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Overview of World Space Launches

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An overview of world space launches from 1957 through 1998 is presented. Space launches with small, medium, and large launch vehicles are included, launch system success rates are compared, and space launch failures that occurred in all of the space-faring nations of the world are identified. Particular attention is paid to the review and analysis of world space launch vehicle failures in 1983–1998. Recommendations are made for reliability enhancement of launch systems and propulsion subsystems. The purpose of the study is to provide lessons learned from the past in order to mitigate launch failures in the future.

Historical Background

SPACE launches mainly involve solid rocket motors (SRMs) and/or liquid rocket engines (LREs) as propulsive and lifting devices to deliver payloads into orbit. Historically,[1] solid rockets were used for fireworks, lifesaving apparatus, signal and illumination devices, and whaling operations. Solid rockets using gunpowder (a mixture of charcoal, sulfur, and potassium nitrate) as propellant were first used as military weapons by the Chinese army to shoot fire-arrows at invading Mongols in 1232 in the Battle of Kai-Fung-Fu. However, rocket performance was not improved much from the 13th century through the 18th century. Effective artillery solid rockets carrying bombs were developed by William Congreve of England in the early 19th century and used during the bombardment of Baltimore in 1814, at Waterloo in the war with Napoleon in 1815, and in the Opium War with China in 1842. Lawyer Francis Scott Key wrote a poem after watching the British bombardment of Baltimore and observing the American flag illuminated by "the rockets' red glare." His poem entitled "The Defense of Fort McHenry," which was changed to the title "The Star Spangled Banner" in 1931, became the U.S. national anthem. The early Congreve rockets were not very accurate in hitting targets. William Hale of England developed stickless spinning rockets and obtained improved accuracy in 1844. In the early 20th century Wilhelm Teodore Unge of Sweden improved the mechanical strength and workability of solid propellant and developed launcher-rotated rockets that reached 5-mile ranges with great accuracy. Y. P. G. Le Prieur of France invented stick-guided solid rockets for firing through steel tubes mounted on the wing strut of a biplane, which were used successfully in World War I against German observation balloons in 1917. These were the early version of air-launched missiles. All of the rockets developed for fireworks or military weapons applications from ancient times through the first quarter of the 20th century used solid propellant.

The idea of using rockets for space exploration was first introduced by Konstantin Eduardovitch Tsiolkovsky[2] of Russia in 1903, followed by Robert Hutchings Goddard[3] of the U.S. in 1919, Hermann Oberth[4] of Germany in 1923, and Robert Esnault-Pelterie[5] of France in 1928. Professor Goddard was the first to build a successful rocket using liquid propellant (gasoline as fuel and liquid oxygen as oxidizer) in 1926. Based on Goddard's 1939 design of the liquid rocket, Germans successfully tested the first full-scale ballistic missile V-2 [Vergeltungswaffe-2 (Weapon of Retaliation-2)] in 1942 for reaching faraway targets. The V-2, using a mixture of ethyl alcohol as fuel and liquid oxygen as oxidizer, had a range of 320 km and carried warheads from the European continent to England during the siege of London near the end of World War II. Modern liquid rockets all have their heritage traced to the V-2, which in turn was the extension of Professor Goddard's original work. At the end of World War II, the Russian army captured V-2 manufacturing plants together with many German rocket scientists and engineers and started the ballistic missiles and space launch programs under the leadership of Sergei P. Korolev. Meanwhile, Wernher von Braun, the leader of the German V-2 program, and coworkers surrendered to the U.S. Army and continued their research on ballistic missiles and space launch vehicle development in the United States. The science and engineering of rocketry then took a giant leap forward as the result of ballistic missile buildup and the space race during the 46 years (1946–1991) of Cold War between the United States and the former Soviet Union.

Introduction

The human space age started when the first artificial satellite was put into orbit by the USSR with a liquid-fueled Sputnik (SL-1) launch vehicle on 4 October 1957. At the present time there are nine countries/consortia, namely, the United States, the Commonwealth of Independent States, the European consortium, Japan, China, India, Israel, Brazil, and North Korea, that possess space launch systems, demonstrate space launch capability, and/or are currently active in space launch operations. Many current major world space launch systems are derived from early ballistic missile technology, which put priority on cost/schedule instead of quality/reliability. The inherent design features of these space launch systems leave room for improvement, as can be attested to by many launch failures occurring in the past. The emphasis of this study, therefore, is on the identification and analysis of space launch failures.

A space launch failure is defined in this overview as an unsuccessful attempt to place a payload into the intended orbit. It 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 includes also the failure of an upperstage, which is dedicated for that particular launch vehicle and whose service is required for delivering the payload to the low earth parking orbit. But a launch failure does not include the failure of an upperstage released from a U.S. space shuttle. The U.S. space shuttle is both a launch vehicle and a space vehicle. An upperstage released from a space shuttle is considered a transfer vehicle (not a launch vehicle). A small launch vehicle like the U.S. Pegasus vehicle costs about 15 million dollars, but a versatile, reusable launch vehicle like a U.S. space shuttle costs well over one billion dollars. A small experimental satellite can be purchased for a few million dollars, but an advanced spy satellite or scientific satellite can also cost more than one billion dollars. A space mission involving a large launch vehicle and a sophisticated satellite requires many years of planning, design, programming, and hardware manufacturing, and can, therefore, easily cost hundreds of millions of dollars. This cost does not include the expense,

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time, and effort spent during the recovery period and the damage to national prestige in the event of a launch failure. Investigation of costly launch failure often provided most direct and valuable lessons for vehicle improvement—a silver lining behind the dark cloud. This study reviews[6–13] the world space launches, provides statistical data of space launches in the past 42 years (1957–1998), and explores some lessons learned and knowledge gained from the space launch failures in the past 16 years (1983–1998).

World Space Launch Statistics

Figures 1 and 2 show the total number and average success rate of world space launches. During the review period (1957–1998), the success rate of world space launches is 91.1% (3917/4299), which includes United States 87.5% (1125/1285), Commonwealth of Independent States/Soviet Union 93.5% (2560/2739), Europe 89.9% (107/119), Japan 86.7% (52/60), China 82.5% (52/63), India 50.0% (6/12), Israel 75% (3/4), Brazil 0% (0/1), and North Korea 0% (0/1). It is worthwhile to point out that there were only 12 space launches for India, 4 for Israel, 1 for Brazil, and 1 for North Korea. The small numbers of launches imply that the success rates for these four countries can vary significantly in the future. Table 1 chronologically lists the number of space launches from all of the space-faring nations of the world. The data include all of the space launches with small, medium, and large vehicles. Listed also in Table 1 are the success rates of space launches carried out individually by France, the United Kingdom, and Australia more than 24 years ago. The countries/consortia on the left-hand side of the dashed line in Table 1 are currently active in space launch operations, whereas the ones on the right-hand side are no longer individually conducting space launch operations. Suborbital missions or sounding rocket tests, whose payloads or capsules do not complete one orbit around the Earth, are not considered in the space launch statistics of this study. Table 1 includes information released by Russia, after the collapse of the Soviet Union on 21 December 1991, on many USSR space launch vehicle failures that were not previously known to the Western world. The total number of space launch failures in the world in 1957–1998 is 382 with associated loss or significantly reduced service life of 446 satellites (including multiple payloads in some launches) during space launch operations. These numbers may vary slightly depending on the data source of the CIS/USSR space launches. In the United States alone there were 160 space launch failures with associated loss or significantly reduced service life of 201 satellites.

In the past 42 years the Commonwealth of Independent States/Soviet Union conducted more space launches than all of the other countries of the world combined. The numbers of space launches carried out by the Commonwealth of Independent States/Soviet Union and the United States far exceed those by the other countries. Traditionally, the space launch arena was dominated by the Soviet Union and the United States. Recently, however, the European consortium with the Ariane launch system is catching up and captures a big share of the commercial space launch market. The number of yearly launches for Europe reached double digits in 1995–1998. Japan and China have also been successful in enhancing their space launch capabilities. After the end of the Cold War, national boundaries in the space launch business world have become less distinct. The CIS/USSR launch vehicles are being marketed for commercial launch service by various companies in the world: 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. The first satellite (Sputnik 1) launched in 1957 weighed 184.3 lbm (83.6 kg). During the moon landing mission on 16 July 1969, the U.S. Saturn V launch vehicle, which could lift 262,000 lbm (118,842 kg) payload to low Earth orbit, lofted Apollo 11 with a mass of 96,586 lbm (43,811 kg) to lunar orbit. Today the U.S. Space Transportation System (STS) routinely launches the Space Shuttle Orbiter weighing more than 242,506 lbm (110,000 kg) to low Earth orbit. The progress in space

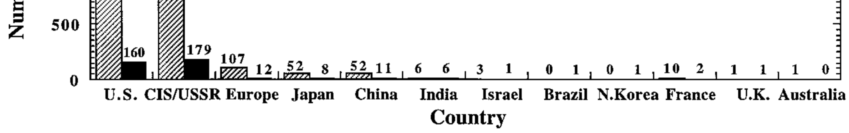

Fig. 1 Number of space launches (1957–1998).

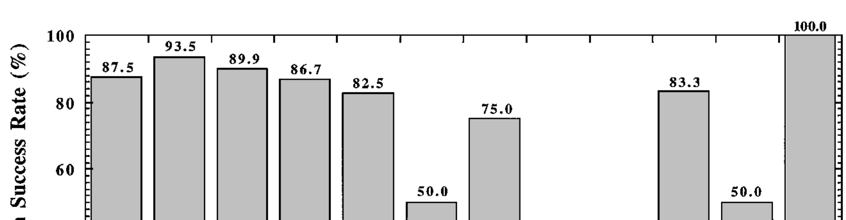

Fig. 2 Success rate of space launches (1957–1998).

