices.

The space-based lasers currently under study accomplish ground moving target indication, and air moving target indication, which would be part of missile defense.<sup>29</sup> The main difficulty with the laser is designing a power plant, which can produce the required energy in space without the enormous solar arrays required. By using a solar power satellite to beam power to the laser, this eliminates the problem.

Another project, which would benefit from integration with a solar power satellite, is a device, which would beam RF power to a particular geographic location to blind or disable any unprotected ground communications, radar, optical, and infrared sensors.<sup>30</sup> As with the laser and other directed energy applications, the limiting factor right now is generating enough power in space to energize the RF beam.

### **Space-based Radar**

A space-based radar concept is currently in work at an Air Force Research Laboratory. It requires large amounts of electrical power and the engineers have found no optimum solution to the problem.<sup>31</sup> The space-based radar in use today is limited in resolution and coverage by on-orbit power.<sup>32</sup> As with the space-based laser and RF jamming device, a space-based radar receiving power from a solar power satellite eliminates this problem.

### **Communications Satellites**

A few entrepreneurs propose to place small communications satellites in huge constellations in low earth orbit. They will relay voice, video, and data to anywhere on earth using microwave beams. Motorola's Iridium program already started launching the 66 communication satellites for their constellation.<sup>33</sup> Microsoft and Mobile Telecommunications plan to launch Teledesic with 288 satellites by 2002.<sup>34</sup>

Communications satellites in low earth orbit, with the numbers the telecommunications industry plans to place in space, could provide data and electricity. Communications satellites and the power beam function of a solar power satellite could share the same frequency by “modulating the beam to provide down link data transfer.”<sup>35</sup> The satellites’ low orbit puts them closer to earth and they are very numerous, therefore, the solar collectors and rectennas could be smaller and less costly than other proposals.<sup>36</sup> Paul Glaser in his book, *Solar Power Satellites: A Space Energy System for Earth*, has a chapter on the same idea. Electrical energy and information could come from communications satellites simultaneously.<sup>37</sup> Martin Hoffert and Seth Potter stated that the “space power industry could emerge from global communications components – satellite constellations, microwave technology, ground stations, and control systems – reconfigured to transmit power.”<sup>38</sup>

Should the information and power merger occur, this would open other avenues for the Air Force to receive power at deployed locations. The numbers of satellites in these constellations assure that no site on earth will ever be out of range to receive power or data. The Air Force already purchases commercial communications satellite time for exercises and contingencies when the Air Force’s requirements exceed current military systems. In addition to purchasing the satellite time for communications, the Air Force could purchase the electrical power for deployments or exercises as well. The benefits are the same as mentioned in the logistics portion earlier, reduced airlift requirements, reduced noise, a lower heat signature, reduced hazardous emissions, and elimination of specialized spares, tools, and fuel for the generators.

## **Summary**

It is clear that solar power satellites have many implications for the Air Force. Solar power satellites fit within the framework for the future Air Force operating environment. Several

studies such as *Spacecast 2020* and *New World Vistas*, in addition to the *USSPACECOM Long Range Plan*, *Joint Vision 2010*, *Global Engagement*, and Air Force doctrine all reflect avenues for the application of solar power satellites.

Terrestrially solar power satellites enable information superiority technologies such as the unmanned aerial vehicle. Coupling an unmanned aerial vehicle with a solar power satellite enables it to loiter over an area indefinitely. Using solar power satellites to power deployed sites enables focused logistics by reducing airlift requirements, various signatures, and the logistics tail. In garrison, the use of solar power satellites to power home bases enables the Air Force to comply with public law to meet its environmental obligations. Electrical power received from a solar power satellite also enables base independence from the local power grid in times of emergencies.

In addition to terrestrial applications, solar power satellites are an enabler for space assets. The ability to rapidly reconstitute space assets is enabled by solar power satellites. With a solar power satellite on orbit, satellites launched without internal power production capabilities would be smaller and easier to launch. Small satellites are gaining popularity in an age of decreasing budgets and increasing demands for information provided from space. Solar power satellites are an enabler here also. A few solar power satellites may power a constellation of small satellites. To achieve smaller satellites, eliminate individual power production capabilities, this would then require the small satellites to receive power on orbit from a solar power satellite. To increase survivability of a satellite, new methods to increase its maneuverability are under study. Solar power satellites coupled with electric propulsion enable satellites to achieve maneuverability without decreasing operational life span. One of the reasons space-based radar has a limited viewing area is lack of enough power generating capability. Although the National Security

Strategy does not currently call for force application from space, one of the technological issues is generating enough power to enable force application technologies. A solar power satellite could supply the power required for these technologies. Coupling space-based radar with a solar power satellite enables the radar to increase its coverage. Finally, the commercial communications satellite industry is under study as a possible power-generating source. Should this occur, a deployed unit could receive its communications and power from one microwave beamed source.

