A STUDY OF ORBITAL CARRIER ROCKET AND SPACECRAFT FAILURES: 2000-2009

Anatoliy GORBENKO, Vyacheslav KHARCHENKO,
Olga TARASYUK, and Sergiy ZASUKHA

Abstract: Aerospace industry has become one of the most important and dynamically developed sectors of the world economy in the last decades. It brings in billions of US dollars due to commercialization of space projects, especially by provisioning telecommunications services, Earth observation and navigation, weather monitoring, etc. Space projects belong to so-called mission critical applications, i.e. applications, whose failures cause both material and pecuniary losses (and sometimes, unfortunately, loss of human lives) and also can ruin long-term scientific, military and other important government or commercial programs. Besides, high reliability and safety of rocket-space systems are of an increasing economic importance, since the disasters and space accidents lead not only to missing profits, but also to millions of dollars loss. The purpose of the paper was to analyze the risks of the launch vehicle crashes and spacecraft failures, which occurred during the first decade of the 21st century. In the paper we present orbital carrier rockets and spacecrafts launch statistics from 2000 to 2009. We investigate the causes of launch vehicle crashes and spacecraft failures and also analyze faults in different subsystems resulted in such accidents, focusing mainly on the influence of computer-based control systems, their hardware and software components on reliability and safety of rocket-space systems..

Keywords: Reliability and safety of rocket-space systems, risks of orbital carrier rockets and spacecraft failures, computer systems reliability, software faults.

Introduction

Aerospace industry has become one of the most important and dynamically developed sectors of the world economy in the last decades. It brings in billions of US dollars due to commercialization of space projects, especially by provisioning telecommunications services, Earth observation and navigation, weather monitoring, etc. Aerospace industry is an important part of the country's prestige in the world community. High achievements in this industry domain are only possible under conditions of high reliability and safety of rocket-space systems. This factor is of an increasing economic importance, since the disasters and space accidents lead not only to missing profits, but also to millions of dollars loss. Space projects belong to so-called mission critical applications, i.e. applications, whose failures cause both material and pecuniary losses (and sometimes, unfortunately, loss of human lives) and also can ruin long-term scientific, military and other important government or commercial programs. The latest example of such an accident occurred on 5 December 2010 when the Russian *Proton-M* orbital carrier rocket with a new upper stage (booster) *Block DM-03* failed to inject three *Glonass-M* navigation satellites into the orbit. This failure cost more than fifty million dollars and also prevented Russia from completing the *GLONASS* (*Russian GLObal NAvigation Satellite System*) orbit group. The launch failure was caused by an incorrect fuelling of a booster making the rocket too heavy to reach its parking orbit.[1] This example, as well as many others, gives evidence that reliability and safety of rocket and space technologies are far from being perfect and still need much effort to reduce risks and improve their safety. A lot of statistical data concerning failures, accidents and disasters of rockets, artificial satellites and spacecrafts has been collected since the USSR launched its first earth satellite in 1957 and thereby opened the space age. Most of such events happened during 1960-1990 are described and investigated in the A.B. Zheleznyakov' monograph.[2] This monograph was used as a main source to perform statistical analysis of rockets launches and risk assessment.[3] We investigated the causes of rocket crashes and satellite failures and also analyzed faults in different subsystems resulted in such accidents, focusing mainly on the influence of computer-based control systems, their hardware and software components on reliability and safety of rocket-space systems.[4] According to our previous analysis and results of risks assessment, every 100th space launch during 1960-2000 failed due to software faults, which also caused 6 of the 7 failures of computer-based control systems of the rockets and spacecrafts. This shows a growing dependence of the rocket-space complexes on the characteristics of computer-based control systems and, first of all, software reliability. In this connection, we can state that a part of software-implemented functions in the aviation and rocket-space systems is constantly increasing.

For instance, US Department of Defense reported a growth of software-supported functions performed by a military airplane from 8 % for the F-4 in 1960 up to 80 % for the F-22 in 2000.[5] The similar tendency is also observed for the rocket and space systems. This is a mater of a great importance, taking into account the fact that software faults can cause common-mode failures despite using traditional redundancy techniques (e.g. duplication, majority voting, time redundancy, etc.).[6]

The *purpose* of the paper was to analyze the risks of the launch vehicle crashes and spacecraft failures, which occurred during the first decade of the 21st century and caused by the equipment failures and faults of computer-based control systems, their hardware and software components. This paper is a continuation of our previous works.[7] Together they provide a comprehensive survey of space accidents during the last fifty years. The rest of the paper is organized as follows. In the first section we provide an overview of the source information, describe analysis principles and explain research methodology used. The second section summarizes statistics of orbital carrier rocket launches by years and launching countries. In the third and fourth sections we estimate probability of launch and spacecraft failures and also perform comparison of failure rates between the last decade of the 20th century and the first decade of 21st century. The fifth section analyses different causes of the space accidents placing emphasis on failures of on-board hardware and software. The sixth section provides an overview of major incidents caused by failure of computer systems that happened on the International Space Station *Alpha*. The last section concludes with the statistical laws and lessons learnt.