Table 1 World space launches (1957–1998)

Year	United States S	United States F	CIS/USSR S	CIS/USSR F	Europe S	Europe F	Japan S	Japan F	China S	China F	India S	India F	Israel S	Israel F	Brazil S	Brazil F	North Korea S	North Korea F	France S	France F	United Kingdom S	United Kingdom F	Australia S	Australia F	Total S	Total F	Year
1957	0	1	2	0	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	2	1	1957
1958	5	18	1	4	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	6	22	1958
1959	11	8	3	1	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	14	9	1959
1960	16	13	5	6	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	21	19	1960
1961	22	19	6	3	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	28	22	1961
1962	48	11	20	2	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	68	13	1962
1963	37	9	17	7	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	54	16	1963
1964	56	8	30	6	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	86	14	1964
1965	61	9	48	6	—	—	—	—	—	—	—	—	—	—	—	—	—	—	1	0	—	—	—	—	110	15	1965
1966	72	5	43	11	—	—	0	2	—	—	—	—	—	—	—	—	—	—	1	0	—	—	—	—	116	18	1966
1967	58	3	68	8	—	—	0	1	—	—	—	—	—	—	—	—	—	—	2	0	—	—	1	0	129	12	1967
1968	43	5	74	8	0	1	0	0	—	—	—	—	—	—	—	—	—	—	0	0	—	—	—	—	117	14	1968
1969	38	3	69	15	0	1	0	1	—	—	—	—	—	—	—	—	—	—	0	0	—	—	—	—	107	20	1969
1970	28	2	81	7	0	1	1	1	1	0	—	—	—	—	—	—	—	—	2	0	0	1	—	—	113	12	1970
1971	31	4	83	9	0	1	2	0	1	0	—	—	—	—	—	—	—	—	1	1	1	0	—	—	119	15	1971
1972	31	2	74	5	0	0	1	0	0	0	—	—	—	—	—	—	—	—	0	0	—	—	—	—	106	7	1972
1973	23	2	86	4	0	0	0	0	0	1	—	—	—	—	—	—	—	—	0	1	—	—	—	—	109	8	1973
1974	23	2	81	4	0	0	1	0	0	2	—	—	—	—	—	—	—	—	0	0	—	—	—	—	105	8	1974
1975	27	4	89	4	0	0	2	0	3	0	—	—	—	—	—	—	—	—	3	0	—	—	—	—	124	8	1975
1976	24	2	98	2	0	0	1	1	2	1	—	—	—	—	—	—	—	—	—	—	—	—	—	—	125	6	1976
1977	23	3	98	4	0	0	2	0	0	0	—	—	—	—	—	—	—	—	—	—	—	—	—	—	123	7	1977
1978	32	1	87	4	0	0	3	0	1	0	—	—	—	—	—	—	—	—	—	—	—	—	—	—	123	5	1978
1979	16	0	87	3	1	0	2	0	0	1	0	1	—	—	—	—	—	—	—	—	—	—	—	—	106	5	1979
1980	12	3	87	3	0	1	2	0	0	0	1	0	—	—	—	—	—	—	—	—	—	—	—	—	102	7	1980
1981	18	1	97	2	2	0	3	0	1	0	0	1	—	—	—	—	—	—	—	—	—	—	—	—	121	4	1981
1982	18	0	100	9	0	1	1	0	1	0	0	0	—	—	—	—	—	—	—	—	—	—	—	—	120	10	1982
1983	22	0	97	3	2	0	3	0	1	0	1	0	—	—	—	—	—	—	—	—	—	—	—	—	126	3	1983
1984	21	1	97	1	4	0	3	0	2	1	0	0	—	—	—	—	—	—	—	—	—	—	—	—	127	3	1984
1985	17	1	97	4	3	1	2	0	1	0	0	0	—	—	—	—	—	—	—	—	—	—	—	—	120	6	1985
1986	6	3	91	5	2	1	2	0	2	0	0	0	—	—	—	—	—	—	—	—	—	—	—	—	103	9	1986
1987	8	1	95	3	2	0	3	0	2	0	0	1	—	—	—	—	—	—	—	—	—	—	—	—	110	5	1987
1988	11	1	90	5	7	0	2	0	4	0	0	1	1	0	—	—	—	—	—	—	—	—	—	—	115	7	1988
1989	18	0	74	1	7	0	2	0	0	0	0	0	0	0	—	—	—	—	—	—	—	—	—	—	101	1	1989
1990	26	1	74	5	5	1	3	0	5	0	0	0	1	0	—	—	—	—	—	—	—	—	—	—	114	7	1990
1991	17	2	59	2	8	0	2	0	0	1	0	0	0	0	—	—	—	—	—	—	—	—	—	—	86	5	1991
1992	28	1	54	1	7	0	1	0	3	1	1	0	0	0	—	—	—	—	—	—	—	—	—	—	94	3	1992
1993	23	2	46	2	7	0	1	0	1	0	0	1	0	0	—	—	—	—	—	—	—	—	—	—	78	5	1993
1994	26	1	48	1	6	2	2	0	5	0	2	0	0	0	—	—	—	—	—	—	—	—	—	—	89	4	1994
1995	26	4	31	2	11	0	1	1	2	1	0	0	1	0	—	—	—	—	—	—	—	—	—	—	72	8	1995
1996	32	1	23	4	10	1	1	0	2	2	1	0	0	0	—	—	—	—	—	—	—	—	—	—	69	8	1996
1997	37	1	27	2	12	0	2	0	6	0	0	1	0	0	0	1	—	—	—	—	—	—	—	—	84	5	1997
1998	34	2	23	1	11	0	1	1	6	0	0	0	0	1	0	0	0	1	—	—	—	—	—	—	75	6	1998
Total	1125	160	2560	179	107	12	52	8	52	11	6	6	3	1	0	1	0	1	10	2	1	1	1	0	3917	382	Total
1957–98	87.5%		93.5%		89.9%		86.7%		82.5%		50.0%		75.0%		0%		0%		83.3%		50.0%		100.0%		91.1%		1957–98

science and engineering during the past 42 years is remarkable. Technologies developed for space applications and their spin-offs have dramatically improved human life.

World Space Launch Systems Reliability

Table 2 shows the success rates for the U.S. space launch systems for the past 42 years. The launch systems on the left-hand side of the dotted line are in operation, whereas the ones on the right-hand side are no longer in production. The launch systems are listed in Table 2 from left to right in descending order of lift capability. Similarly, Tables 3–7 list the success rate for space launch systems in the rest of the world. The United States is the first country to put men on the moon with the giant Saturn V rocket, which is the largest and most powerful operational rocket ever built by mankind. The United States also developed the first reusable STS to launch the Space Shuttle Orbiter, which launches like a rocket, flies like a spacecraft, and lands like a glider. The Scout launch vehicle holds the longest streak of 19 years of consecutive successful launches without a failure in the U.S. space launch program.

The Soviet Union was the first country to orbit a satellite and a man around the Earth. Through the years the Commonwealth of Independent States/Soviet Union has developed many different space launch systems and launched more satellites than all of the other countries of the world combined. Statistically, the Soyuz vehicle is the most reliable expendable launch vehicle in the world.

France is the third country after the Soviet Union and the United States to attain space launch capability with her Diamant-A rocket placing a satellite into orbit in 1965. The United Kingdom developed a small Black Arrow vehicle, which was launched successfully in 1971. Presently, France and the United Kingdom participate in the European Space Agency (ESA) in the development of the Ariane launch systems.

The 14 member states of ESA are Austria, Belgium, Denmark, Finland, France, Germany, Ireland, Italy, The Netherlands, Norway, Spain, Sweden, Switzerland, and the United Kingdom. The Ariane vehicles, developed by ESA, are launched from French Guiana in South America, which is only 5.2° north of the Equator and is an excellent location for launching satellites into geosynchronous orbit. The Ariane vehicles compete successfully in the commercial launch service market that used to be dominated by the U.S. launchers.

The National Space Development Agency (NASDA) and the Institute for Space and Astronautical Science (ISAS) are responsible for space research and development in Japan. The NASDA H-II and ISAS Mu-5 vehicles use state-of-the-art technology and represent the Japanese government's commitment to become a major player in the space arena. Japan had a long streak of 18 years (1977–1994) of consecutive space launches without any failure.

In China the first two successful space launches in 1970 and 1971 were publicized by their government as great national achievements in science and engineering. The Chinese CZ-2C vehicle has a perfect record of 11 launch successes. Over the last few years the Chinese government has made considerable investment in improving launch base infrastructure to gain a share of the commercial space market.

Undaunted by a string of technical setbacks and launch failures in her fledgling space program, India is determined to have indigenous launch capability and allocates a significant portion of the government yearly budget for the development of space technology. Israel Space Agency launched the first satellite with the Shavit launch system on 19 September 1988. The third satellite launched on 5 April 1995 contains surveillance equipment designed to provide reconnaissance and military observation. Brazil's first satellite launch attempt with the Veiculo Launcadror de Satelites (VLS, satellite launch vehicle) from Alcantara launch site failed on 2 November 1997. North Korea claimed that the small Kwangmyongsong-1 satellite was launched by a Taepo Dong-1 vehicle successfully on 31 August 1998 into orbit. But no signal can be received by other countries, and the launch is considered a failure (third-stage malfunction) in this paper.

In 1967 Australia launched a small Sparta (special anti-missile research tests, Australia) vehicle, which was a modified U.S. Redstone rocket. Today Australia does not have her own launch system. The Woomera Rocket Range in Australia is presently dedicated for weapons and sounding rocket testing.