### Notes

<sup>1</sup> *Spacecast 2020: Introduction*. (Maxwell AFB, AL: Air University) June 1994. 1.

<sup>2</sup> USAF Scientific Advisory Board. *New World Vistas: Air and Space Power for the 21<sup>st</sup> Century: Space Technology Volume*. Department of the Air Force, 1995. A-1.

<sup>3</sup> *Joint Vision 2010*. Chairman of the Joint Chiefs of Staff. 1997. 16.

<sup>4</sup> *Global Engagement: A Vision for the 21<sup>st</sup> Century Air Force*. USAF Chief of Staff. 1997. 14.

<sup>5</sup> Noor, Ahmea K. and Samuel L. Venneri. "Perspectives on Future Aeronautical and Space Systems." In *Future Aeronautical and Space Systems*. Edited by Ahmed K. Noor and Samuel L. Venneri. Virginia: American Institute of Aeronautics and Astronautics, Inc. 1997. 9.

<sup>6</sup> Epley, Lawrence E. "Stratospheric Aircraft, Blimps, Balloons, and Long Endurance Vehicles." In *Future Aeronautical and Space Systems*. Edited by Ahmed K. Noor and Samuel L. Venneri. Virginia: American Institute of Aeronautics and Astronautics, Inc. 1997. 218.

<sup>7</sup> *Ibid.*, 218.

<sup>8</sup> Strack, William C. *Aeropropulsion Opportunities for the 21<sup>st</sup> Century*. NASA technical memorandum 88817. Ohio: Lewis Research Center. Presented at the "Scenario for the 21<sup>st</sup> Century" Aero Engine Design Seminar. Bristol, England May 16-17, 1986. 8.

<sup>9</sup> *Joint Vision 2010*. Chairman of the Joint Chiefs of Staff. 1997. 24.

<sup>10</sup> *Ibid.*, 24, 25.

<sup>11</sup> *Air Force Basic Doctrine*. AFDD . September 1997. 35.

<sup>12</sup> Wertz, Robert O. TSgt. "Kenney Battlelab Initiative: Common Core Power Production." Unpublished report produced at the Air Expeditionary Force Battlelab. 2.

<sup>13</sup> *Ibid.*, 2.

<sup>14</sup> Diver, R.B. and D.F. Menicucci. *Dish/Stirling for Department of Defense Applications Final Report* (SAND 97-0527.UC-1302) Prepared by Sandia National Laboratories, New Mexico for the Department of Energy, 1997.1.

<sup>15</sup> U.S. Code Title 10 – Armed Forces, Subtitle A – General Military Law, Part IV – Service Supply and Procurement, Chapter 172 – Strategic Environmental Research and Development Program, section 2901. Available on line at [www4.law.cornell.edu](http://www4.law.cornell.edu).

<sup>16</sup> *Ibid.*, 3.

## Notes

<sup>17</sup> Muolo, Michale J. *Space Handbook an Analyst's Guide Volume II*. AU-18. Maxwell AFB, AL: Air University Press, December 1993. 153.

<sup>18</sup> Priskiakov, V.F. and others. "Space Vehicle Power Supply from Solar Power Satellite." European Space Agency SP-369. 1995. 135.

<sup>19</sup> *Ibid.*, 135.

<sup>20</sup> USAF Scientific Advisory Board. *New World Vistas: Air and Space Power for the 21<sup>st</sup> Century: Space Technology Volume*. Department of the Air Force, 1995. 15 and 86.

<sup>21</sup> *Spacecast 2020: Volume I*. (Maxwell AFB, AL: Air University) June 1994. J-1.

<sup>22</sup> USAF Scientific Advisory Board. *New World Vistas: Air and Space Power for the 21<sup>st</sup> Century: Space Technology Volume*. Department of the Air Force, 1995. 26.

<sup>23</sup> Bille, Matt and Erika Lichock. *Future Military Applications of Small Satellites*. AIAA 98-5254. American Institute of Aeronautics and Astronautics, Inc: 1998. Presented at AIAA Defense and Space Programs Conference and Exhibit. Huntsville, AL. October 28-30, 1998. 102.

<sup>24</sup> *Ibid.*, 102.