1. Research Methodology and Information Sources Overview

The paper covers the statistical data of space launches, accidents and failures happened in the period 2000-2009. In our survey we omitted information about ballistic and cruise missiles.

Unlike our previous works that used Zheleznyakov's monograph as a primary source of information about space incidents and failures, in this current work we analyzed a broad range of public information sources complementing (but sometimes contradicting) one another: journal publication and conferences talks, newspaper accounts, information agencies reports, thematic Web sites, forums and weblogs, first of all: (1) www.planet4589.org/space/jsr/jsr.html; (2) http://www.spacelaunchreport.com; (3) www.astronautix.com; (4) http://en.wikipedia.org/wiki/2000_in_spaceflight; (5) www.cosmoworld.ru/spaceencyclopedia/; (6) http://www.insur-info.ru/aerospace-insurance/; (7) http://astro.websib.ru/kosm/sprav/itog/i_2000.htm; (8) www.novosti-kosmonavtiki.ru; (9) www.news.cosmoport.com/2000/01/; etc. We should state that none of the information sources used provides the complete launches statistic and exhaustive investigation of space accidents. The results reported in the paper were obtained by complementing different sources and their cross-validation involving judgements of experts from Ukrainian National Space Agency's and National Airspace University. It is worth taking into consideration the fact that the vast majority of the official accident investigation reports are unavailable or has limited access. Nevertheless, the public information of rocket launches and accidents is characterized by the high completeness and trustworthiness whereas there is a lack of trusty and thorough data about satellite/spacecraft failures and incidents. Under the circumstances the authors do not provide one-hundred-percent correct and complete results. Tentatively, the results of failure probabilities estimation, discussed in the paper, tend to be slightly optimistic. For each of the analyzed accidents the exact date/time, type of rocket/satellite/spacecraft, launching country and country of origin, and the most likely cause and consequences were identified. Our investigation has resulted in: (1) statistical estimation and trend analysis of rocket crashes and launch failure probabilities; (2) statistical estimation and trend analysis of satellite/spacecraft failure probability; (3) accident and failure causes analysis. The results, presented in tables, graphics, and diagrams, can be used for further statistical probabilities and risks analysis (e.g. estimation of confidence bounds) using a proven research methodology.[8]

2. Rocket Launch Statistics

Numbers of rocket launches during 2000-2009 aggregated by years and countries of origin are presented in Table 1. It includes launches recorded by the Committee on Space Research (*COSPAR*) and North American Air Defense Command (NORAD). The vast majority of rocket launches traditionally accounts for Russia and USA. Ukraine is among five top leaders behind European Community (EC) and China. Nevertheless, the total number of rocket launches has decreased by 25 percent during the last decade as against the period 1990-1999 (663 against 891). Russia, USA and Ukraine reduced number of orbital carrier rocket launches by one third, European Community – by 22 percents. At the same time, there is a significant positive dynamics shown by Japan (half as many), China (1.7 times as many), India (2.6 times as many). Launches made by Brasilia, Iran, Israel, North and South Koreas were joined together in column titled 'Another countries' (see Table 1) because of their insignificant contribution to the overall sum. It is worth taking into consideration that some countries (particularly Ukraine) developing and manufacturing orbital carrier rockets do not have their own launching sites and, hence, are forced to rent (e.g. Russia rents the *Baikonur* Space Centre in Kazakhstan) or to transfer launching authority to the third countries (e.g. almost all Ukrainian rockets are launched by Russia). In particular, Ukraine manufactures such orbital carrier rockets:

- *Zenit-3SL* launched from the marine-based equatorial launch site by the International *Sea Launch* service in cooperation with Russia, the USA and Norway (32 launches during from 2000 till 2009);
- *Zenit-3SLB*, *Zenit-2SLB*, *Dnepr-1*, *Tsyklon-3* and *Tsyklon-2* launched from the Kazakhstan' *Baikonur* Space Centre and Russian cosmodromes within the international projects *Land Launch* and *Kosmotras* (23 launches in total from 2000 till 2009).

Tsyklon-2 and *Tsyklon-3* made their final flights in 2006 and 2009 respectively (the first rocket of *Tsyklon* family made its maiden flight on August, 6, 1969). Ukrainian-built *Tsyklon-3* made 122 launches in total with only seven reported as unsuccessful whereas all 106 launches of *Tsyklon-2* were successful.

The maiden launch from the Alcantara Launch Centre in Brazil of a new *Tsyklon-4* rocket developed to replace *Tsyklon-2/3* is scheduled for 2012. *Tsyklon* family's orbital carrier rockets are one of the most reliable (94.3% of success rate) and surpass in the reliability all the others (i.e. *Ariane*, *Delta*, *Proton*).[9] Besides, *Tsyklon-2* is the most reliable carrier rocket overall, that together with the USA' *Atlas II* (63 launches) has never experienced a failure. It should be noted, that Wikipedia [10] and some other sources falsely report one of the successful launches made by Tsyklon-2 on 25 April 1973 as a failure. However, launch description [11] states that it was a failure of a payload propulsion system, but not Tsyklon-2 itself that is in-line with Tsyklon's manufacturer statement.

