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The Aerospace Corporation magazine
of advances in aerospace technology

Space Launch Vehicle Reliability

[I-Shih Chang](#)

The 1993 failure of a Titan IV K-11 launch vehicle prompted the U.S. Air Force to request The Aerospace Corporation's participation in an analysis of space-mission failures. I-Shih Chang led the Aerospace study, which was later expanded to support the DOD Broad Area Review of U.S. launch failures between 1985 and 1999. This article is the second in the *Crosslink* series on the history of the corporation's role in national space programs.

When you get into your car and insert the key in the ignition, you expect the car to start. You expect to pull away from the parking spot and drive to your destination without a problem. These expectations are based on the assumption that your vehicle is reliable—you can depend on it to behave the same way time after time. This ideal applies to launch vehicles as well. If the vehicle has been designed, built, and tested well, we expect it to successfully leave its launchpad. But just as personal vehicles can fail in unforeseen ways (radiators leak, engines stall), so too can launch vehicles occasionally fail.

Launch failures have been a fact of life for most space-faring nations since the space age began in 1957. Because a space mission involving a launch vehicle and a sophisticated satellite can easily cost hundreds of millions of dollars, investigation into why launches fail can provide valuable information for improving vehicle systems and cost savings. Any lessons learned from past experiences that could serve to mitigate launch failures in the future would make such an investigation extremely worthwhile.

A space launch failure is an unsuccessful attempt to place a payload into its intended orbit. This definition includes all catastrophic launch mishaps involving launch vehicle destruction or explosion, significant reduction in payload service life, and extensive effort or substantial cost for mission recovery. It also includes the failure of the upper stage of a launch vehicle, up to and including spacecraft separation on orbit. However, this definition does not include the failure of an upper stage released from the U.S. space shuttle. The U.S. space shuttle is both a launch vehicle and a space vehicle. An upper stage released from the space shuttle in orbit is considered a transfer vehicle, not a launch vehicle.

The space age began with the USSR launch of the first artificial satellite, a liquid-fueled Sputnik (SL-1), on October 4, 1957 (see sidebar, [A Brief History of Rocketry](#)). At present, nine countries or consortia—the United States, the Commonwealth of Independent States (CIS, formerly USSR), the European consortium, China, Japan, India, Israel, Brazil, and North Korea—possess space launch systems, demonstrate space launch capability, or conduct space launch operations.

Many current major space launch systems are based on



Titan IV, the Air Force's premier heavy lift vehicle, launched from Vandenberg Air Force Base on November 28, 1992. (Lockheed Martin Corporation)

early ballistic-missile technology, which regarded launch costs and schedules a higher priority than launch quality and reliability. The design of these space launch systems left much room for improvement, as demonstrated by launch failures of the past.

Financially, much is at stake in any kind of space launch. A small launch vehicle, such as the U.S. Pegasus, costs about \$15 million, but a versatile, reusable launch vehicle, such as the U.S. space shuttle, costs well over \$1 billion. A small experimental satellite can be purchased for a few million dollars, but an advanced spy satellite or scientific satellite may cost more than \$1 billion. Furthermore, the possible monetary loss calculated for a launch failure does not include the expense, time, and effort spent during the recovery period or the cost of the damage to national prestige. Analysis of space launch failures is critical to a national space program's future success.

A systematic look at worldwide launch successes as well as failures, including scrutiny of various launch vehicle subsystems, can shed light on precise areas that might be at the root of many problems. This type of study can also help suggest what actions to take to address those problems.

Worldwide Space Launches

To understand space launch reliability, it is helpful to examine the history of launches worldwide since 1957. The progress made in space science and engineering during this period has been truly remarkable, as illustrated by the achievements of the United States and the CIS/USSR, the nations that have dominated the space launch arena.

To get an idea of how great that progress is, consider that in 1957 the USSR's Sputnik 1 weighed only 83.6 kilograms, and on July 16, 1969, the U.S.'s Saturn V, the largest and most powerful operational rocket ever built, lofted Apollo 11, with a mass of 43,811 kilograms, to lunar orbit during the moon-landing mission. Today, the U.S. Space Transportation System routinely launches the shuttle orbiter, weighing more than 110,000 kilograms, to low Earth orbit. The orbiter flies like a spacecraft and lands like a glider.