<sup>25</sup> USAF Scientific Advisory Board. *New World Vistas: Air and Space Power for the 21<sup>st</sup> Century: Space Technology Volume*. Department of the Air Force, 1995. ix.

<sup>26</sup> *Ibid.*, 38.

<sup>27</sup> *United States Space Command Long Range Plan Executive Summary*. Commander in Chief, United States Space Command, March 1998. 4.

<sup>28</sup> *Ibid.*, 8.

<sup>29</sup> Anderson C. and R. Thibodeaux. "Space Power Initiative at Air Force Research Laboratory's Power Division." AIAA 99-1081. Presented at the 37<sup>th</sup> AIAA Aerospace Sciences meeting and Exhibit. January 11-14, 1999, Reno, Nevada. 1.

<sup>30</sup> USAF Scientific Advisory Board. *New World Vistas: Air and Space Power for the 21<sup>st</sup> Century: Space Applications Volume*. Department of the Air Force, 1995. 85.

<sup>31</sup> Anderson C. and R. Thibodeaux. "Space Power Initiative at Air Force Research Laboratory's Power Division." AIAA 99-1081. Presented at the 37<sup>th</sup> AIAA Aerospace Sciences meeting and Exhibit. January 11-14, 1999, Reno, Nevada. 2.

<sup>32</sup> USAF Scientific Advisory Board. *New World Vistas: Air and Space Power for the 21<sup>st</sup> Century: Space Technology Volume*. Department of the Air Force, 1995. 47.

<sup>33</sup> Hoffert, Martin I and Seth D. Potter. "Beam it Down: How the New Satellite Industry can Power the World." *Technology Review* 100, no. 7 (1997) from [www.ghostweb5.epnet.com](http://www.ghostweb5.epnet.com).

<sup>34</sup> *Ibid.*

<sup>35</sup> Hoffert, Martin I. and Seth D. Potter. "Energy and Information from Orbit: Technologies for the Greenhouse Century." *Ad Astra* (Jan/Feb 98): 38.

<sup>36</sup> Hoffert, Martin I and Seth D. Potter. "Beam it Down: How the New Satellite Industry can Power the World." *Technology Review* 100, no. 7 (1997) from [www.ghostweb5.epnet.com](http://www.ghostweb5.epnet.com).

<sup>37</sup> Glaser, Peter E. and others. *Solar Power Satellites: A Space Energy System for Earth*. (New York: Wiley, 1998). 242.

<sup>38</sup> Hoffert, Martin I. and Seth D. Potter. "Energy and Information from Orbit: Technologies for the Greenhouse Century." *Ad Astra* (Jan/Feb 98): 36.

## **Part 4**

### **Conclusions**

Solar power satellites are a means to produce electrical energy in space. They collect solar power, turn it into electricity, convert the electricity into a beam of energy, and beam it to earth or another satellite. The beam of energy could be a microwave or laser. Once the beam reaches its destination, a rectenna converts it back into electricity and feeds it into the local power grid or the electrical systems of the receiving satellite. A similar concept is the power relay satellite. Electricity produced on earth is beamed into space, reflected by the satellite to some other location on earth where a rectenna converts it back into electricity and feeds it into a power grid. This technology has far reaching implications for the Air Force.

Should the Air Force pursue solar power technology it would enable many of the concepts and goals expressed in Air Force doctrine, studies, and vision statements. Unmanned aerial vehicles with indefinite loiter times become possible to enable information superiority and rapid reconstitution. Solar power satellites enable agile combat support and focused logistics by reducing the logistics footprint and airlift requirements for a deployed force. It also enables the Air Force to comply with public law to meet its environmental obligations.

Solar power technology also enables many space applications. Again, rapid reconstitution of space assets occurs with solar power satellites. With power already available, satellites for various tasks are smaller and easier to launch. They are also cheaper. Currently, the maneuver

capability of satellites is constrained. Electrical propulsion combined with electricity beamed from a solar power satellite allows satellites to maneuver at will without degrading their on-orbit life span. Many different concepts for force application are currently under study. Two of them, space-based lasers and an electronics jamming system, are limited by the amount of power current technologies can produce. Add the electricity produced by a solar power satellite into the equation and these concepts become technologically feasible. The same is true for space-based radar. Still more advantageous is the coupling of satellites to provide information services such as voice, video, and Internet access as well as power.

## **Recommendations**

The Air Force possesses many avenues to pursue this enabling technology. The Air Force could take a passive observe and see what happens role, a moderate role or pursue an aggressive role of the expressed concepts.

