6.0 Conclusions and Recommendations

6.1 The Value of Space to the Air Force

The foundation of the New World Vistas study is a vision of the 21st century and how the Air Force will do business in the future. One current trend that will almost certainly continue is the demand that the Air Force do more with less; hence the directive to the Space Technology Panel to identify technologies that fundamentally increase US capabilities in space and significantly lower the costs of operating there. High-risk/high-payoff technologies have traditionally been funded by DoD, where each service keenly recognizes the necessity of keeping the technological edge on the battlefield.

The Air Force must maximize its return on its investment in technology. Although today space may be the Air Force's "best kept secret," space assets proved their worth during Operation Desert Storm and the Air Force's use of space will only increase in the future. Space provides unparalleled access to regions of potential conflict. Space assets are timely, with low-earth-orbiting platforms spanning the globe in 90 minutes and geostationary satellites offering continuous coverage of large areas of the earth. Such an expanding area of operations offers a large payback for technologies that can improve affordability and capability.

6.2 Visions of Spacecraft Technology

The technology of placing a payload outside the earth's atmosphere and having that payload perform a useful task has steadily evolved since the early days of rocketry in the 1940's. This evolutionary process will continue. The Air Force should invest in technologies that steadily improve future generations of space systems, but the highest payoff will be found in areas that fundamentally change the way the Air Force does business in space, whether by enabling new capabilities or significantly reducing costs.

6.2.1 The Evolution of Space Technology in Coming Decades

Over the near term, the driver for space systems will be reducing the cost to perform a particular function in space, which means reducing the life-cycle costs of a given space system. Life-cycle costs consist of three elements:

- The cost to develop and produce the spacecraft
- The cost to launch the spacecraft
- The cost to operate the spacecraft

Historically, the cost to build and launch a spacecraft has scaled, to lowest order, with its mass. This empirical truth is a function of the current paradigm for space. Air Force space payloads share several common characteristics. They are typically:

- Large (10,000 lb)
- Expensive ($40,000/lb to develop, independent of launch costs)
- Essentially custom built
- Multi-mission or multi-function

- Independent of other spacecraft
- Controlled in detail from the ground

The current paradigm presents several disadvantages. Because space assets are so expensive, failure of a system is prohibitably costly. Thus, systems are conservatively designed, based on known and trusted technologies, and rigorously tested (which drives up costs). Systems are called on to perform many tasks rather than being optimized for one role. Although a serious antisatellite (ASAT) threat has not materialized to date, the cost, both in dollars and in functionality, of losing even one satellite to hostile action would be extremely high. The infrastructure, both in equipment and personnel, to operate these platforms is significant. Over the near term, the economic driver for space systems is likely to be dollars/pound to orbit, which argues for technologies that:

- Reduce the cost of launching a given mass
- Reduce the mass of a given payload capability

The most basic problem of space operations, namely, placing a payload in orbit, has historically been solved with chemical rockets. No competing technologies are sufficiently mature to break this monopoly in the coming decade. Therefore, the coming decades will likely see evolutionary changes in launch vehicle technologies that will, over time, yield significant cost savings. There are two paths along which chemical rockets can evolve:

- Expendable launch vehicles
- Reusable launch vehicles

The costs of expendable launchers could be reduced by increasing the payload mass fraction. The ideal chemical rocket would consist of nothing but payload and fuel; the mass of the structure devoted to storing the fuel, moving it, and combusting it in a controlled fashion (the tanks, engines, etc.) is vital to the function of the rocket but is dead weight from the standpoint of payload to orbit. If the components of the launch vehicle could be made of very lightweight materials, then the portion of the mass lifted into orbit that is useful payload would increase and the cost per pound would decrease.

Other economies could be realized by making expendable vehicles simpler to manufacturer and to operate. Exotic materials that are difficult (and hence expensive) to work with and result in marginal weight savings increase the cost of placing a given payload in orbit. Reducing the number of manufacturing steps is another avenue for reducing costs. Finally, reducing the costs of operating the launch vehicle and the number of personnel required to launch it is a means of cost reduction.

Overall, the foreseeable cost reductions of advanced expendable launcher technologies are on the order of factors of 30-50%, which is significant only in the short term.

The same technologies that could be applied to increasing payload mass fraction and simplifying manufacturing and operation of expendable launch vehicles could also be applied to reusable launch vehicles, which would offer the additional economic advantage of spreading the cost of the vehicle itself over many launches. The key to the success of a such a launch vehicle would be making as much of it as possible truly reusable, more like an aircraft that requires only refueling and some routine maintenance between flights than a rocket or even the Space Shuttle, which requires significant refurbishment between flights. Materials technologies that would allow engines to operate at high-temperatures without damage, or that would enable the use of non-ablative heat shields upon reentry, would allow the reusable launch vehicle concept to be economically viable. The reusable launch vehicle offers possible cost saving of an order of magnitude or more over the present state of the art, and thus is a more viable concept for the long term.