The USSR was the first country to place a satellite carrying a person into Earth orbit. Its Soyuz vehicle has been statistically shown to be the most reliable expendable launch vehicle in the world. Since 1957, CIS/USSR has carried out more space launches than all other countries combined. Between 1957 and 1999, 4378 space launches were conducted worldwide, including 2770 CIS/USSR launches and 1316 U.S. launches.

These figures include launches carried out individually by France and the United Kingdom (U.K.) over 25 years ago. France was the third country (after CIS/USSR and the United States) to attain space launch capability, with Diamant, a rocket that placed a satellite in orbit in 1965. The U.K. developed a small vehicle, Black Arrow, which was launched successfully in 1971.

Currently, France and the U.K. participate through the European Space Agency (ESA) in the development of the Ariane launch systems. (The ESA is composed of 14 European nations.) The Ariane vehicles are launched from French Guiana in South America, which is only 5.2 degrees north of the equator and is therefore an excellent location for launching satellites into geosynchronous orbit. Recently, the European consortium has been catching up to CIS/USSR and the United States and capturing a large share of the commercial space launch service market formerly dominated by U.S. launches. From 1995 to 1999, the European consortium consistently conducted 10 or more launches per year.

China and Japan have also invested heavily in space programs. China's government publicized its first two successful space launches—in 1970 and 1971—as great national achievements in science and engineering. The Chinese CZ-2C vehicle holds a perfect record for Chinese launchers of 11 launch successes. Over the last few years, the Chinese government has made considerable investment in improving its launch-base infrastructure to gain a greater share of the commercial space market.



An early morning liftoff of the space shuttle Discovery from Kennedy Space Center on November 27, 1989. (Photo courtesy of NASA)



Delta II launched in 2000 from Vandenberg Air Force Base, California. (U.S. Air Force, 30th Space Wing, VAFB)

In Japan, the National Space Development Agency (NASDA) and the Institute for Space and Astronautical Science (ISAS) are responsible for space research and development. The NASDA H-II and ISAS Mu-5 vehicles use state-of-the-art technology and represent the Japanese government's commitment to becoming a major player in space. Japan had an 18-year streak (1977–1994) of successful consecutive space launches.



Scout lifting a radar calibration satellite into orbit in June 1993. (U.S. Air Force, 30th Space Wing, VAFB)

The remaining nations whose launches have been tracked have, for the most part, conducted space programs for very brief time periods. They have experienced mixed success records. India, undaunted by a series of technical setbacks and launch failures in its fledgling space program, allocates a significant portion of its yearly budget to space technology development. Israel's Space Agency launched its first satellite with the Shavit launch system on September 19, 1988. Its third satellite, launched April 5, 1995, contains surveillance equipment designed to provide reconnaissance and military observation.

Brazil's satellite launch attempts using the Veiculo Lançador de Satélites (VLS)—"satellite launch vehicle"—from the Alcântara launch site failed on November 2, 1997, and December 11, 1999. North Korea claimed to have successfully launched the small Kwangmyongsong-1 satellite into orbit by a Taepo Dong-1 vehicle on August 31, 1998. But other countries have received no signal from it, and the launch is considered a failure (third-stage malfunction).

Australia launched a small Sparta (SPecial Anti-missile Research Tests, Australia) vehicle in 1967, which was a modified U.S. Redstone rocket. Today Australia does not have its own launch system. The Woomera Rocket Range in Australia is currently dedicated to weapons and sounding rocket testing.

It is also worth noting that since the end of the Cold War, national boundaries in the space launch business have become less distinct. Companies throughout the world have been marketing CIS/USSR launch vehicles for commercial launch service: Proton by Lockheed Martin, Zenit by Boeing, Kosmos by Cosmos U.S.A., Soyuz by a France-Russia consortium, and Rokot by a Germany-Russia consortium.

Space Launch Failures

Of the 4378 space launches conducted worldwide between 1957 and 1999, 390 launches failed (the success rate was 91.1 percent), with an associated loss or significant reduction of service life of 455 satellites (some launches included multiple payloads). A brief look at some of the most publicized, critical launch failures around the world will highlight the nature of system failures (see chart, [Launch Successes and Failures, 1957–1999](#)).

In the United States, 164 space launches failed, with an associated loss or significantly reduced service life of 205 satellites (see chart, [U.S. Launch Successes and Failures, 1957–1999](#)). Most of the U.S. space launch failures (101 out of the 164) occurred during the first 10 years of space exploration (1957–1966). In that period, the United States was diligently attempting to catch up to the USSR, which had gained an early lead in space exploration. The first space launch failure involved a U.S. Vanguard vehicle, which exploded two seconds after liftoff on December 6, 1957. The failure, which attracted tremendous public attention and criticism in the wake of two successful USSR Sputnik flights, was the result of a low fuel tank and low injector pressure that allowed the high-pressure chamber gas to enter the fuel system through the fuel-injector head. A fire started in the fuel injector, destroying the injector and causing a complete loss of thrust immediately following liftoff.