- The passive role of course is the simplest and least costly. Commercial utilities are starting to explore the idea of solar power satellites with the scientific community. Other nations such as Japan with limited fossil fuel resources of their own and a heavy dependence on imported fuels will lead in the development of the technology. The Air Force could see what develops and apply the technology on an ad hoc basis. The danger in this is that the current advocates of space solar power technology express the technology in terms of benefits to humanity and the global environment. A passive role on the Air Force's part may lead to a situation similar to force applications in space, where treaty and policy limits technological possibilities and applications.
- Taking on a more moderate role, the Air Force has avenues to conduct further study and research into solar power satellites. The Air Force Logistics Management Agency

regularly sponsors studies to develop new methods to achieve focused logistics and agile combat support. They could further study a transition plan from current energy production, which involves diesel generators, to power received from a relay satellite or solar power satellite. Another place to conduct further study is at the Air Force Research Laboratory's Power Division located at Wright Patterson Air Force Base, Ohio where they focus on power generation for satellites. Other areas of solar power satellites that require further study are its vulnerabilities, and measures a hostile force could take against a deployed force to deny them power. A possible counter measure could be to encrypt the beam.

- Another moderate role option for the Air Force involves the potential for communications frequency interference by a beam of a solar power satellite. Currently, only limited experimentation has occurred about the effects of the beam on communications frequencies. This is particularly important for a deployed unit, since most if not all of their external communications will be over communications satellites.
- A third moderate role option for the Air Force is a cost analysis of the Air Force investing in its own solar power satellites or buying power from a commercial solar power satellite. A question to consider, does the Air Force have a large enough deployed power requirement to justify satellites dedicated to its use? Instead of a solar power satellite, would a power relay satellite better serve the needs of the Air Force? Solar power satellites could be treated the same way extra airlift and bandwidth are treated. The Air Force purchases them on an as needed basis from civilian commercial providers.

- The final moderate role option involves research into the implications for the Air Force for solar power satellite use by other nations. Due to the high cost, many nations are considering cooperative agreements to share the initial costs and benefits. Japan already entered such an agreement with five other nations. Should a conflict arise with only one member of such a cooperative agreement, how does the Air Force go about targeting the power of that country, especially when it has the potential to effect other countries that the United States has no issues with at the time? Another hypothetical case involves international control of the satellites with the rectennas owned by the hosting nation. A likely scenario in a conflict would be to deny the hostile country power simply by a diplomatic agreement not to send a power beam to them. Since solar power satellites likely development path involves multiple nations or multinational businesses, it is likely to cause complicated targeting situations and require creative problem solving for solutions.
- An aggressive role on the Air Force's part would be to actually allocate monies into the budget for technological demonstrations sponsored by the military. These demonstrations should build upon the work already conducted. A good place to start would be unmanned aerial vehicles powered with wireless power transmissions from the ground. Considering the high demand for these assets in regional conflicts, it would not take long to prove or disprove their application.

There exist a number of avenues the Air Force could explore concerning solar power satellites. One course of action is a wait and see what happens, which has the pitfall of creating complications later. The Air Force could take a more moderate approach and sponsor research and studies that use electricity generated by solar power satellites. Such studies would involve

transition plans, satellite power usage, vulnerabilities, frequency interference, cost analysis, and target selection.

As an enabling technology, solar power satellites fit well within Air Force doctrine, core competencies, joint doctrine, and many studies of future technologies. The Air Force should pay close attention to its development if not actively promote its development. The concept requires further research to address the implications fully.