Space Launch Vehicle Failures

Table 8 lists all of the 382 space launch failures in the world for 1957–1998, which include 160 failures in the United States, 179 failures in the Commonwealth of Independent States/Soviet Union, and 43 failures in the rest of the world. The dates shown are year, month, and day (Greenwich Mean Time) format. Most of the U.S. space launch failures (101 out of 160) occurred during the first 10 years (1957–1966) of space exploration when the United States was trying diligently to catch up with the Soviet Union's early lead. The first space launch failure involved a U.S. Vanguard vehicle, which exploded 2 s after liftoff on 6 December 1957. The failure attracted tremendous public attention and criticism in the wake of two successful USSR Sputnik flights. The cause of failure[14] for the unfortunate Vanguard vehicle was a low fuel tank and injector pressure, which allowed the chamber hot gas to enter the fuel system through the fuel-injector head. The fire started in the fuel injector and resulted in destruction of the injector and complete loss of thrust immediately after vehicle liftoff.

The largest launch vehicle ever successfully built and flown by mankind, the U.S. Saturn V vehicle, had a single failure in the Apollo 6 mission on 4 April 1968, when the third-stage engine failed to restart because of fuel-injector burnthrough. The versatile STS also suffered a single launch failure on 28 January 1986, when the STS *Challenger*[15] with its seven-member crew and payload exploded at 73 s into the flight because launch management waived the temperature-dependent launch commit criteria and launched the vehicle at a temperature colder than that derived from experience. The rubber O-rings in the motor case joint lost their resiliency at the cold temperature, and the combustion flame leaked through the O-rings and case joint and caused the vehicle explosion. The newly developed commercial launch systems including Delta III, Conestoga, Athena, and Pegasus in the United States suffered launch failures during their early development flights, a repeat of Vanguard, Juno, Thor, and Atlas in the late 1950s and early 1960s.

The Commonwealth of Independent States/Soviet Union had an impressive number of space launches and 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 in the Commonwealth of Independent States. In 1996–1998, for example, the United States conducted more space launches than the Commonwealth of Independent States/Soviet Union for the first time in 30 years. Space launch failure in a closed society like the Soviet Union or the People's Republic of China was guarded as a state secret and was not publicized in news media. Recently, because of glasnost in Russia, commercial competition, and requirements by the launch service insurance company, information flow on space activities has improved dramatically. The vast amount of information, from both successful and failed launch operations, existing in the Commonwealth of Independent States/Soviet Union is yet to be assimilated by space launch communities of the world.

One of the recent space launch failures in the Commonwealth of Independent States/Soviet Union involved a SL-12 Proton vehicle[16] carrying a Mars-96 spacecraft on 16 November 1996. Following successful burns of the Proton's first three stages and the first burn of the fourth stage, the second burn of the fourth stage did not take place. The spacecraft did not reach the interplanetary trajectory and reentered over the South Pacific Ocean. The spacecraft was launched without prelaunch systems checkout at launch site for lack of funds. Some of the mechanical integration of the spacecraft and launcher was carried out by kerosene lantern light (electrical power was cut off because of unpaid bills). Tight funding also made ground control difficult, even during the critical period right after launch. The fourth stage was commanded by the spacecraft, indicating possible incorrect commands sent by the spacecraft. It took 10 years to complete the $300 million Mars-96 satellite with 24 instruments from 22 countries. The launch failure sets back the plan of many astronautical scientists to gather valuable data on the planet Mars.

Table 2 Launch vehicle success rate (1957–1998)—United States

Year	STS		Titan		Atlas		Delta[a]		Taurus		Athena		Pegasus		Saturn		Thor[b]		Conestoga		Scout		Juno[c]		Vanguard		Pilot		Total		Year
	S	F	S	F	S	F	S	F	S	F	S	F	S	F	S	F	S	F	S	F	S	F	S	F	S	F	S	F	S	F	
1957	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	0	1	—	—	0	1	1957
1958	—	—	—	—	1	0	—	—	—	—	—	—	—	—	—	—	0	3	—	—	—	—	3	4	1	5	0	6	5	18	1958
1959	—	—	—	—	0	1	—	—	—	—	—	—	—	—	—	—	7	3	—	—	—	—	2	2	2	2	—	—	11	8	1959
1960	—	—	—	—	1	4	2	1	—	—	—	—	—	—	—	—	12	6	—	—	0	1	1	1	—	—	—	—	16	13	1960
1961	—	—	—	—	4	7	3	0	—	—	—	—	—	—	0	0	13	7	—	—	1	3	1	2	—	—	—	—	22	19	1961
1962	—	—	—	—	11	5	9	0	—	—	—	—	—	—	0	0	25	4	—	—	3	2	—	—	—	—	—	—	48	11	1962
1963	—	—	—	—	9	1	7	0	—	—	—	—	—	—	0	0	17	5	—	—	4	3	—	—	—	—	—	—	37	9	1963
1964	—	—	2	1	15	3	4	1	—	—	—	—	—	—	3	0	25	2	—	—	7	1	—	—	—	—	—	—	56	8	1964
1965	—	—	8	2	14	5	7	1	—	—	—	—	—	—	3	0	24	1	—	—	5	0	—	—	—	—	—	—	61	9	1965
1966	—	—	10	1	31	2	8	0	—	—	—	—	—	—	1	0	14	2	—	—	8	0	—	—	—	—	—	—	72	5	1966
1967	—	—	9	1	14	0	12	0	—	—	—	—	—	—	1	0	16	0	—	—	6	2	—	—	—	—	—	—	58	3	1967
1968	—	—	10	0	6	2	7	1	—	—	—	—	—	—	3	1	12	1	—	—	5	0	—	—	—	—	—	—	43	5	1968
1969	—	—	8	0	5	0	9	2	—	—	—	—	—	—	4	0	11	0	—	—	1	1	—	—	—	—	—	—	38	3	1969
1970	—	—	6	1	2	1	7	0	—	—	—	—	—	—	1	0	9	0	—	—	3	0	—	—	—	—	—	—	28	2	1970
1971	—	—	8	0	4	2	4	1	—	—	—	—	—	—	2	0	8	1	—	—	5	0	—	—	—	—	—	—	31	4	1971
1972	—	—	7	2	6	0	7	0	—	—	—	—	—	—	2	0	4	0	—	—	5	0	—	—	—	—	—	—	31	2	1972
1973	—	—	8	1	4	0	5	1	—	—	—	—	—	—	4	0	1	0	—	—	1	0	—	—	—	—	—	—	23	2	1973
1974	—	—	7	1	2	0	6	1	—	—	—	—	—	—	0	0	2	0	—	—	6	0	—	—	—	—	—	—	23	2	1974
1975	—	—	8	1	3	2	12	0	—	—	—	—	—	—	1	0	1	0	—	—	2	1	—	—	—	—	—	—	27	4	1975
1976	—	—	8	1	4	0	9	0	—	—	—	—	—	—	—	—	1	1	—	—	2	0	—	—	—	—	—	—	24	2	1976
1977	—	—	7	0	6	1	8	2	—	—	—	—	—	—	—	—	1	0	—	—	1	0	—	—	—	—	—	—	23	3	1977
1978	—	—	6	1	14	0	10	0	—	—	—	—	—	—	—	—	1	0	—	—	1	0	—	—	—	—	—	—	32	1	1978
1979	—	—	5	0	4	0	3	0	—	—	—	—	—	—	—	—	1	0	—	—	3	0	—	—	—	—	—	—	16	0	1979
1980	—	—	3	0	6	2	3	0	—	—	—	—	—	—	—	—	0	1	—	—	0	0	—	—	—	—	—	—	12	3	1980
1981	2	0	5	0	5	1	5	0	—	—	—	—	—	—	—	—	—	—	—	—	1	0	—	—	—	—	—	—	18	1	1981
1982	3	0	5	0	3	0	7	0	—	—	—	—	—	—	—	—	—	—	—	—	0	0	—	—	—	—	—	—	18	0	1982
1983	4	0	3	0	6	0	8	0	—	—	—	—	—	—	—	—	—	—	—	—	1	0	—	—	—	—	—	—	22	0	1983
1984	5	0	7	0	4	1	4	0	—	—	—	—	—	—	—	—	—	—	—	—	1	0	—	—	—	—	—	—	21	1	1984
1985	9	0	1	1	5	0	0	0	—	—	—	—	—	—	—	—	—	—	—	—	2	0	—	—	—	—	—	—	17	1	1985
1986	1	1	0	1	3	0	1	1	—	—	—	—	—	—	—	—	—	—	—	—	1	0	—	—	—	—	—	—	6	3	1986
1987	0	0	3	0	2	1	2	0	—	—	—	—	—	—	—	—	—	—	—	—	1	0	—	—	—	—	—	—	8	1	1987
1988	2	0	2	1	2	0	1	0	—	—	—	—	—	—	—	—	—	—	—	—	4	0	—	—	—	—	—	—	11	1	1988
1989	5	0	4	0	1	0	8	0	—	—	—	—	—	—	—	—	—	—	—	—	0	0	—	—	—	—	—	—	18	0	1989
1990	6	0	4	1	3	0	11	0	—	—	—	—	1	0	—	—	—	—	—	—	1	0	—	—	—	—	—		26	1	1990
1991	6	0	2	0	3	1	5	0	—	—	—	—	0	1	—	—	—	—	—	—	1	0	—	—	—	—	—	—	17	2	1991
1992	8	0	3	0	4	1	11	0	—	—	—	—	0	0	—	—	—	—	—	—	2	0	—	—	—	—	—	—	28	1	1992
1993	7	0	1	1	5	1	7	0	—	—	—	—	2	0	—	—	—	—	—	—	1	0	—	—	—	—	—	—	23	2	1993
1994	7	0	5	0	7	0	3	0	1	0	—	—	2	1	—	—	—	—	—	—	1	0	—	—	—	—	—	—	26	1	1994
1995	7	0	4	0	12	0	2	1	0	0	0	1	1	1	—	—	—	—	0	1	—	—	—	—	—	—	—	—	26	4	1995
1996	7	0	4	0	7	0	10	0	0	0	0	0	4	1	—	—	—	—	—	—	—	—	—	—	—	—	—	—	32	1	1996
1997	8	0	5	0	8	0	10	1	0	0	1	0	5	0	—	—	—	—	—	—	—	—	—	—	—	—	—	—	37	1	1997
1998	5	0	2	1	6	0	12	1	2	0	1	0	6	0	—	—	—	—	—	—	—	—	—	—	—	—	—	—	34	2	1998
Total	92	1	180	19	252	44	249	15	3	0	2	1	21	4	25	1	205	37	0	1	86	14	7	9	3	8	0	6	1125	160	Total
1957–98	98.9%		90.5%		85.1%		94.3%		100.0%		66.7%		84.0%		96.2%		84.7%		0%		86.0%		43.8%		27.3%		0%		87.5%		1957–98

[a]Includes TAD (thrust-augmented delta). [b]Includes TAT (thrust-augmented thor), LLTAT (long tank thrust-augmented thor), and Thorad (thrust-augmented thor delta). [c]Includes Juno-I and Juno-II.