Apart from *Tsyklon,* the last decade was also transitional for many other rocket families. Thus, *Atlas II* and *Ariane-4* also retired during 2000-2009 whereas *Soyuz-FG*, *Atlas V*, *Delta IV*, *Soyuz-2* and *Proton-M* launch vehicles made their maiden flights.

Table 1. Lunch attempts from 2000 to 2009.

Year	*Russia*	*US*	*EU*	*China*	*Ukraine*	*Japan*	*India*	*Other*	*Total*
2000	32	28	12	5	7	1	0	0	85
2001	19	22	8	1	6	1	2	0	59
2002	25	17	12	5	1	3	1	1	65
2003	21	23	4	7	3	3	2	1	64
2004	18	16	3	8	7	0	1	1	54
2005	26	12	5	4	5	2	1	0	55
2006	23	18	5	6	7	6	1	0	66
2007	22	19	6	10	5	2	3	1	68
2008	24	16	6	11	8	1	3	0	69
2009	27	24	7	6	6	3	2	3	78
Total	237	195	68	63	55	22	16	7	663

3. Launch Failure Statistics And Probability Estimation

3.1. The period from 2000 to 2009

Launch failure statistics is presented in Table 2. A number of failures were grouped according to years, countries of origin and failure types (fatal or partial launch failures) and their effects. A fatal launch failure (FLF) results in rocket fall, explosion or auto-disruption due to a wrong trajectory and other accidents preventing the placement of a payload to orbit (payload failure to orbit, PFO). A partial launch failure (PLF) results in payload placement in the incorrect orbit, IOP. In this case some spacecrafts have a chance to correct the orbit using their own thrusters, reducing the lifespan. For example, on July 12, 2001 due to premature cut-off of the Ariane 5G second stage the *Artemis* and *BSAT-2B* satellites were placed in orbit much lower than the target geostationary. However, the *Artemis* managed to reach the correct orbit under its own power, whereas *BSAT-2B* was abandoned in useless orbit. Finally, in just eight cases out of 14 (see Table 2) the spacecrafts, placed in the wrong orbit, managed to correct it by themselves. Launch failure probability curves for different countries are shown in Figure 1. In addition to Brasilia, Iran, Israel, North and South Korea, 'Other countries' curve represents also Japan and India.

Probability of a launch failure (1) was estimated as a ratio between number of launch failures (both fatal N_{PLF} and partial N_{PLF}) and the total number of launch attempts (N_{LA}).

$$P_{LF} = (N_{FLF} + N_{PLF})/N_{LA.} \tag{1}$$

An annual average value of launch failure probability varies in a range [0.04, 0.10]. The maximal failure probability (0.106) was fixed in 2006 when 7 launches out of 66 were unsuccessful. An average value estimated for all 10 years from 2000 to 2009 equals 0.072, including the probability of a payload failure to orbit (0.051), and the probability of placing payload in incorrect orbit (0.021). This tendency seems to become stabilize and will remain so in the near future. It means that launch authorities and rockets owners have to agree to lose from 2 to 9 (from 4 to 10 taking into account partial launch failures) rockets per every hundred launches.

3.2. Comparing the decades of 1990-1999 and 2000-2009

In the first decade (2000-1999) of the 21st century the launch failure probability increased half as much against the last decade (1990-1999) of the 20th. At the same time (see Table 3), the total number of launches during 2000-2009 years decreased by 25% as compared to 1990-1999. Such negative tendency was most likely caused by the retirement of the high-reliable but outmoded orbital carrier rockets, first of all *Tsyklon-2/3* and *Atlas II/III*, and putting into operation of a new rockets that are more effective and powerful but not well-tried. There are two main factors characterizing the operational reliability of carrier rockets. The first one is the statistical estimation of the probability of failure (probability of success). The second one is the number of the latest successful launches.

Table 2. Launch failures from 2000 to 2009.

Year	*Failure type and effect**	*Russia*	*US*	*EU*	*China*	*Ukraine*	*Japan*	*India*	*Other*	*Total*
2000	FLF/PFO	1	0	0	0	2	1	0	0	4
	PLF/IOP	0	1	0	0	0	0	0	0	1
2001	FLF/PFO	1	1	0	0	0	0	0	0	2
	PLF/IOP	0	0	1**	0	0	0	1**	0	2
2002	FLF/PFO	1	0	1	1	0	1***	0	0	4
	PLF/IOP	1**	0	0	0	0	0	0	0	1
2003	FLF/PFO	0	1	0	1	0	1	0	1	4
	PLF/IOP	0	0	0	0	0	0	0	0	0
2004	FLF/PFO	0	0	0	0	0	0	0	1	1
	PLF/IOP	0	1**	0	0	2	0	0	0	3
2005	FLF/PFO	4	0	0	0	0	0	0	1	5
	PLF/IOP	0	0	0	0	0	0	0	0	0
2006	FLF/PFO	1	3	0	0	1	0	1	0	6
	PLF/IOP	0	1**	0	0	0	0	0	0	1
2007	FLF/PFO	1	1	0	0	1	0	0	0	3
	PLF/IOP	0	1	0	0	0	0	1	0	2
2008	FLF/PFO	0	1	0	0	0	0	0	1	2
	PLF/IOP	1	0	0	0	0	0	0	0	1
2009	FLF/PFO	0	2	0	0	0	0	0	1	3
	PLF/IOP	1	0	0	1	0	0	0	1	3
Total	FLF/PFO	9	9	1	2	4	3	1	5	**34**
	PLF/IOP	3	4	1	1	2	0	2	1	**14**