The U.S. Saturn V had a single failure in the Apollo 6 mission on April 4, 1968, when the third-stage engine failed to restart because of fuel-injector burnthrough. The versatile Space Transportation System also suffered a single launch failure on January 28, 1986, when the Challenger, carrying a seven-member crew, exploded 73 seconds into flight. The launch management had waived the temperature-dependent launch commit criteria and launched the vehicle at a colder temperature than experience indicated was prudent. At such a low temperature, the rubber O-rings in the motor case joint lost their resiliency, and the combustion flame leaked through the O-rings and case joint, causing the vehicle to explode. The newly developed U.S.

commercial launch systems, including Delta III, Conestoga, Athena, and Pegasus, suffered launch failures during their early developmental flights, a repeat of Vanguard, Juno, Thor, and Atlas failures in the late 1950s and early 1960s.

CIS/USSR experienced an impressive number of space launches and a strong launch success rate in the past. However, the number of space launches and the success rate in recent years have declined, mainly because of domestic financial problems. From 1996 to 1999, for example, the United States conducted more space launches than CIS/USSR for the first time in 30 years.

Space launch failure in a closed society like the USSR or the People's Republic of China was guarded as a state secret and not publicized in news media. Recently, though, because of "glasnost" in Russia, commercial competition, and requirements by the launch service insurance company, information flow on space activities has improved dramatically. Since the collapse of the USSR on December 26, 1991, CIS has released information on many USSR space launch vehicle failures that were not previously known to the West. Making this information accessible has provided a much more complete picture of worldwide space launches, although the vast amount of information existing in CIS/USSR from both successful and failed launch operations is yet to be assimilated by space launch communities of the world.

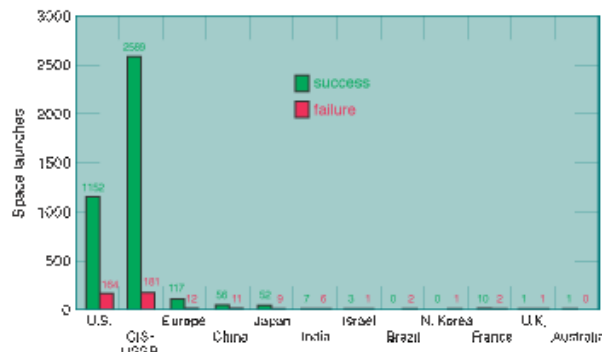


Atlas vehicle carrying the DSCS III B13 spacecraft into orbit in October 1997. (Lockheed Martin Corporation)

One CIS/USSR space launch failure involved an SL-12 Proton vehicle carrying a Mars-96 spacecraft on November 16, 1996. The second burn of the Proton's fourth stage did not take place, and the spacecraft did not reach the interplanetary trajectory. It reentered Earth's atmosphere over the South Pacific Ocean. For lack of funds, CIS launched this spacecraft without conducting a prelaunch systems checkout at the launch site. Some of the mechanical integration of the spacecraft and launcher was carried out by the light of a kerosene lantern (electrical power had been cut off because of unpaid bills). Tight funding also made ground control difficult, even during the critical period immediately following launch. The spacecraft itself commanded the fourth-stage release, indicating that it had possibly sent incorrect commands. It took 10 years to complete the \$300 million Mars-96 spacecraft carrying two dozen instruments supplied by 22 countries. This launch failure stalled plans for gathering valuable data about the planet Mars.

The failures of the European Launcher Development Organization (ELDO) Europa vehicle were reminiscent of the early launch failures in the U.S. space program. (ELDO was one of the predecessors of ESA.) After terminating the Europa program, Europe spent many years planning the Ariane launch systems, which have experienced eight failures since 1980.

A recent failure involved a new Ariane-5 vehicle, the most powerful in the Ariane family. During its maiden flight on June 4, 1996, it veered off its flight path and exploded at an altitude of 3700 meters only 40 seconds after liftoff. The failure was attributed to errors in the design and testing of the flight software. The flight software was programmed for Ariane-4 launch conditions, but it was never tested in conditions that simulated Ariane-5's trajectory. The more powerful Ariane-5 travels at a much faster horizontal velocity than the Ariane-4. Significant horizontal drift caused an overflow error in the inertial reference system (IRS) software, halted the primary and backup IRS processors, and resulted in the total loss of accurate flight guidance information.