Table 3 Launch vehicle success rate (1957–1998)—Commonwealth of Independent States/Soviet Union

Year	Proton SL-9, 12, 13		Zenit SL-16		Soyuz[a] SL-4		Molniya SL-6		Tsiklon SL-10, 11, 14		Rokot		Kosmos SL-8		Start SL-18		Shtil-1		N-1 SL-15		Energia SL-17		Vostok[b] SL-3		Polyot SL-5		Sputnik SL-1, 2		B-1 SL-7		Total		Year
	S	F	S	F	S	F	S	F	S	F	S	F	S	F	S	F	S	F	S	F	S	F	S	F	S	F	S	F	S	F	S	F	
1957	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	2	0	—	—	2	0	1957
1958	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	0	3	—	—	1	1	—	—	1	4	1958
1959	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	3	1	—	—	—	—	—	—	3	1	1959
1960	—	—	—	—	—	—	0	2	—	—	—	—	—	—	—	—	—	—	—	—	—	—	5	4	—	—	—	—	—	—	5	6	1960
1961	—	—	—	—	—	—	2	0	—	—	—	—	—	—	—	—	—	—	—	—	—	—	4	1	—	—	—	—	0	2	6	3	1961
1962	—	—	—	—	—	—	6	0	—	—	—	—	—	—	—	—	—	—	—	—	—	—	7	1	—	—	—	—	7	1	20	2	1962
1963	—	—	—	—	1	0	3	1	—	—	—	—	—	—	—	—	—	—	—	—	—	—	8	2	1	0	—	—	4	4	17	7	1963
1964	—	—	—	—	5	0	4	4	—	—	—	—	1	1	—	—	—	—	—	—	—	—	12	0	1	0	—	—	7	1	30	6	1964
1965	2	0	—	—	13	0	11	1	0	1	—	—	6	0	—	—	—	—	—	—	—	—	9	1	—	—	—	—	7	3	48	6	1965
1966	1	1	—	—	15	2	8	1	2	3	—	—	0	1	—	—	—	—	—	—	—	—	11	1	—	—	—	—	6	2	43	11	1966
1967	2	2	—	—	21	3	7	0	11	1	—	—	6	2	—	—	—	—	—	—	—	—	8	0	—	—	—	—	13	0	68	8	1967
1968	4	1	—	—	34	0	4	2	7	2	—	—	7	2	—	—	—	—	—	—	—	—	2	0	—	—	—	—	16	1	74	8	1968
1969	2	9	—	—	37	0	4	0	4	1	—	—	6	1	—	—	—	—	0	2	—	—	2	1	—	—	—	—	14	1	69	15	1969
1970	4	2	—	—	31	1	7	0	6	0	—	—	10	2	—	—	—	—	0	0	—	—	5	0	—	—	—	—	18	2	81	7	1970
1971	6	0	—	—	32	4	3	0	6	0	—	—	19	1	—	—	—	—	0	1	—	—	5	0	—	—	—	—	12	3	83	9	1971
1972	1	1	—	—	31	1	11	0	1	0	—	—	13	1	—	—	—	—	0	1	—	—	5	0	—	—	—	—	12	1	74	5	1972
1973	7	0	—	—	40	1	10	0	1	1	—	—	15	2	—	—	—	—	—	—	—	—	3	0	—	—	—	—	10	0	86	4	1973
1974	6	0	—	—	36	3	7	0	3	0	—	—	17	0	—	—	—	—	—	—	—	—	6	0	—	—	—	—	6	1	81	4	1974
1975	4	1	—	—	40	1	12	0	4	0	—	—	18	2	—	—	—	—	—	—	—	—	6	0	—	—	—	—	5	0	89	4	1975
1976	5	0	—	—	38	1	10	1	8	0	—	—	28	0	—	—	—	—	—	—	—	—	5	0	—	—	—	—	4	0	98	2	1976
1977	4	1	—	—	37	2	10	0	10	0	—	—	28	1	—	—	—	—	—	—	—	—	7	0	—	—	—	—	2	0	98	4	1977
1978	4	4	—	—	45	0	9	0	3	0	—	—	21	0	—	—	—	—	—	—	—	—	5	0	—	—	—	—	—	—	87	4	1978
1979	6	1	—	—	45	2	7	0	3	0	—	—	18	0	—	—	—	—	—	—	—	—	8	0	—	—	—	—	—	—	87	3	1979
1980	5	0	—	—	45	0	10	2	5	0	—	—	16	0	—	—	—	—	—	—	—	—	6	1	—	—	—	—	—	—	87	3	1980
1981	7	0	—	—	41	0	13	1	12	1	—	—	18	0	—	—	—	—	—	—	—	—	6	0	—	—	—	—	—	—	97	2	1981
1982	8	2	—	—	43	3	10	1	12	0	—	—	22	3	—	—	—	—	—	—	—	—	5	0	—	—	—	—	—	—	100	9	1982
1983	12	0	—	—	42	1	10	1	7	0	—	—	22	1	—	—	—	—	—	—	—	—	4	0	—	—	—	—	—	—	97	3	1983
1984	13	0	—	—	44	0	11	0	10	1	—	—	19	0	—	—	—	—	—	—	—	—	0	0	—	—	—	—	—		97	1	1984
1985	10	0	1	3	40	0	16	0	17	0	—	—	12	1	—	—	—	—	—	—	—	—	1	0	—	—	—	—	—	—	97	4	1985
1986	8	2	2	0	36	1	13	1	16	1	—	—	16	0	—	—	—	—	—	—	—	—	0	0	—	—	—	—	—	—	91	5	1986
1987	11	2	5	0	43	1	4	0	17	0	—	—	14	0	—	—	—	—	—	—	1	0	0	0	—	—	—	—	—	—	95	3	1987
1988	11	2	2	0	42	3	11	0	13	0	—	—	8	0	—	—	—	—	—	—	1	0	2	0	—	—	—	—	—	—	90	5	1988
1989	11	0	0	0	38	0	6	0	10	1	—	—	9	0	—	—	—	—	—	—	—	—	0	0	—	—	—	—	—	—	74	1	1989
1990	10	1	1	1	30	2	11	1	12	0	—	—	10	0	—	—	—	—	—	—	—	—	0	0	—	—	—	—	—	—	74	5	1990
1991	9	0	0	1	24	0	5	0	9	0	USSR	—	11	1	—	—	—	—	—	—	—	—	1	0	—	—	—	—	—	—	59	2	1991
1992	8	0	2	1	24	0	8	0	5	0	CIS	—	7	0	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	54	1	1992
1993	5	1	2	0	16	1	8	0	8	0	—	—	6	0	1	0	—	—	—	—	—	—	—	—	—	—	—	—	—	—	46	2	1993
1994	13	0	4	0	15	0	3	0	7	1	1	0	5	0	0	0	—	—	—	—	—	—	—	—	—	—	—	—	—	—	48	1	1994
1995	7	0	1	0	12	0	4	0	3	0	0	0	4	1	0	1	—	—	—	—	—	—	—	—	—	—	—	—	—	—	31	2	1995
1996	6	2	1	0	7	2	3	0	2	0	0	0	4	0	0	0	—	—	—	—	—	—	—	—	—	—	—	—	—	—	23	4	1996
1997	8	1	0	1	10	0	3	0	2	0	0	0	2	0	2	0	—	—	—	—	—	—	—	—	—	—	—	—	—	—	27	2	1997
1998	7	0	2	1	7	0	3	0	1	0	0	0	2	0	0	0	1	0	—	—	—	—	—	—	—	—	—	—	—	—	23	1	1998
Total	227	36	23	8	1060	35	287	19	237	14	1	0	420	23	3	1	1	0	0	4	2	0	151	16	2	0	3	1	143	22	2560	179	Total
1957–98	86.3%		74.2%		96.8%		93.8%		94.4%		100.0%		94.8%		75.0%		100.0%		0%		100.0%		90.4%		100.0%		75.0%		86.7%		93.5%		1957–98

[a]Includes Voskhod space launch vehicle (293 successes, 13 failures) in 1963–1976. [b]Includes Luna space launch vehicle (3 successes, 5 failures) in 1958–1960.