Notes. **FLF/PFO – fatal launch failure resulted in payload failure to orbit; PLF/IOP – partial launch failure resulted in payload placement in the incorrect orbit. **The satellites placed in the incorrect orbit were unable to successfully correct it using their own propulsion and were abandoned in useless orbit. ***DASH spacecraft failed to separate itself from the upper stage during maiden flight of Japanese H-IIA 2024, whereas MDS-1 satellite was successfully placed in orbit.*

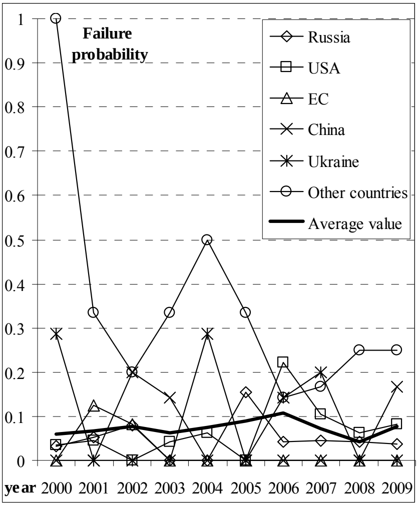

Figure 1. Launch failure probability curves during 2000-2009 yrs

Table 3. Comparison of launch attempts and failures in 1990-1999 and 2000-2009

Year	*Number of launches*	*Number of*	*Risk*	*Year*	*Number of*	*Number of*	*Risk*
1990	117	1	.009	2000	85	5	.059
1991	89	1	.011	2001	59	4	.068
1992	96	1	.010	2002	65	5	.077
1993	82	3	.037	2003	64	4	.063
1994	93	4	.043	2004	54	4	.074
1995	81	7	.086	2005	55	5	.091
1996	76	3	.039	2006	66	7	.106
1997	91	5	.055	2007	68	5	.074
1998	83	6	.072	2008	69	3	.043
1999	83	10	.120	2009	78	6	.077

3.3. Reliability of Orbital Carrier Rockets

Table 4 summarizes the operational reliability of the frequently used orbital carrier rockets (rockets *Tsyklon-2/3*, *Dnepr-1*, *Rokot*, *Start* are upgraded intercontinental ballistic missiles). The results presented in Table 4 are in line with the space launch report [12] where a more detailed analysis has been carried out taking into account different modifications of launch vehicles. According to Table 4, there are several rockets all launches of which have been successful so far: (i) *Tsyklon-2* and *Atlas II/III* that were retired in 2006 and 2005 respectively; (ii) *Soyuz-FG* launch vehicle made its maiden flight on May 20, 2001. It is an improved version of the *Soyuz-U* using new engines of the first and the second stages. American *Delta II* and Russian *Soyuz-U* and *Proton-K* have the greatest number of the latest successful launches among the active carrier rockets. Their latest failures happened in 1997 (*Delta II*), 2002 (*Soyuz-U*) and 1999 (*Proton-K*). Two most recent fatal launch failures happened in 2010 (*Proton-M*) and 2007 (*Zenit-3SL*). *Soyuz-U* is the most used and one of the most reliable launch vehicle ever made with 18 fatal failures and 698 successes.

It is worth considering that the statistical reliability estimation is complicated by the fact that launch vehicles have variety of active modifications using different engines,

Table 4. Orbital carrier rockets operating reliability

Rocket	*Maiden launch date*	*Last launch date***	*Last date of a fatal failure*	*Number of launch attempts*		*Number of failures*		*Reliability, %*****	
				total	last successes	fatal	partial		
Tsyklon-2*	06.08.69	25.06.06	-	106	106	0	0	100.00	(100.00)
Atlas II/III*	07.12.91	03.02.05	-	70	70	0	0	100.00	(100.00)
Soyuz-FG	20.01.01	15.12.10	-	33	33	0	0	100.00	(100.00)
Atlas V	21.08.02	21.09.10	-	23	23	0	1	100.00	(95.65)
Delta IV	11.03.03	21.11.10	21.12.04	14	10	0	1	100.00	(92.86)
Soyuz-2	08.11.04	02.11.10	-	9	9	0	1	100.00	(88.89)
Delta II	14.02.89	06.11.10	17.01.97	148	93	1	1	99.32	(98.65)
Soyuz-U	18.05.73	27.10.10	15.10.02	716	46	18	1	97.49	(97.35)
Ariane-4*	22.01.90	15.02.03	01.12.94	116	73	3	0	97.41	(97.41)
Proton-M	07.07.01	26.12.10	05.12.10	50	1 (***)	2	3	96.00	(90.00)
Tsyklon-3*	24.06.77	30.01.09	27.12.00	122	3	5	2	95.90	(94.26)
Kosmos-3M	15.05.67	27.04.10	20.11.00	446	22	20	1	95.52	(95.29)
Ariane-5	04.06.96	29.12.10	11.12.02	55	41	3	1	94.55	(92.73)
Zenit-3SL/3SLB	28.03.99	30.11.09	31.01.07	34	10	2	1	94.12	(91.18)
Dnepr-1	21.04.99	21.06.10	26.07.06	16	9	1	0	93.75	(93.75)
Proton-K	10.03.67	28.02.09	27.10.99	310	44	26	9	91.61	(88.71)
Rokot	20.11.90	08.09.10	08.10.05	18	7	2	0	88.89	(88.89)
Zenit-2/2M	13.03.85	22.06.09	09.09.98	38	7	5	0	86.84	(86.84)
Start	25.03.93	25.04.06	28.03.95	7	5	1	0	85.71	(85.71)