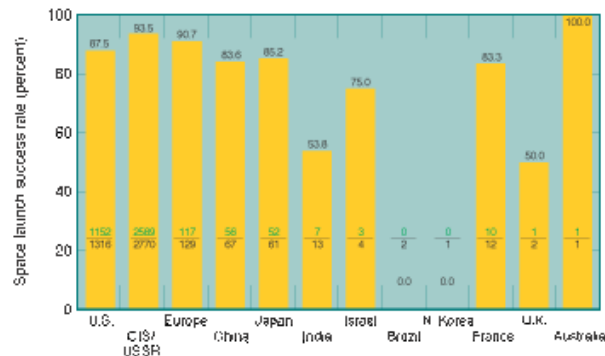
The number of successful and failed launches for the space-faring nations of the world between 1957 and 1999. The CIS/USSR has carried out more launches than all other countries combined.

From 1991 to 1996, the Chinese space launch record was marred by five failures. The most catastrophic failure occurred during the launch of a CZ-3B vehicle carrying a commercial satellite, Intelsat 708, on February 14, 1996. The 55-meter-tall CZ-3B is China's most advanced vehicle. On its maiden flight, the CZ-3B began to veer off course two seconds after liftoff, before it even cleared the tower at the Xichang launch site. The vehicle and its payload hit the ground and exploded in an inhabited area near the launch site 22 seconds after liftoff. The explosion demolished a village and a nearby military base, and caused severe casualties and property damage.

The cause of failure was traced to the CZ-3B's guidance and control subsystem. A gold-aluminum solder joint in the output of one of the gyro servo loops failed, cutting electrical current output from the power module and causing the inertial reference platform of the vehicle's guidance and control system to slope. This caused computers to send the vehicle veering off the planned trajectory shortly after liftoff. The failed module was the only one of six similar modules that lacked conductive adhesive to reinforce the solder joint.

Japanese liquid-propellant rockets (H-II) suffered two launch failures during 1998 and 1999. Japan's other seven launch failures (including four Lambda-4S failures during the period 1966-1969) involved solid-propellant rockets. One of the failures occurred on January 15, 1995, during the last flight of the Mu-3S-II vehicle. At 103 seconds after launch, the vector control thrusters, which partly control the rocket's pitch, began to oscillate. The rocket veered off course at 140 seconds after liftoff.

The payload of the Mu-3S-II, a German satellite (Express 1), was put in the wrong orbit of 120 kilometers altitude, instead of the intended orbit of 210 kilometers altitude. The satellite, which fell into a jungle in Ghana after circling Earth two and a half times, failed because of improper modeling of the flight control dynamics relative to the weight of the payload. (Prior to the failure, the heaviest payload carried by the Mu-3S-II had been 430 kilograms; Express 1 weighed 748 kilograms.) Extra propellant had been added to the three stages and to the kick motor of the vehicle to provide extra thrust for the flight of the Express 1 satellite. The flight was the eighth and final mission of the Mu-3S-II vehicle.



Each space-faring nation's launch success rate as a percentage of its total launches.

Several satellites have plunged into Bengal Bay since India's space program began in 1979. India's Polar Satellite Launch Vehicle (PSLV) is designed to place payloads into a polar sun-synchronous Earth orbit. On its maiden flight on September 20, 1993, the PSLV experienced an unplanned change in pitch when the spent second stage separated from the vehicle at 260 seconds into flight. The third and fourth stages ignited normally, but the vehicle was unable to recover from the pitch change and did not reach sufficient altitude. The payload was placed in a 349-kilometer orbit instead of the planned 814-kilometer polar orbit. Shifting liquid fuel in the second stage of the vehicle may have caused the change in the vehicle's pitch. Malfunction of the vehicle's guidance system or failure of the control system to respond properly to the course deviation could have been the cause of the failure.

Causes of Failure

Available launch-failure data reveal much about patterns in the possible causes of failure. Many failure causes fall into the category of human error: poor workmanship, judgment, or launch-management decisions. Some failures are the result of defective parts. Failure can have its root in any phase of launch vehicle development-difficulties have been noted in inadequate designs and component tests; in improper handling in manufacturing and repair processes; and in insufficient prelaunch checkouts. Many past failures could have been prevented if rigorous reliability-enhancement measures had been taken.