## *Bibliography*

- Air Force Basic Doctrine*. Air Force Doctrine Document 1. Secretary of the Air Force. September 1997.
- Anderson, C. and R. Thibodeaux. *Space Power Initiative at Air Force Research Laboratory's Power Divisions*. AIAA 99-1081. Presented at the 37<sup>th</sup> AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nevada, January 11-14, 1999.
- Bekey, Ivan and Richard Boudreault. "An Economically Viable Space Power Relay System." *Space Energy and Transportation* 3, no. 3 (1998): 157-166.
- Bille, Matt and Erika Lishock. *Future Military Applications of Small Satellites*. AIAA-98-5254. Presented at AIAA Defense and Space Programs Conference and Exhibit, Huntsville AL, October 28-30, 1998.
- Boucher, Robert J. *Starduster: A Solar Powered High Altitude Airplane*. AIAA-85-1449. Presented at the 21<sup>st</sup> Joint Propulsion Conference, Monterey, CA, 1985.
- Dickinson, Richard M. "Lasers that Beam Power to Earth." *Aerospace America* (July 1999): 50-54.
- Diver, R.B. and D.F. Menicucci. *Dish/Stirling for Department of Defense Applications Final Report*. SAND97-0527. UC-1302. Prepared by Sandia National Laboratories New Mexico for the Department of Energy, 1997.
- "Emerging Space Industries for the Next Century." *Space Business News*, 31 March 1999, 4.
- Epley, Lawrence E. "Stratospheric Aircraft, Blimps, Balloons, and Long Endurance Vehicles." In *Future Aeronautical and Space Systems*, edited by Ahmed K. Noor and Samuel L. Venneri. Virginia: American Institute of Aeronautics and Astronautics, Inc., 1997.
- Glaser, Peter E. "A Global Perspective on Renewable and Solar Energy." *The Journal of Social, Political and Economic Studies* 19, no. 1 (Spring 1994): 3-12.
- Glaser, Peter E. and others. *Solar Power Satellites: A Space Energy System for Earth*. New York: Wiley, 1998.
- Global Engagement: A Vision for the 21<sup>st</sup> Century Air Force*. Secretary of the Air Force. 1997.
- Harmats, M. and D. Weihs. "Hybrid Propulsion High Altitude Long endurance Remotely Piloted Vehicle." *Journal of Aircraft* (March-April 1999): 321-331.
- Hoffert, Martin I. and Seth D. Potter. "Beam It Down: How the New Satellites can Power the World." *Technology Review* 100, no. 7 (1997): np. Available on-line [www.ehostwebs.epnet.com](http://www.ehostwebs.epnet.com).
- Hoffert, Martin I. and Seth D. Potter. "Energy and Information from Orbit: Technologies for the Greenhouse Century." *Ad Astra* January/February 1998, 36-39.
- Joint Vision 2010*. Chairman of the Joint Chiefs of Staff. 1997.
- Kaya, Nobuyuki. "Japan's Solar Systems." *Ad Astra* January/February 1998, 40-45.
- Joint Communications Support Element. *CAI Planner's Guide*. Macdill AFB, FL 1998.
- Muolo, Michael J. *Space Handbook Analyst's Guide: Volume II*. AU-18. Maxwell AFB, AL: Air University Press, December 1993.

- Nansen, Ralph. *Sun Power: The Global Solution for the Coming Energy Crisis*. Canada: Ocean Press, 1995.
- National Power Research Institute, Inc. "Space Based Solar Energy: A Brief Review and Analysis. 1998. On-line Internet, 25 October 1999. Available from <http://www.nspri.org>.
- Noor, Ahmed K. and Samuel L. Venneri. "Perspectives on Future Aeronautical and Space Systems." In *Future Aeronautical and Space Systems*, edited by Ahmed K. Noor and Samuel L. Venneri. Virginia: American Institute of Aeronautics and Astronautics, Inc., 1997.
- Prisniakov, V.F. and others. "Space Vehicle Power Supply from Solar Power Satellite." *ESA SP* 369 (1995): 135-138.
- Spacecast 2020: Introduction*. Maxwell AFB, AL: Air University, June 1994.
- Spacecast 2020: Volume I*. Maxwell AFB, AL: Air University, June 1994.
- Strack, William C. Aeropropulsion Opportunities for the 21<sup>st</sup> Century. NASA Technical Memorandum 88817. Ohio: Lewis Research Center. Presented at the "Scenario for the 21<sup>st</sup> Century Aero Engine Design" Seminar Bristol England, May 16-17, 1986.
- United States Air Force Scientific Advisory Board. *New World Vistas: Air and Space Power for the 21<sup>st</sup> Century: Space Technology Volume*. Department of the Air Force, 1995.
- United States Air Force Scientific Advisory Board. *New World Vistas: Air and Space Power for the 21<sup>st</sup> Century: Space Applications Volume*. Department of the Air Force, 1995.
- U.S. Code Title 10 – Armed Forces, Subtitle A – General Military Law, Part IV – Service Supply and Procurement, Chapter 172 – Strategic Environmental Research and Development Program, section 2901. Available on line at [www4.law.cornell.edu](http://www4.law.cornell.edu).
- United States Space Command Long Range Plan*. Commander in Chief. USSPACECOM. March 1998.
- Wertz, Robert D. "Kenney Lab Initiative: Common Core Power Production." Draft report to start an alternative power source demonstration at the Air Expeditionary Force Battle Lab.

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