Table 4 Launch vehicle success rate (1968–1998)—Europe

	Ariane-5		Ariane-44L		44LP		42L		44P		42P		40		Ariane-3		Ariane-2		Ariane-1		Europa		Total		
Year	S	F	S	F	S	F	S	F	S	F	S	F	S	F	S	F	S	F	S	F	S	F	S	F	Year
1968	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	0	1	0	1	1968
1969	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	0	1	0	1	1969
1970	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	0	1	0	1	1970
1971	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	0	1	0	1	1971
1972	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	0	0	1972
1973	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	0	0	1973
1974	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	0	0	1974
1975	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	0	0	1975
1976	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	0	0	1976
1977	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	0	0	1977
1978	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	0	0	1978
1979	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	1	0	—	—	1	0	1979
1980	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	0	1	—	—	0	1	1980
1981	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	2	0	—	—	2	0	1981
1982	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	0	1	—	—	0	1	1982
1983	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	2	0	—	—	2	0	1983
1984	—	—	—	—	—	—	—	—	—	—	—	—	—	—	2	0	—	—	2	0	—	—	4	0	1984
1985	—	—	—	—	—	—	—	—	—	—	—	—	—	—	2	1	—	—	1	0	—	—	3	1	1985
1986	—	—	—	—	—	—	—	—	—	—	—	—	—	—	1	0	0	1	1	0	—	—	2	1	1986
1987	—	—	—	—	—	—	—	—	—	—	—	—	—	—	1	0	1	0	—	—	—	—	2	0	1987
1988	—	—	—	—	2	0	—	—	—	—	—	—	—	—	3	0	2	0	—	—	—	—	7	0	1988
1989	—	—	2	0	2	0	—	—	—	—	—	—	—	—	1	0	2	0	—	—	—	—	7	0	1989
1990	—	—	2	1	1	0	—	—	—	—	1	0	1	0	—	—	—	—	—	—	—	—	5	1	1990
1991	—	—	4	0	1	0	—	—	2	0	0	0	1	0	—	—	—	—	—	—	—	—	8	0	1991
1992	—	—	3	0	1	0	—	—	0	0	3	0	0	0	—	—	—	—	—	—	—	—	7	0	1992
1993	—	—	2	0	2	0	1	0	0	0	1	0	1	0	—	—	—	—	—	—	—	—	7	0	1993
1994	—	—	2	0	2	1	1	0	0	0	1	1	0	0	—	—	—	—	—	—	—	—	6	2	1994
1995	—	—	1	0	2	0	3	0	2	0	1	0	2	0	—	—	—	—	—	—	—	—	11	0	1995
1996	0	1	5	0	1	0	0	0	2	0	2	0	0	0	—	—	—	—	—	—	—	—	10	1	1996
1997	1	0	3	0	2	0	2	0	4	0	0	0	0	0	—	—	—	—	—	—	—	—	12	0	1997
1998	1	0	2	0	2	0	2	0	2	0	1	0	1	0	—	—	—	—	—	—	—	—	11	0	1998
Total	2	1	26	1	18	1	9	0	12	0	10	1	6	0	10	1	5	1	9	2	0	4	107	12	Total
1968–98	66.7%		96.3%		94.7%		100.0%		100.0%		90.9%		100.0%		90.9%		83.3%		81.8%		0%		89.9%		1968–98

Table 5 Launch vehicle success rate (1966–1998)—Japan

Year	H-II		Mu-5		H-I		N-II		N-I		Mu-3S-II		Mu-3S		Mu-3H		Mu-3C		Mu-4S		Lamda-4S		Total		Year
	S	F	S	F	S	F	S	F	S	F	S	F	S	F	S	F	S	F	S	F	S	F	S	F	
1966	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—		0	2	0	2	1966
1967	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	0	1	0	1	1967
1968	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	0	0	0	0	1968
1969	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	0	1	0	1	1969
1970	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	0	1	1	0	1	1	1970
1971	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	2	0	—	—	2	0	1971
1972	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	1	0	—	—	1	0	1972
1973	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	0	0	1973
1974	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	1	0	—	—	—	—	1	0	1974
1975	—	—	—	—	—	—	—	—	1	0	—	—	—	—	—	—	1	0	—	—	—	—	2	0	1975
1976	—	—	—	—	—	—	—	—	1	0	—	—	—	—	—	—	0	1	—	—	—	—	1	1	1976
1977	—	—	—	—	—	—	—	—	1	0	—	—	—	—	1	0	0	0	—	—	—	—	2	0	1977
1978	—	—	—	—	—	—	—	—	1	0	—	—	—	—	2	0	0	0	—	—	—	—	3	0	1978
1979	—	—	—	—	—	—	—	—	1	0	—	—	—	—	—	—	1	0	—	—	—	—	2	0	1979
1980	—	—	—	—	—	—	—	—	1	0	—	—	1	0	—	—	—	—	—	—	—	—	2	0	1980
1981	—	—	—	—	—	—	2	0	0	0	—	—	1	0	—	—	—	—	—	—	—	—	3	0	1981
1982	—	—	—	—	—	—	0	0	1	0	—	—	0	0	—	—	—	—	—	—	—	—	1	0	1982
1983	—	—	—	—	—	—	2	0	—	—	—	—	1	0	—	—	—	—	—	—	—	—	3	0	1983
1984	—	—	—	—	—	—	2	0	—	—	—	—	1	0	—	—	—	—	—	—	—	—	3	0	1984
1985	—	—	—	—	—	—	0	0	—	—	2	0	—	—	—	—	—	—	—	—	—	—	2	0	1985
1986	—	—	—	—	1	0	1	0	—	—	0	0	—	—	—	—	—	—	—	—	—	—	2	0	1986
1987	—	—	—	—	1	0	1	0	—	—	1	0	—	—	—	—	—	—	—	—	—	—	3	0	1987
1988	—	—	—	—	2	0	—	—	—	—	0	0	—	—	—	—	—	—	—	—	—	—	2	0	1988
1989	—	—	—	—	1	0	—	—	—	—	1	0	—	—	—	—	—	—	—	—	—	—	2	0	1989
1990	—	—	—	—	2	0	—	—	—	—	1	0	—	—	—	—	—	—	—	—	—	—	3	0	1990
1991	—	—	—	—	1	0	—	—	—	—	1	0	—	—	—	—	—	—	—	—	—	—	2	0	1991
1992	—	—	—	—	1	0	—	—	—	—	0	0	—	—	—	—	—	—	—	—	—	—	1	0	1992
1993	—	—	—	—	—	—	—	—	—	—	1	0	—	—	—	—	—	—	—	—	—	—	1	0	1993
1994	2	0	—	—	—	—	—	—	—	—	0	0	—	—	—	—	—	—	—	—	—	—	2	0	1994
1995	1	0	—	—	—	—	—	—	—	—	0	1	—	—	—	—	—	—	—	—	—	—	1	1	1995
1996	1	0	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	1	0	1996
1997	1	0	1	0	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	2	0	1997
1998	0	1	1	0	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	1	1	1998
Total	5	1	2	0	9	0	8	0	7	0	7	1	4	0	3	0	3	1	3	1	1	4	52	8	Total
1966–98	83.3%		100.0%		100.0%		100.0%		100.0%		87.5%		100.0%		100.0%		75.0%		75.0%		20.0%		86.7%		1966–98

Table 6 Launch vehicle success rate (1970–1998)—China

	CZ-3B		CZ-2E		CZ-3A		CZ-4A		CZ-3		CZ-2D		CZ-2C/SD		CZ-2C		CZ-2		FB-1		CZ-1		Total		
Year	S	F	S	F	S	F	S	F	S	F	S	F	S	F	S	F	S	F	S	F	S	F	S	F	Year
1970	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	1	0	1	0	1970
1971	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	1	0	1	0	1971
1972	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	0	0	1972
1973	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	0	1	—	—	0	1	1973
1974	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	0	1	0	1	—	—	0	2	1974
1975	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	1	0	2	0	—	—	3	0	1975
1976	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	1	0	1	1	—	—	2	1	1976
1977	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	0	0	0	0	—	—	0	0	1977
1978	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	1	0	0	0	—	—	1	0	1978
1979	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	0	1	—	—	0	1	1979
1980	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	0	0	—	—	0	0	1980
1981	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	1	0	—	—	1	0	1981
1982	—	—	—	—	—	—	—	—	—	—	—	—	—	—	1	0	—	—	—	—	—	—	1	0	1982
1983	—	—	—	—	—	—	—	—	—	—	—	—	—	—	1	0	—	—	—	—	—	—	1	0	1983
1984	—	—	—	—	—	—	—	—	1	1	—	—	—	—	1	0	—	—	—	—	—	—	2	1	1984
1985	—	—	—	—	—	—	—	—	0	0	—	—	—	—	1	0	—	—	—	—	—	—	1	0	1985
1986	—	—	—	—	—	—	—	—	1	0	—	—	—	—	1	0	—	—	—	—	—	—	2	0	1986
1987	—	—	—	—	—	—	—	—	0	0	—	—	—	—	2	0	—	—	—	—	—	—	2	0	1987
1988	—	—	—	—	—	—	1	0	2	0	—	—	—	—	1	0	—	—	—	—	—	—	4	0	1988
1989	—	—	—	—	—	—	0	0	0	0	—	—	—	—	0	0	—	—	—	—	—	—	0	0	1989
1990	—	—	1	0	—	—	1	0	2	0	—	—	—	—	1	0	—	—	—	—	—	—	5	0	1990
1991	—	—	0	0	—	—	0	0	0	1	—	—	—	—	0	0	—	—	—	—	—	—	0	1	1991
1992	—	—	1	1	—	—	0	0	0	0	1	0	—	—	1	0	—	—	—	—	—	—	3	1	1992
1993	—	—	0	0	—	—	0	0	0	0	0	0	—	—	1	0	—	—	—	—	—	—	1	0	1993
1994	—	—	1	0	2	0	0	0	1	0	1	0	—	—	0	0	—	—	—	—	—	—	5	0	1994
1995	—	—	2	1	0	0	0	0	0	0	0	0	—	—	0	0	—	—	—	—	—	—	2	1	1995
1996	0	1	0	0	0	0	0	0	1	1	1	0	—	—	0	0	—	—	—	—	—	—	2	2	1996
1997	2	0	0	0	1	0	0	0	1	0	0	0	2	0	0	0	—	—	—	—	—	—	6	0	1997
1998	2	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0	—	—	—	—	—	—	6	0	1998
Total	4	1	5	2	3	0	2	0	9	3	3	0	6	0	11	0	3	1	4	4	2	0	52	11	Total
1970–98	80.0%		71.4%		100.0%		100.0%		75.0%		100.0%		100.0%		100.0%		75.0%		50.0%		100.0%		82.5%		1970–98