Reducing the cost of a particular payload capability centers on two approaches:

- Building payload components from lightweight materials
- Reducing the size of payload components

Some of the same materials technologies that could be used to decrease the mass of a launch vehicle could be used to reduce the mass of a payload structure as well. Furthermore, any spacecraft, regardless of its mission, must perform certain basic functions. It must generate or gather power, store energy for later use, convert prime power into electrical power to run its other systems, communicate with the ground, and manage its attitude and configuration. A satellite or other payload would benefit from technologies that allow power generation and conditioning, and energy storage in lower-mass packages, or from lightweight deployable antennas or solar panels. Some technologies, such as optical computing, may allow for both increased performance and reduced mass for data buses as copper wires are replaced with glass fibers.

Miniaturization of components offers multiple benefits; smaller components are not only less massive in their own right, but typically require less power, shorter interconnects, etc., reducing demands on the supporting systems of the spacecraft. Micro-machining techniques, the descendants of integrated circuit technologies, offer the prospect of orders of magnitude decreases in the size of some components.

Decreased payload mass and decreased cost/pound are complementary approaches to reducing the overall cost of performing the Air Force mission in space.

6.2.2 A New Paradigm for the Air Force in Space

The Air Force should try to develop not only those technologies that incrementally improve capabilities in space, but those that enable a radical change in the present paradigm for activities in space. One can reasonably project technologies that, over the next few decades, would allow the Air Force to abandon the current mode of operation in favor of another where its space payloads would be:

- Small (less than 1000 lb)
- Inexpensive
- Mass-produced
- Optimized for a single function
- Networked with other space assets

- Highly autonomous

In addition, one can project technologies that would make much higher levels of power available to spaceborne assets. This would enable many capabilities that at present do not exist, whether in the areas of communications, active sensing, or force application. Under this model, each space asset would operate as part of a larger system in space. This approach offers several advantages. Systems of satellites would be inherently more robust than a single satellite performing the same function; if any single satellite were to fail or be destroyed, the system as a whole would continue to operate. The system itself could be reconstituted or upgraded by launching new payloads. Autonomous systems by their nature would require a smaller infrastructure to operate. The goal of greater capabilities at lower cost would become attainable.

6.3 An Investment Strategy for Technologies

The reduction of resources available to the DoD in the post-Cold War era means that DoD investment in space technologies and space systems must be firmly rooted in the goal of affordable systems. To this end, the DoD must plan its technology investment with a clear view of technological advances in the commercial world. It is undesirable and unnecessary for the DoD to develop every technology for its space systems on its own. There are many technologies that the commercial sector will develop that the military can adapt for its use with minimal investment. On the other hand, there will always be unique requirements for military systems that necessitate the use of technologies that have no commercial application, that push the performance limits of dual-use technologies, or whose timescale and risk are not attractive to the commercial sector. The DoD should carefully target its investments in technology to achieve the highest possible return. Technologies that are candidates for DoD investments fall into one of three possible categories:

- Revolutionary technologies in which the DoD must invest vigorously, because they are critical to the military mission and have little or no application in the commercial sector; without DoD investment, these technologies will not advance. These technologies will enable a *substantial increase in the exploitation of space* by the DoD. They will enable functions that are currently unaffordable or technically impossible.

- Evolutionary technologies in which the DoD should invest, because they are similarly critical to the military mission and have little or no commercial application. These technologies will enable gradual improvements that over time can significantly improve the performance or reduce the life-cycle costs of military systems.

- Technologies in which little DoD investment is required, because they will be led by the commercial sector. In these areas, the DoD should carefully monitor the progress that industry is making and invest only to the level necessary to adapt commercial technologies to the military mission.

The DoD should not underestimate the benefits of a healthy synergism between military and commercial research and development.

6.3.1 Revolutionary Technologies in Which the Air Force Must Invest

Several key technologies offer the possibility of a substantial increase in the exploitation of space by the Air Force, the potential impact of which is so great that the Air Force must invest now. The first three of these technologies will enable much larger payload fractions to be lifted to orbit by factors of four or more and combined with affordable operations will enable much cheaper access to orbit. Therefore they have the potential to revolutionize the launch equation and remove the significant barrier that high launch costs impose. These technologies are:

- High-energy-density chemical propellants to enable spacelift with high payload mass fractions—specific impulses of 1000 seconds or greater (in high-thrust) systems should be the goal of this effort
- Lightweight integrated structures combining reusable cryogenic storage, thermal protection, and self diagnostics to enable a *responsive* reusable launch capability
- High-temperature materials for engines and rugged thermal protection systems