Notes: **Tsyklon-2/3, Atlas II/III and Ariane-4 have been retired.* ***Information is updated up 31 Dec 2010.* ****Taking into account the fact that the latest Proton-M failure was caused by incorrect fuelling, rather than by rocket malfunction itself.* *****Success probability accounting both fatal and partial failures (e.g. placing the payload in incorrect orbit) is given in brackets.*

boosters, upper stages, fuel tanks, control systems, etc. For example, Ariane 5 has been refined since the first launch in successive versions: ‘G’, ‘G+’, ‘GS’, ‘ECA’, ‘ES’, ‘ECB’. Taken separately each modification commonly has scanty launch statistics that decreases the confidence in the reliability whereas the overall estimation could be rough.

4. Spacecrafts Failure Statistics And Probability Estimation

4.1. The period from 2000 to 2009

Table 5 summarizes the spacecrafts failure statistics during 2000-2009 years. The main causes of spacecraft failures are as follows:[13] (1) fatal launch failure (e.g. rocket explosion) resulting in payload failure to orbit including undocking problems (FLF/PFO); (2) partial launch failure due to rocket malfunction (e.g. propulsion premature cut-off) resulting in payload placement in incorrect orbit (PLF/IOP); (3) deployment failure in orbit (DFI), e.g. failure of solar array or communications antenna deployment, wrong orientation or impossibility of stabilization, etc.; (4) failure to contact the ground immediately after deployment (FCG); (5) onboard equipment failures (OEF) and mechanical failures and damages (MFD) occurring during spacecraft operation. As it has already been mentioned, some spacecrafts, placed in incorrect orbit can nevertheless reach the correct orbit using their own thruster. However, this reduces spacecraft's life span (which is supposed to be about 12 years on the average for the navigation and communication satellites) by the factor 2..4. In total, there were 191 spacecraft failures registered and 128 spacecrafts (among those 1060 launched) lost during 2000-2009. Analyzing spacecraft failures we took out of consideration numerous failures and breakages at the *Alpha* international space station. Besides, we omitted the failures of spacecrafts launched to orbit before 2000. According to Table 5, 7.36 percents of spacecrafts failed to reach the correct orbit ($PFO \cup IOP_{FF}$) due to carrier rocket accident of malfunction. The largest number of satellites lost because of this was observed in 2006 when 18 out of 23 satellites were lost that year due to single launch failure of Dnepr-1 orbital carrier rocket on 26 July. 1.98 percents of spacecrafts failed to deploy in orbit or to contact the ground after deployment (SDF). Finally, 2.74 percents of spacecraft failures resulted in their losses were caused by onboard equipment breakdowns or mechanical damages during the operation ($SEF_{FF} \cup SMD_{FF}$).

Out of 103 spacecraft failures, 50 were fatal (resulted in a spacecraft loss), 27 were partial (reduced spacecraft functionality) and 26 were tolerated due to equipment redundancy or maintenance operations (for instance, by updating software of on-board computers). Figure 2 shows probability trends of spacecrafts failures caused by different reasons. The cumulative spacecrafts failure probability (taking out of consideration those failures successfully tolerated) was estimated by the equation (2).

$$P_{SF} = \frac{N_{PFO} + N_{IOP(FF+PF)}}{N_{SL}} + \\ + \frac{N_{SDF} + N_{SEF(FF+PF)} + N_{SMD(FF+PF)}}{N_{SL}}, \qquad (2)$$

where N_{PFO} is the number of spacecrafts failed to reach the orbit because of launch vehicle accidents (e.g. explosion); $N_{IOP\ (FF+PF)}$ is the total number of spacecrafts placed in incorrect orbit due to malfunction of orbital carrier rockets (e.g. premature upper stage's engine cut-off); N_{SDF} is the number of spacecrafts failed to deploy in orbit or to contact ground after deployment; $N_{SEF(FF+PF)}$ is the number of fatal and partial failures of on-board equipment during spacecraft operation; $N_{SMD(FF+PF)}$ is the number of fatal and partial mechanical failures and damages during operation; N_{SL} is the total number of spacecraft launched to orbit in 2000-2009. Figure 2 shows that the cumulative probability of the fatal and partial spacecraft failures ($PFO \cup IOP_{FF} \cup IOP_{PF} \cup SDF \cup SEF_{FF} \cup SEF_{PF} \cup SMD_{FF} \cup SMD_{PF}$) has significant jitter as compared to launch failure probability (see Fig. 1). In average, it equals 0.15 which is twice as much as launch failure probability. Maximum of the spacecraft failure probability was observed in 2006, which was mainly caused by exposure of *Dnepr-1* launch vehicle carried 18 satellites.