Table 7 Launch vehicle success rate (1965–1998)—others

	India						Israel		Brazil		North Korea		France						United Kingdom		Australia		
	PSLV		ASLV		SLV-3		Shavit		VLS		Taepo Dong-I		Diamant-BP4		Diamant-B		Diamant-A		Black Arrow		Sparta		
Year	S	F	S	F	S	F	S	F	S	F	S	F	S	F	S	F	S	F	S	F	S	F	Year
1965	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	1	0	—	—	—	—	1965
1966	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	1	0	—	—	—	—	1966
1967	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	2	0	—	—	1	0	1967
1968	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	1968
1969	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	1969
1970	—	—	—	—	—	—	—	—	—	—	—	—	—	—	2	0	—	—	0	1	—	—	1970
1971	—	—	—	—	—	—	—	—	—	—	—	—	—	—	1	1	—	—	1	0	—	—	1971
1972	—	—	—	—	—	—	—	—	—	—	—	—	—	—	0	0	—	—	—	—	—	—	1972
1973	—	—	—	—	—	—	—	—	—	—	—	—	—	—	0	1	—	—	—	—	—	—	1973
1974	—	—	—	—	—	—	—	—	—	—	—	—	—	—	0	0	—	—	—	—	—	—	1974
1975	—	—	—	—	—	—	—	—	—	—	—	—	2	0	1	0	—	—	—	—	—	—	1975
1976	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	1976
1977	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	1977
1978	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	1978
1979	—	—	—	—	0	1	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	1979
1980	—	—	—	—	1	0	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	1980
1981	—	—	—	—	0	1	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	1981
1982	—	—	—	—	0	0	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	1982
1983	—	—	—	—	1	0	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	1983
1984	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	1984
1985	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	1985
1986	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	1986
1987	—	—	0	1	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	1987
1988	—	—	0	1	—	—	1	0	—	—	—	—	—	—	—	—	—	—	—	—	—	—	1988
1989	—	—	0	0	—	—	0	0	—	—	—	—	—	—	—	—	—	—	—	—	—	—	1989
1990	—	—	0	0	—	—	1	0	—	—	—	—	—	—	—	—	—	—	—	—	—	—	1990
1991	—	—	0	0	—	—	0	0	—	—	—	—	—	—	—	—	—	—	—	—	—	—	1991
1992	—	—	1	0	—	—	0	0	—	—	—	—	—	—	—	—	—	—	—	—	—	—	1992
1993	0	1	0	0	—	—	0	0	—	—	—	—	—	—	—	—	—	—	—	—	—	—	1993
1994	1	0	1	0	—	—	0	0	—	—	—	—	—	—	—	—	—	—	—	—	—	—	1994
1995	0	0	0	0	—	—	1	0	—	—	—	—	—	—	—	—	—	—	—	—	—	—	1995
1996	1	0	0	0	—	—	0	0	—	—	—	—	—	—	—	—	—	—	—	—	—	—	1996
1997	0	1	0	0	—	—	0	0	0	1	—	—	—	—	—	—	—	—	—	—	—	—	1997
1998	0	0	0	0	—	—	0	1	0	0	0	1	—	—	—	—	—	—	—	—	—	—	1998
Total	2	2	2	2	2	2	3	1	0	1	0	1	2	0	4	2	4	0	1	1	1	0	Total
1965–98	50.0%		50.0%		50.0%		75.0%		0%		0%		100.0%		66.7%		100.0%		50.0%		100.0%		1965–98

Table 8 Space launch failures (1957–1998)

United States											
57-12-06	Vanguard	60-02-04	Thor	61-11-01	Scout	64-04-21	Thor	68-09-18	Delta	80-07-14	Thor
58-02-05	Vanguard	60-02-19	Thor	61-11-05	Thor	64-06-25	Scout	69-07-26	Delta	80-12-09	Atlas
58-03-05	Juno	60-02-26	Atlas	61-11-18	Atlas	64-06-30	Atlas	69-08-27	Delta	81-12-18	Atlas
58-04-28	Vanguard	60-03-23	Juno	61-11-22	Atlas	64-09-01	Titan	69-10-01	Scout	84-06-09	Atlas
58-05-27	Vanguard	60-05-13	Delta	61-12-22	Atlas	64-10-08	Atlas	70-11-06	Titan	85-08-28	Titan
58-06-26	Vanguard	60-06-29	Thor	62-01-13	Thor	64-11-05	Atlas	70-11-30	Atlas	86-01-28	STS
58-07-25	Pilot	60-08-18	Thor	62-01-24	Thor	65-01-21	Atlas	71-02-17	Thor	86-04-18	Titan
58-08-12	Pilot	60-09-25	Atlas	62-01-26	Atlas	65-03-02	Atlas	71-05-08	Atlas	86-05-03	Delta
58-08-17	Thor	60-10-11	Atlas	62-02-21	Thor	65-05-27	Atlas	71-10-21	Delta	87-03-26	Atlas
58-08-22	Pilot	60-10-26	Thor	62-04-09	Atlas	65-07-12	Atlas	71-12-04	Atlas	88-09-02	Titan
58-08-24	Juno	60-11-30	Thor	62-04-26	Scout	65-08-25	Delta	72-02-16	Titan	90-03-14	Titan
58-08-25	Pilot	60-12-04	Scout	62-05-10	Thor	65-09-02	Thor	72-05-20	Titan	91-04-18	Atlas
58-08-26	Pilot	60-12-15	Atlas	62-05-23	Scout	65-10-15	Titan	73-06-26	Titan	91-07-17	Pegasus
58-08-28	Pilot	61-02-22	Thor	62-06-17	Atlas	65-10-25	Atlas	73-07-16	Delta	92-08-22	Atlas
58-09-26	Vanguard	61-02-24	Juno	62-07-22	Atlas	65-12-21	Titan	74-01-19	Delta	93-03-25	Atlas
58-10-11	Thor	61-03-30	Thor	62-12-17	Atlas	66-01-06	Thor	74-02-11	Titan	93-08-02	Titan
58-10-23	Juno	61-04-25	Atlas	63-02-28	Thor	66-04-07	Atlas	75-02-20	Atlas	94-06-27	Pegasus
58-11-08	Thor	61-05-24	Juno	63-03-18	Thor	66-05-03	Thor	75-04-12	Atlas	95-06-22	Pegasus
58-12-06	Juno	61-06-08	Thor	63-04-05	Scout	66-05-17	Atlas	75-05-20	Titan	95-08-05	Delta
59-04-13	Vanguard	61-06-30	Scout	64-04-26	Scout	66-08-26	Titan	75-12-05	Scout	95-08-15	Athena
59-06-03	Thor	61-07-21	Thor	63-04-26	Thor	67-01-31	Scout	76-02-19	Thor	95-10-23	Conestoga
59-06-22	Vanguard	61-08-03	Thor	63-06-12	Atlas	67-04-26	Titan	76-09-15	Titan	96-11-04	Pegasus
59-06-25	Thor	61-08-23	Atlas	63-06-12	Thor	67-05-29	Scout	77-04-20	Delta	97-01-17	Delta
59-07-16	Juno	61-08-25	Scout	63-09-27	Scout	68-04-04	Saturn	77-09-13	Delta	98-08-12	Titan
59-08-14	Juno	61-09-09	Atlas	63-11-09	Thor	68-05-18	Thor	77-09-29	Atlas	98-08-26	Delta
59-09-17	Thor	61-10-21	Atlas	64-03-19	Delta	68-08-10	Atlas	78-03-25	Titan		
59-11-26	Atlas	61-10-23	Thor	64-03-24	Thor	68-08-16	Atlas	80-05-29	Atlas		
Commonwealth of Independent States/Soviet Union											
58-04-27	SL-2	65-02-20	SL-7	68-06-15	SL-8	71-08-19	SL-4	79-01-05	SL-13	87-01-30	SL-12
58-09-23	SL-3	65-04-10	SL-6	68-12-16	SL-6	71-11-24	SL-7	79-02-16	SL-4	87-04-24	SL-12
58-10-12	SL-3	65-07-13	SL-3	69-01-20	SL-12	71-12-03	SL-4	79-10-12	SL-4	87-06-18	SL-4
58-12-04	SL-3	65-12-16	SL-10	69-01-25	SL-11	72-04-25	SL-7	80-02-12	SL-6	88-01-18	SL-12
59-07-18	SL-3	65-12-28	SL-7	69-02-01	SL-3	72-07-29	SL-13	80-03-18	SL-3	88-02-17	SL-12
60-04-15	SL-3	66-02-05	SL-10	69-02-19	SL-12	72-09-02	SL-4	80-04-18	SL-6	88-07-09	SL-4
60-04-16	SL-3	66-02-21	SL-7	69-02-20	SL-15	72-10-17	SL-8	81-01-23	SL-14	88-07-27	SL-4
60-07-28	SL-3	66-03-18	SL-10	69-03-27	SL-12	72-11-23	SL-15	81-09-11	SL-6	88-11-11	SL-4
60-10-10	SL-6	66-03-24	SL-9	69-04-02	SL-12	73-04-25	SL-11	82-03-04	SL-8	89-06-09	SL-14
60-10-14	SL-6	66-03-27	SL-6	69-06-04	SL-12	73-05-25	SL-8	82-03-28	SL-4	90-04-03	SL-4
60-12-22	SL-3	66-05-17	SL-4	69-06-14	SL-12	73-06-26	SL-8	82-05-15	SL-4	90-06-21	SL-6
61-10-27	SL-7	66-05-20	SL-10	69-07-03	SL-15	73-07-04	SL-4	82-06-12	SL-4	90-07-03	SL-4
61-12-11	SL-3	66-05-24	SL-7	69-07-23	SL-7	74-04-12	SL-4	82-07-23	SL-12	90-08-09	SL-12
61-12-21	SL-7	66-09-16	SL-3	69-09-23	SL-12	74-05-23	SL-4	82-08-30	SL-8	90-10-04	SL-16
62-06-01	SL-3	66-11-16	SL-8	69-10-22	SL-12	74-07-11	SL-7	82-11-24	SL-8	91-06-25	SL-8
62-10-25	SL-7	66-12-14	SL-4	69-11-28	SL-12	74-08-30	SL-4	82-12-08	SL-6	91-08-30	SL-16
63-02-03	SL-6	67-03-22	SL-10	69-12-27	SL-8	75-04-05	SL-4	82-12-24	SL-12	92-02-05	SL-16
63-04-06	SL-7	67-06-21	SL-4	70-01-30	SL-7	75-06-03	SL-8	83-01-25	SL-8	93-04-27	SL-4
63-06-01	SL-7	67-06-26	SL-8	70-02-06	SL-12	75-10-16	SL-12	83-07-08	SL-6	93-05-27	SL-12
63-07-10	SL-3	67-07-20	SL-4	70-05-22	SL-7	75-12-19	SL-8	83-09-26	SL-4	94-05-25	SL-14
63-08-22	SL-7	67-09-01	SL-4	70-06-27	SL-8	76-09-01	SL-6	84-11-27	SL-14	95-03-28	SL-18
63-10-24	SL-7	67-09-27	SL-8	70-07-21	SL-4	76-10-04	SL-4	85-04-13	SL-16	95-10-06	SL-8
63-11-28	SL-3	67-09-28	SL-12	70-08-08	SL-13	77-02-22	SL-4	85-06-21	SL-16	96-02-19	SL-12
64-02-19	SL-6	67-11-22	SL-12	70-12-22	SL-8	77-08-04	SL-13	85-10-23	SL-8	96-05-14	SL-4
64-03-21	SL-6	68-02-07	SL-6	71-03-05	SL-7	77-08-10	SL-4	85-12-28	SL-16	96-06-20	SL-4
64-04-20	SL-6	68-03-06	SL-7	71-03-05	SL-4	77-11-29	SL-8	86-03-26	SL-4	96-11-16	SL-12
64-06-04	SL-6	68-04-22	SL-12	71-06-24	SL-15	78-05-27	SL-12	86-10-03	SL-6	97-05-20	SL-16
64-10-23	SL-8	68-05-21	SL-10	71-06-25	SL-4	78-08-17	SL-12	86-10-15	SL-14	97-12-24	SL-12
64-12-01	SL-7	68-05-28	SL-10	71-07-22	SL-8	78-10-17	SL-12	86-11-29	SL-13	98-09-09	SL-16
65-02-12	SL-7	68-06-04	SL-8	71-08-03	SL-7	78-12-19	SL-12	86-12-29	SL-13		
Europe		Japan		China		India		Israel		France	
68-11-30	Europa-I	66-09-26	Lambda-4S	73-09-18	FB-1	79-08-10	SLV-3	98-01-22	Shavit	71-12-05	Diamant-B
69-07-02	Europa-I	66-12-20	Lambda-4S	74-07-14	FB-1	81-05-31	SLV-3			73-05-21	Diamant-B
70-06-12	Europa-I	67-04-13	Lambda-4S	74-11-05	CZ-2	87-03-24	ASLV				
71-11-05	Europa-II	69-09-22	Lambda-4S	76-11-10	FB-1	88-07-13	ASLV	Brazil		United Kingdom	
80-05-23	Ariane-1	70-09-25	Mu-4S	79-07-28	FB-1	93-09-20	PSLV	97-11-02	VLS	70-09-02	Black Arrow
82-09-10	Ariane-1	76-02-04	Mu-3C	84-01-29	CZ-3	97-09-29	PSLV	North Korea			
85-09-12	Ariane-3	95-01-15	Mu-3S-II	91-12-28	CZ-3						
86-05-31	Ariane-2	98-02-21	H-II	92-12-21	CZ-2E			98-08-31	Taepo Dong-1		
90-02-22	Ariane-4			95-01-26	CZ-2E						
94-01-24	Ariane-4			96-02-14	CZ-3B						
94-12-01	Ariane-4			96-08-18	CZ-3						