The next two technologies will enable space-based weapons such as high power lasers, space-based radars with wide search areas and satellites that can maneuver almost at will. They have the potential to substantially remove orbital dynamics as a barrier to where satellites can go. These technologies are:

- High performance maneuvering technologies such as electric propulsion (with thrusts greater than tens of Newtons at specific impulses of thousands of seconds at near 100% efficiency the goal for electric propulsion) and tethers for momentum exchange
- Technologies for high power generation (greater than 100 kiloWatts) such as nuclear power, laser power beaming, and electrodynamic tethers

The final set of technologies will enable a new vision for space applications where functionality is spread over many satellites rather than only in a single satellite. They have the potential to enable new applications from space (such as Global Awareness) at affordable cost. These technologies are:

- Technologies for clusters of cooperating satellites (e.g., high-precision stationkeeping, autonomous satellite operations, and signal processing for sparse apertures)

6.3.2 Evolutionary Technologies in Which the Air Force Should Invest

The Air Force should invest for evolutionary improvements in performance or reduced life-cycle costs to its systems. The technologies that offer such benefits are:

- Launch vehicle technologies
  - Engines, upper stages, and solar thermal propulsion
  - Vehicle structures (e.g., aluminum-lithium or advanced composite tankage, as well as multifunctional structures)

- Satellite bus technologies
  - Structure technologies (e.g., lightweight structures, active vibration suppression, precision deployable structures, and software-controlled multifunctional surfaces)
  - Innovative energy storage technologies (e.g., the electromagnetic flywheel battery)
  - Attitude control technologies, including attitude sensors and attitude control system (ACS) algorithms
  - Radiation hardening technologies for spacecraft electronics
  - Low-observable technologies
  - Microelectromechanical systems (MEMS) technologies
- Sensor technologies
  - Large, sensitive focal plane arrays and associated readout and cooler technologies for hyper- and ultraspectral sensing of small low-contrast targets and long-wavelength detection against the cold background of space
  - Active sensor technologies (e.g., large lightweight antennas, high-efficiency radiofrequency (RF) sources for synthetic aperture radar (SAR) and moving target indicator (MTI) radar, and high-energy lasers for lidar)
  - MEMS (including on-chip optics)
- Communications technologies
  - Very high-rate, long-distance optical communications
  - Multi-beam adaptive nulling antennas
- Data fusion technologies, including automatic target recognition
- Space-based weapons technologies
  - Laser weapons technologies (e.g., large lightweight optics)
  - Technologies for smart interceptors (e.g., autonomous guidance, MEMS)
  - RF weapons technologies (e.g., lightweight energy storage) for electromagneticpulse (EMP) and jamming

6.3.3 Commercially Led Technologies

Another set of technologies that will allow for evolutionary change in Air Force space operations will be driven by the commercial sector. These technologies merit minimal investment by the Air Force, yet the Air Force should invest as necessary to adapt these technologies to its needs. These technologies are:

- Small launch vehicles

- High-efficiency energy conversion and storage
- High-data-rate RF communications
- Technologies for debris reduction
- Information storage, retrieval, and processing technologies and protocols
- Image processing, coding, compression, and very large scale integration (VLSI) architectures
- Neural networks and artificial intelligence
- Technologies for spacecraft manufacturing
- Technologies for vehicle and spacecraft operations

6.3.4 Recommendations for Management Improvements

Space technology development occurs currently under NASA, DoD, NRO, DoE, and industry auspices. Execution of the resulting programs is only loosely coordinated through teaming, informal communication between investigators, professional society fora, and ad hoc topical organizations. Planning of the technology investment and programs by the various agencies is largely independent and uncoordinated. To create an efficient, coherent national space technology strategy, the Air Force should take the lead in establishing collaborative planning, advocating appropriate changes to US Space Policy, and encouraging coordinated execution of space technology development among all these organizations.

The chance to exploit commercial leads in some space technologies presents the opportunity for reduced government technology investment, reduced cycle time, and lower cost space systems, but, the ability to reap those benefits requires the discipline to accept the constraints of commercial capability in acquisition and in technology investment.

The recommended revolutionary and evolutionary technologies will provide the greatest benefit to the Air Force in the future and will not be developed by the commercial and civil communities. The least expensive route to meet the future needs in space is a sustained government investment and continuity of effort.

In conclusion, the Space Technology Panel has determined:

- The international exploitation of space services will grow
- The Air Force will be able to take advantage of complementary commercial investment
- There are revolutionary technologies that will enable a new vision for the Air Force in space
- To effectively support the warfighter from space, active and sustained investment in these revolutionary technologies is essential