Launch Vehicle Subsystem Failures, 1980-1999								
Country	Propulsion	Avionics	Separation	Electrical	Structural	Other	Unknown	Total
U.S.	15	4	8	1	1	1		30

CIS/USSR	33	3	2			1	19	58
Europe	7	1						8
China	3	1			2			6
Japan	2	1						3
India	1	1	1	1		1		5
Israel	1							1
Brazil	2							2
N. Korea							1	1
Total	64	11	11	2	3	3	20	114

Launch vehicle failure is usually attributed to problems associated with a subsystem, such as propulsion, avionics, separation/staging, electrical, or structures. In some cases failure is ascribed to problems in another area altogether (e.g., launchpad, ground power umbilical, ground flight control, lightning strike), or to unknown causes (usually when subsystem failure information is not available).

Launch vehicle failures between 1980 and 1999 have been investigated, and launch failure causes in the United States have been found to include fuel leaks (resulting from welding defects, tank and feedline damage, etc.), payload separation failures (from incorrect wiring, defective switches, etc.), engine failure (the result of insufficient brazing in the combustion chamber), and loss of vehicle control (because of lightning, damaged wires that caused shorts, and control-system design deficiencies). In Europe and China, launch failure causes during the same period included engine failure (from combustion instability, hydrogen injector valve leakage, clogged fuel lines, etc.), short circuits, engine thrust loss, software design errors that resulted in guidance system failure, wind shear, and residual propellants.

Statistics show that among the causes of failure for space launch vehicles worldwide from 1980 to 1999, propulsion subsystem problems predominated. That particular subsystem appears to be the Achilles' heel of launch vehicles. Fifteen of the 30 U.S. failures were failures of the propulsion subsystem. The unknown failures in the CIS/USSR could include many in the propulsion subsystem.

The propulsion subsystem, the heaviest and largest subsystem of a launch vehicle, consists of components that produce, direct, or control changes in launch vehicle position or attitude. Its many elements include main propulsion components of rocket motors, liquid engines, and thrusters; combustion chamber; nozzle; propellant (both solid and liquid); propellant storage; thrust vector actuator and gimbal mechanism; fuel and propulsion control components; feed lines; control valves; turbopumps; igniters; motor and engine insulation. Similar components are also used as separation mechanisms in the separation/staging subsystem.

Propulsion subsystem failures can be divided into failures in solid-rocket motors and liquid-rocket engines. Solid-propellant launch systems include Taurus, Conestoga, Athena, Pegasus, and Scout. Liquid-propellant launch systems include Titan II, Titan IIIA, Titan IIIB, Atlas (except Atlas IIAS), and Delta DM19, A, B, and C. Hybrid launch systems, consisting of liquid-propellant and solid-propellant rockets, include STS, Titan IV, all other Titan III, Atlas IIAS, and all other Deltas. The success rate of the propulsion subsystem in the United States from 1980 to 1999 was 98.8 percent for solid-rocket motors and 97.5 percent for liquid-rocket engines (see [launch vehicle comparison chart](#)).

Addressing the Propulsion Problem

Solid-rocket motors and liquid-rocket engines of the propulsion and separation/staging subsystems both require sets of precautionary measures to maximize reliability and safeguard against failure. First, consider solid-rocket motors. In the design phase, to reduce risk it is important to apply current analysis techniques to ensure fast, accurate, and low-cost modeling of precise configurations prior to hardware fabrication (see sidebar, [Solid and Liquid Rockets](#)).

In the construction of solid-rocket motors, a number of safeguards apply to the preparation of solid propellant:

- Upon receipt from the supplier and prior to use, the propellant ingredient should be checked to ensure that it meets specifications, and the propellant mix procedure and burn rate should be checked for every mix before casting.
- Motors should be cast from a single lot of material to minimize thrust imbalance of vehicles with multiple solid-rocket motors.
- Solid propellant should be cast in a vacuum, if possible, to reduce the number and size of internal voids.
- Modern techniques (e.g., computer tomography) should be used to detect solid-propellant defects

and propellant-to-insulation bondline separation before motor assembly.

Still other steps can be taken to help increase the likelihood of solid-rocket motor launch success. Chemical fingerprinting can be implemented for rare and sensitive chemicals such as propellant binder, motor case resins, flexseal elastomers, and adhesives. It should be possible to schedule into the development and qualification programs a motor-case cure study wherein a cured case is dissected to assess the adequacy of the process used in case-manufacturing.