The failures of the Europa vehicle for the European Launcher Development Organization were reminiscent of the early launch failures in the U.S. space program. After termination of the Europa program and many years of planning, Europe has developed the Ariane launch systems, which had eight failures since 1979. A very recent failure involved a brand new Ariane-5 vehicle, which is the most powerful vehicle in the Ariane family. During its maiden flight on 4 June 1996, the Ariane-5 vehicle veered off its flight path and exploded at an altitude of 12,140 ft (3700 m) 40 s after liftoff. The failure[17] was attributed to errors in the design and testing of the flight software. The flight software was programmed for Ariane-4 launch conditions and was never tested in conditions simulating Ariane-5's trajectory. The Ariane-5 is more powerful and travels much faster in horizontal velocity than the Ariane-4. The large apparent 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 correct flight guidance information.

The Japanese liquid-propellant rockets have suffered only one launch failure (H-II) since the liquid-propellant launch vehicle was first put into service in 1975. All of the other seven launch failures (including four Lamda-4S failures in 1966–1969) in Japan involved solid-propellant rockets. One of the failures involving the last flight of the Mu-3S-II vehicle[18] occurred on 15 January 1995. At 103 s after launch, the vector control thrusters, which partly control the rocket's pitch, began to oscillate. The rocket veered off course at 140 s after liftoff. The payload, a German satellite (Express 1), was put in a wrong orbit of 74.5 miles (120 km) altitude, instead of the intended orbit of 130 miles (210 km) altitude. The satellite fell into the African jungle in Ghana after circling the Earth two-and-a-half times. The failure was attributed to improper modeling of the flight control dynamics relative to the weight of the payload. Previous to the failure, the heaviest payload carried by the Mu-3S-II was 948 lbm (430 kg). Extra propellant had been added to the three stages and to the kick motor of the Mu-3S-II vehicle to provide extra thrust for the flight of the 1649 lbm (748 kg) Express 1 satellite. The flight was the eighth and final mission for the Mu-3S-II vehicle.

The Chinese space launch record had been marred by five failures in the past eight years. The most catastrophic failure occurred during the launch of a CZ-3B vehicle carrying a commercial satellite, Intelsat 708, on 14 February 1996. The 180-ft-tall (55-m-tall) CZ-3B is China's newest and most advanced vehicle. On its maiden flight[19] the CZ-3B began to veer off course before it even cleared the tower at the Xichang launch site at 2 s after liftoff. The vehicle with its Intelsat 708 payload impacted the ground and exploded in an inhabited area near the launch site at 22 s after liftoff. The explosion erased a village and a nearby military base and caused severe casualties and property damage. The cause of failure was traced to the vehicle's guidance and control subsystem. The inertial reference platform of the vehicle's first-stage guidance and control system for the CZ-3B maiden flight slanted, causing computers to send the vehicle veering off the planned trajectory shortly after liftoff. The inertial reference platform slanted because there was no electrical current output from the power module in the servo-loop.

Several satellites were dumped into the ocean in Bengal Bay since India's space program started in 1979. The new Polar Satellite Launch Vehicle (PSLV) is designed to place payload into a polar sun-synchronous Earth orbit. On its maiden flight[20] on 20 September 1993, the PSLV experienced an unplanned change in pitch at the time when the spent second-stage separated from the vehicle at 260 s 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 217-miles (349-km) orbit instead of the planned 506-miles (814-km) polar orbit. Shifting liquid fuel in the second stage of the vehicle could be the cause of 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 be the cause of the failure.

Analysis of Space Launch Vehicle Failures

The failure of a launch vehicle can be attributed to the problem associated with one of the following subsystems: propulsion, separation/staging, avionics, electrical, structures, other (relates to launch pad, ground power umbilical, ground flight control, lightning strike, and so forth), and unknown (indicates subsystem failure information is not available). The launch vehicle failures in 1983–1998 have been investigated.[21–25] Table 9 shows the statistics of subsystem failures in the world.

Table 9 shows that the predominant cause of the world launch vehicle failures from 1983–1998 is in the propulsion subsystem (U.S. 50.0%; non-U.S. 66.67%). In the United States, 11 of the 22 failures are in the propulsion subsystem. The failures in the propulsion subsystem can be further divided into failures in solid rocket motors and liquid rocket engines. The solid-propellant launch systems include Taurus, Conestoga, Athena, Pegasus, and Scout. The liquid-propellant launch systems include Titan II and Atlas (except Atlas IIAS). The hybrid launch systems, which consist of liquid-propellant cores and solid-propellant boosters, include STS, Titan IV, Titan III, Atlas IIAS, and Delta. The study shows that the success rate of the propulsion subsystem in the United States is 98.6% for solid rocket motors and 98.2% for liquid rocket engines from 1983–1998. The causes of the U.S. and non-U.S. launch vehicle failures can be summarized as follows in the next subsections.