4.2. Comparing the decades of 1990-1999 and 2000-2009

The comparative analysis of the decades o 2000-2009 and 1990-1999 [14] shows that despite decreased number of rockets launches, the total number of spacecrafts

Table 5. Statistics of spacecrafts launches and failures

Year	Number of launches	Number of spacecrafts failures by causes										Total failures
		PFO	IOP		SDF	SEF			SMD			
			FF	PF*		FF	PF	TF	FF	PF	TF	
2000	130	9	1		6	2	1	2				21
2001	91	6	2	1	1	3	1	2				16
2002	103	5	1		1	1	1	1			1	11
2003	104	8				2	1			3		14
2004	77	1	3	3		1	2	1		1		12
2005	74	5			1	1	2	4				13
2006	116	23	1		7	3	2	4	1			41
2007	119	3		3	1	5	4	4		2		22
2008	114	5		1		4	2	2	1	3		18
2009	132	4	1	2	4	5	2	5				23
Total	1060	69	9	10	21	27	18	25	2	9	1	191

Notes. *The following abbreviations are used in the table: PFO – payload failure to orbit caused by rocket accident; IOP – payload placement in incorrect orbit; SDF – spacecraft deployment failure caused by the inability to deploy successfully after reaching correct orbit or to contact ground after deployment; SEF – spacecraft onboard equipment failure during operation; SMD – spacecraft mechanical damage during operation; FF – fatal failures; PF – partial failures (*including those when spacecraft managed to reach correct orbit using its own thruster, but reducing lifespan); TO – tolerated failure.*

launched to orbit increased by the factor 1.25 (see Table 6). At the same time, the probability of fatal and partial spacecraft failures and mechanical damages ($SDF \cup SEF_{FF} \cup SEF_{PF} \cup SMD_{FF} \cup SMD_{PF}$) has also increased from 0.059 to 0.073.

One of the important facts is that 9.34 percent of spacecrafts in 2000-2009 were lost during launching, deployment or immediately after deployment in orbit ($PFO \cup IOP_{FF} \cup SDF \cup SEF_{FF} \cup SMD_{FF}$). This takes 77.3 (!) percents of the total number of spacecrafts loses. The rest were lost because of fatal failures of onboard equipments and physical damages during operation.

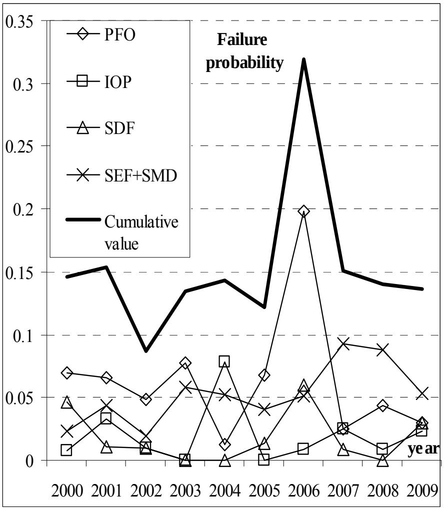

Figure 2. Spacecraft failure probabilities

Table 6. Comparison of numbers of spacecrafts launches and failures between 1990-1999 and 2000-2009

Year	*Launches*	*Failures*	*Risk*	*Year*	*Launches*	*Failures*	*Risk*
1990	116	2	.017	2000	130	9	.069
1991	88	2	.023	2001	91	5	.055
1992	95	0	0	2002	103	3	.029
1993	79	0	0	2003	104	6	.058
1994	89	2	.022	2004	77	4	.052
1995	74	3	.041	2005	74	4	.054
1996	73	1	.014	2006	116	13	.112
1997	86	12	.14	2007	119	12	.101
1998	77	16	.208	2008	114	10	.088
1999	73	12	.164	2009	132	11	.083

5. Rocket and Spacecraft Failure Cause Analysis

5.1. Classification of causes for failure

On the basis of analysis of space accident descriptions and taking into account other study results,[15] we distinguish several basic cause modes resulted in launch and spacecrafts failures. Launch failure causes (by failure source): 1) malfunction of the first rocket stage (1S); 2) malfunction of the second rocket stage (2S); 3) malfunction of the third rocket stage (3S); 4) payload undocking failure including failures of fairing separation (PUF); 5) upper-stage malfunction (US); 6) computer control system hardware fault (HW); 7) computer control system software fault (SW).

The most frequent causes of launch failures are formulated as 'an ingress of extraneous solid particle into rocket stage engine causing rocket explosion' and 'premature cut-off of propulsion system causing payload failure to orbit or placement in incorrect orbit'. According to expert judgments such evasive statements are used when the exact cause cannot be found. For the spacecraft failure causes we have defined eight subsets based on the subsystem where a failure has occurred: 1) radio equipment failures (RE); 2) hardware failures and glitches (HW); 3) software faults (SW); 4) power-supply system failures, including accumulators and solar arrays (EPS); 5) gyroscope failures (GS); 6) satellite mechanical damages (SMD); 7) failures of propulsion subsystem (PS); 8) human errors made by maintenance staff (HE). Tables 7 and 8 summarize different causes of carrier rocket and spacecraft failures happened during 2000-2009 and their consequences. We only omitted the space shuttle *Columbia* disaster while re-entering the atmosphere on 1 February 2003 and numerous failures happened on board of the ISS *Alpha*.