The liquid-rocket engines of propulsion and separation/staging subsystems should be designed and built with robustness and with high thermal and structural margins to allow for manufacturing deviations. Welded joints instead of seals ought to be used for fluid lines; high-pressure margins should be allowed in tanks, hydraulic lines, and plumbing; and 100 percent inspection, rather than spot-checking, must be applied to all welds.

Other preventive measures for liquid engines include the application of redundancy in fluid valves and igniters; the utilization of effective liquid film cooling or ceramic coatings to increase thrust-chamber durability; and the application of advanced high-strength (aluminum-magnesium) welding and milling for the construction of thin-walled fuel and oxidizer tanks. Helium purging (for cryogenic propellants) or nitrogen purging (for storable propellants) of oxidizer/fuel pumps and pipelines needs to be done before engine start-up, and purging of the chamber cooling duct should be done at engine shutdown, to provide a clean flow duct and to avoid the danger of fire or explosion.

Testing liquid engines is also important. They should be qualified at above the maximum operating environment, conditions, and duration. And extensive tests on engine operation ought to be conducted under various conditions after transportation of the engine, since transporting an engine subjects it to a harsh environment that can alter its operation.

Enhancing Launch Reliability

Information gathered from failure studies of past launch vehicles indicates that following certain work practices could greatly enhance the reliability of launch vehicle systems. Of primary importance is the need to review and implement all lessons learned from past failure studies to avoid failure recurrences. It is necessary to incorporate preventive measures in all aspects of system development—design, building, testing, and operations. Launch vehicles should be designed for low cost in manufacturing, operations, materials, and processes rather than for maximum performance or minimum weight. Comprehensive design analyses should be conducted, with positive margins.



Reliability for each space-faring nation's launch vehicles between 1957 and 1999 is calculated from a cumulative statistical distribution function that is related to the percentage of launch successes. Separate historical and operational (current) graphs represent the United States and the CIS/USSR, the two nations with the most extensive launch histories.

In the manufacturing phase, only flight-proven and defect-free components should be used. Advanced electronic beam welding, automation, and robotics should be applied for quality component manufacturing. Stringent control of raw materials, components, and semifinished products ought to be practiced. Multistring/redundant avionics, electrical, and ordnance components should be implemented for fault tolerance. Pyro-shock levels ought to be reduced whenever possible.

Testing is a critical area for reliability enhancement. It is important for a design to be validated by testing components to the point of destruction or with a high enough margin to allow for manufacturing and operating environment variances, like the successful design margin testing performed on ballistic missiles. Electrical and pneumatic connection tests should be performed for each stage and between the stages before vehicle assembly.

Components, software, and system-level electrical elements need to be tested under conditions that simulate an actual launch; system performance and flight simulation tests should be conducted; the results of testing during the development phase should be analyzed, and measures taken to improve product reliability. The separation mechanism function should be confirmed with a full-size dummy booster. Hardware reworks should be minimized, and inspection testing should be tailored for specific reworks.

When the system is operational, it is important to limit space launch operation to the design environment and flight experience. Prelaunch procedures and launch processes should be simplified to reduce contamination and damage in handling and processing. Launch-management training needs to be improved where possible. Finally, technical risks associated with schedule-driven launch dates should be reduced.

Conclusion

The technologies that have been developed for space applications and their spin-offs have dramatically improved human life, and they will no doubt continue to do so. Global high-speed telecommunication, videoconferencing, and Internet applications require many satellites, which means the need for launch services will continue to grow.

In times of conflict as well as peacetime, space technology is of critical importance to the nation. Just as, more than half a century ago, the air advantage of the Allied Forces contributed significantly to the course of World War II, so in the future, space technology will have the ability to influence conflicts. The Falkland Islands War of 1982 and the Persian Gulf War of 1991 are two examples of how the intelligent utilization of space resources affects outcome.

In coming years, needs for commercial and national defense space-related technologies are expected to multiply in many areas: propulsion, guidance and control, communications, navigation, tracking and data relay, weather forecast, remote sensing, surveillance, reconnaissance, early warning and missile defense, and interplanetary exploration. The demand for space launch services is ever increasing and may soon exceed the U.S. government's defense budget.

As more launches are conducted, more possibilities for failure will present themselves. The need for developing reliable launch systems will be ongoing. It is clear that any lessons learned from past failures are worth judiciously implementing if doing so can preclude future ones.

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