U.S. Launch Vehicles

1) Fuel leak is caused by welding defects in tanks and fuel lines.
2) There are oxidizer and fuel leaks in feedline clamps and engine.
3) A hot gas leak occurred through SRM joint in cold weather.
4) Motor case burnthrough is caused by case insulation debond.
5) Short circuit in electrical relays is caused by vehicle vibration.
6) Loss of vehicle control is caused by a triggered lightning strike.
7) Fuel leak comes from damage in tanks or feedlines.
8) Payload separation failure is caused by incorrect wiring.
9) Turbopump failure comes from solidified air in pump/gearbox.
10) There exist incomplete stage and payload fairing separations.
11) There is a loose or misadjusted set screw in the fuel regulator.
12) Motor case burnthrough is caused by flame propagation into propellant cut.

Table 9 Subsystem failures (1983–1998)

Country	Propulsion	Avionics	Separation	Electrical	Structures	Other	Unknown	Total
United States	11	3	5	2	——	1	——	22
Commonwealth of Independent States/Soviet Union	30	3	2	——	——	1	6	42
Europe	5	1	——	——	——	——	——	6
Japan	1	1	——	——	——	——	——	2
China	3	1	——	——	2	——	——	6
India	1	1	——	1	——	1	——	4
Israel	1	——	——	——	——	——	——	1
Brazil	1	——	——	——	——	——	——	1
North Korea	——	——	——	——	——	——	1	1
Total	53	10	7	3	2	3	7	85

13) Erroneous aerodynamic load is used in autopilot software.
14) Stage separation failure is caused by an incorrectly installed interstage part.
15) SRM separation failure comes from overheating of explosive transfer lines.
16) There exist cables overheating and navigation system malfunction.
17) There is an error in filtering function of flight computer software.
18) Payload separation failure is caused by a defective switch.
19) The composite motor case is damaged in processing, handling, or assembly.

Non-U.S. Launch Vehicles

1) Engine failure was caused by combustion instability comes from inadequate injector design.
2) Engine turbopump failure is caused by insufficient lubrication or damage in gear trains.
3) Engine failure is caused by a leakage in hydrogen injector valve.
4) Engine failure is caused by a combination of imperfect processes in the ignition sequence.
5) Engine overheating comes from water flow blockage by a piece of cloth.
6) Engine shutdown is caused by bearing overheating.
7) Engine thrust loss is caused by obstruction of liquid oxygen flow to gas generator.
8) Guidance system failure is caused by design errors in the avionics software.
9) Vehicle lost attitude stability control is caused by a broken wire in the pitch-rate gyro circuit.
10) Engine shutdown prematurely comes from overheating and burnthrough of the turbine housing wall.
11) Engine shutdown comes from gas leakage in helium pressurization circuit for cryogenic propellant flow control.
12) Payload fairing structural damage or satellite explosion inside payload bay is caused by winds aloft or wind shear.
13) Guidance system defect caused the vehicle to veer off course.
14) Engine shutdown occurred prematurely because of a liquid hydrogen control valve leak.
15) Control system malfunction is caused by an electrical relay component defect or contact separation.
16) Engine shutdown is caused by a fuel line clogged or destruction.
17) Residual propellants in the stage caused an explosion.
18) Engine failure comes from a fuel line clogged by a piece of rag.
19) Engine shutdown comes from debris clogging in a fuel valve.
20) Payload shroud broke up, and the vehicle veered off course.
21) There was improper control dynamics modeling for heavy payload.
22) A short circuit occurred in the engine ignition system.
23) High winds and premature cutoff of strap-on boosters occurred.
24) Shifting liquid fuel caused the vehicle to veer off course.

Detailed discussions of the causes of failure and corrective actions for the U.S., European, and Chinese launch vehicles are presented in Refs. 21–25. Some of the failures are related to human errors, improper handling, poor procedures, management, workmanship, or judgment. In hindsight, many of these failures could have been prevented if rigorous reliability enhancement measures had been taken into account.

Launch Vehicle Reliability Enhancement

The experience and information gathered from the failure study of launch vehicles in the past indicate that the reliability of a launch vehicle system could be enhanced through the following working practices:

1) Review and incorporate all of the lessons learned in the past failure study to avoid recurrence of launch failures.
2) Limit space launch operation within the envelope of design environment and flight experience.
3) Validate the design by testing components to the point of destruction or with a high margin to allow for manufacturing and operating environment variances such as design margin testing successfully performed on ballistic missile programs.
4) Implement multistring/redundant avionics, electrical, and ordnance components for fault tolerance.
5) Perform electrical and pneumatic connection tests for each stage and between the stages before vehicle assembly.
6) Test components, software, and system level electrical at conditions similar to those in real operation.
7) Conduct system performance and flight simulation tests.
8) Utilize only flight-proven and defect-free components.
9) Apply advanced electronic beam welding, automation, and robotics for quality component manufacturing.
10) Confirm the separation mechanism function with a full-size dummy booster.
11) Simplify prelaunch procedures and launch processes to reduce contamination/damage in handling/processing.
12) Analyze the results of testing during development phase and take measures to improve product reliability.
13) Use stringent input control of raw materials, semifinished products, and components.
14) Design launch vehicles for low cost in manufacturing, operations, materials, and processes rather than for maximum performance or minimum weight.
15) Improve workmanship, component tests, manufacturing and assembly process, prelaunch check-out procedures, and launch management training.
16) Conduct comprehensive design analyses and show positive margins.
17) Minimize hardware reworks and tailor inspection testing for specific reworks.
18) Reduce pyro-shock levels whenever possible.
19) Reduce technical risks associated with schedule-driven launch dates.

Review of the causes of failure for space launch vehicles has revealed that the propulsion subsystem is the Achilles' heel of the space program. The propulsion subsystem is the heaviest and largest subsystem of a launch vehicle and consists of components that produce, direct, or control changes in launch vehicle position or attitude. It includes main propulsion components of rocket motors, liquid engines, and thrusters; combustion chamber; nozzle; solid propellant; liquid propellant; thrust vector actuator and gimbal mechanism; propellant storage; fuel and propulsion control components; feed lines; control valves; turbopumps; igniters; and motor and engine internal and external insulation and bondline. Similar propulsion components in the propulsion subsystem are also used as separation mechanisms in the separation/staging subsystem. Special attention[26] needs to be paid to the SRMs and/or LREs of the propulsion subsystem and of the separation/staging subsystem in the areas discussed in the next subsection.

Solid Rocket Motors

1) Control propellant ingredient upon receipt and prior to use and verify propellant mix procedure and burn rate for every mix before casting.
2) Cast motors from a single lot of material to minimize thrust imbalance for the vehicle with multiple SRMs.
3) Use high safety factor (1.5) for nozzle ablative material.
4) Cast solid propellant in vacuum if possible to reduce number and size of voids in propellant.
5) Use modern techniques (e.g., computer tomography) to detect solid-propellant defects and propellant-to-insulation bondline separation before motor assembly.
6) Minimize the number of field joints or utilize monolithic design or nonseparable, bolted-flange joint for SRM.
7) Control the bondline formation process for fault tolerance and long service life for SRM.
8) Apply new analysis techniques[27–29] for fast, accurate, and low-cost modeling of exact design configuration prior to hardware fabrication for reduced risk.

9) Implement chemical fingerprinting for rare and sensitive chemicals such as propellant binder, motor case resins, flexseal elastomers, adhesives, etc.

10) Plan into the development and qualification programs a motor case cure study wherein a cured case is dissected to assess the adequacy of the case manufacturing process.

Liquid Rocket Engines

1) Qualify liquid engines at above the maximum operating environments, conditions, and duration.

2) Design and build engines with robustness and with high thermal and structural margins to allow for manufacturing deviations.

3) Use welded joints instead of seals for fluid lines.

4) Allow high-pressure margin in tanks, hydraulic lines, and plumbing, and inspect all welds with 100% coverage.

5) Apply redundancy in fluid valves and igniters.

6) Utilize effective liquid film cooling or ceramic coatings to increase thrust-chamber durability.

7) Apply advanced high-strength (aluminum-magnesium) welding and milling for construction of thin-walled fuel and oxidizer tanks.

8) Eliminate fracture problem by rolling the tank shell segments before machining the isogrid.

9) Conduct extensive test program for engine operation at various operating conditions after exposure to harsh transportation environment.

10) Use helium (for cryogenic propellants) or nitrogen (for storable propellants) purging of pipelines and oxidizer/fuel pumps before engine startup and purging of chamber cooling duct at engine shutdown to provide a clean flow duct and to avoid fire/explosion danger.

Conclusions

More than half a century ago, air advantage of the Allied Forces contributed significantly to the course of World War II. In the future the outcome of conflicts will rely upon space technology. The Falkland Islands War of 1982 and the Persian Gulf War of 1991 are two examples impacted decisively by intelligent utilization of space resources. Future commercial and national defense needs of space-related technologies in propulsion, guidance and control, communications, navigation, tracking and data relay, weather forecast, remote sensing, surveillance, reconnaissance, early warning and missile defense, and interplanetary exploration are expected to increase. Global high-speed telecommunication, video-conference, and Internet applications require launching of many satellites. The demand for space launch services is ever increasing, soon to exceed the U.S. government's defense budget, and launch failures will occur in the coming years. This paper reviewed the success rate of all of the launch systems, identified the worldwide launch failures for the past 42 years, and provided some of the lessons learned for the past 16 years. It is hoped that the information contained in this paper will be of some help in mitigating launch failures in the future.

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