5.2. Computer Systems Failures and Glitches

According to Figure 3, faults of control system software caused 13 percent of the total number of launch failures and 20 percent of spacecraft failures (see Figure 4). In addition to that, another 6 percent of spacecrafts operational failures were caused by hardware failures and glitches, whereas this cause is not typical of launch failures. At the same time, software faults caused only 6 percent of fatal spacecrafts failures and as much as 15 percent of fatal launch failures. Such a difference is explained by the fact that spacecrafts unlike launch vehicles in most cases can be repaired from software bugs by software updating (from the mission control centre) after coming computer system into a protected usage mode. On average, software faults resulted in fatal or partial launch failure in one out of 110 launches during 2000-2009 which is in line with 1990-2000 when every hundredth launch was failed due to software malfunction. However, a part of launch failures caused by software faults or computer glitches can be significantly higher in reality.

The thing is that one third of rockets failures was officially reported to be caused by *premature cut-off of a rocket engine*. As a matter of fact, such an occurrence can be caused either by engine malfunction itself or by erroneous command to cut off a propulsion system sent by on-board computer control system (its software) performing crucial navigation, stabilizations, fuel consumption, stages and payload separation

Table 7. Causes and consequences of orbital carrier rocket failures

Failure source	Failure consequence		Total
	Fatal launch failure	Payload placement in incorrect orbit	
1S	9	2	11
2S	7	4	11
3S	5	4	9
PUF	5	1	6
SW	5	1	6
US	1	2	3
HW	1	0	1
Total	33	14	47

Table 8. Causes and consequences of spacecraft failures

Failure source	Failure consequence			Total
	Fatal failures	Partial failures	Tolerated failure	
RE	20	11	0	31
SW	3	2	16	21
EPS	15	3	2	20
SMD	5	8	2	15
HW	3	0	3	6
GS		2	3	5
PS	2	2	0	4
HE	1	0	0	1
Total	49	28	26	103

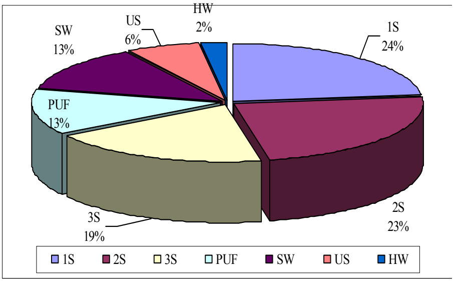

Figure 3. Different sources of orbital carrier rocket failures

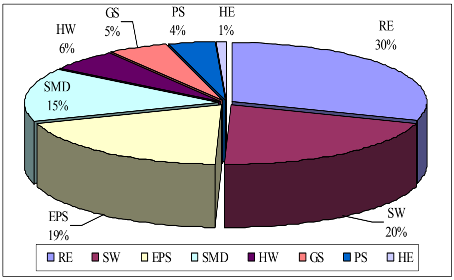

Figure 4. Different sources of spacecraft failures

controlling functions. In this connection *Zenit-3SL* accident happened on March, 12, 2000 is of particular interest to software engineers. The failure cause analysis panel has stated that the launch abort was caused by software error resulted in the premature cut-off of the second stage, leaving the ICO F-1 satellite unable to reach orbit. A logical error was introduced into software algorithm of ground complex of automated control systems of processing and launch. A necessary command to close an electropneumatic valve of the second stage's pneumatic system had not been sent. This resulted in an unauthorized termination of second stages' steering engine operation at 461st second into the flight due to considerable gas release. The rocket was autodestructed when the trajectory deviation became critical. The ground complex of automated control systems of processing and launch has been developed by the engineers of Rocket and Space Corporation *Energia* (Russia). An important thing is that a logical mistake was made by the developer during software upgrading (!): the ground control software had been modified to accommodate a slight change in requirements prior to launch of Zenit-3SL.[16] One line of code, a conditional meant to close a valve just prior to launch, was somehow deleted. Pre-flight tests missed the error. Moreover, according to further statement of Zenit's developer *Yuzhnoye* Design Bureau (Ukraine) this was the second launch failure caused by the same software error. The first one happened during the first international commercial satellite launch attempt of *Zenit-2* launch vehicle with 12 Globalstar satellites. The rocket suffered a control system failure during the second stage burn on 9 September 1998. However, a true failure cause was not disclosed at that time and occurred again 18 months later. Thus, one software failure resulted in considerable loss of customer trust in *Zenit* reliability and could also contribute to bankruptcy of the Sea Launch Company in 2009.

6. Study of ISS Alpha's Computer Systems Failures

Grave doubts about the software stability of the enormously complex International Space Station were discussed in many studies.[17] Indeed, 3.5 million lines of code, coming from multiple countries, with little indication of the verification methodologies can cause a potential software nightmare for International space station that has been confirmed by numerous computer glitches and failures which happened during the past ten years on board of the International Space Station. For instance, on February 21, 2000 a failure of the primary ISS command and control computer knocked the station out of contact with mission control, but a backup computer took over and was prime for about an hour until it also stopped work. As it was reported, the station's command and control software was updated shortly before the incident. Thus, the software-related problems were suspected in multiple computer glitches. The ISS has suffered a series of glitches during 25-28 April 2001 that left ground controllers with only tentative command. A computer crash in the U.S. Destiny laboratory forced the Mission Control to reroute communications through the shuttle Endeavour, which was visiting at the time. Failed hard drives in all three command and control computers were identified as the cause of the incident. A computer problem on 4 February 2002 caused the station to lose some power. The central computer in the Russian segment of the station stopped working. Although the cause of the failure was not known for sure, ground controllers were able to restart the computer. However, the failure caused other systems to shut down temporarily, including those that control the movement of the station's solar panels so they can track the Sun. With those systems offline the station's electrical generating capacity was reduced, requiring the crew to shut down some secondary systems.

A software failure caused a three-hour shutdown of scientific equipments and life support systems on 21 May 2002. On 12 June 2007 a major failure within the six-computer navigation and control system in charge of the Russian segment of the space station caused a false fire alarm and shut down crucial navigation and life support systems. Each of the two sets of computers has three redundant channels ('lanes'), at least one of which must work for each system. However, all six lanes crashed and could not be automatically restarted. The problem was caused by a short circuit because of water condensed on cable wires. As a result, a false 'power-off' command coming from inside a power-monitoring device was sent to primary and backup computer.[18] It took several days to install new cables to bypass a faulty electronics box and work around the glitch. A failure of the command and control multiplexer/demultiplexer computer and its backup occurred on 21 February 2010. An erroneous command from the Columbus control centre caused incorrect parameters to be sent to the command and control computer causing a cascading crash. Thus, despite the multiple computer redundancy ISS computer control system cannot be prevented from numerous glitches especially when software faults arise. However, software cannot be considered just as a source of common mode failures. It also provides a flexible mechanism to counter with design defects and spacecraft system failures occurred during operation. For example, a problem of poor quality and lack of height accuracy of data acquired by Japanese DAICHI advanced land observing satellite was resolved by using especially developed software for block noise reduction and height accuracy enhancement.[19] Another example is the story of the HAYABUSA (Japan) spacecraft successful coming back to the Earth in spite of losing its reaction wheels, reaction control system (fine thrusters), and some of its ion thrusters (main propulsion) during its long journey toward Itokawa asteroid. New software was developed by Japanese engineers, uploaded into the spacecraft computer system and successfully used to perform the emergency attitude control by utilizing solar light pressure and jetting out xenon gas initially used as a propellant for the ion engines.

Conclusion

The paper presents the analysis of rocket space accidents in the first decade of the 21st century. The comparative analysis of carrier rocket and spacecraft failures between the last decade of the previous century and the first decade of this century has shown that the total risks have not decreased but increased. A part of accidents caused by computer systems failures has also increased. Failures and glitches of onboard hardware and software (20% and 6% correspondingly) rank second amongst the spacecraft failure causes after breakdowns of radio-equipment. Besides, a part of radio-equipment breakdowns can be actually caused by computer hardware failures. Every seventh failure on carrier rocket is caused by software faults, while computer hardware failures are not typical of an orbital carrier rocket. Among the failure causes for orbital carrier rockets manufactured by the countries with the developed rocket space industry (above all Russia, the USA, Europe Union) three basic groups can be distinguished: (i) premature cut-off of propulsion systems of different stages of a launch vehicle; (ii) separation problems of stages, boosters, upper-stages, fairings and deployment platforms; (iii) extraneous particles getting into critical elements of propulsion systems and electrical devices. At first glance, the premature cut-off of propulsion systems can be caused both by anomalies in the propulsion operation and by the failures of on-board control systems. The failures of the second group are, most likely, stipulated by the faults of pyrotechnical electromechanical devices of separation elements, and also can be caused by the lack of timely commands to separate sent by computer control systems or by the faults of cable bonds. The third group of failures indicates possible faults of manufacturing and assembly of launch vehicle elements or design deficiency (for instance, the Ariane-5 ECA launch vehicle with a new Vulcain-2 first-stage engine failed during its maiden flight on 11 December 2002. The fault was determined to have been caused by a leak in coolant pipes allowing the nozzle to overheat [20]). Clear understanding of the initial causes of these accidents will stimulate the reduction of a launch failure probability. Orbital carrier rockets accidents built by other countries were usually caused by the immature technologies and design imperfection.

Tendencies. For many orbital carrier rocket families the years 2000-2009 are a transition border to new versions of launch vehicles (e.g. Proton-M, Zenit-3SL, Delta-IV, Atlas-V). For Russian launch vehicles, for example, Proton-M 8K82KM (the maiden launch was made on 7 April 2001) and Soyuz-2.1, this period is characterized by the replacement of analogue control systems with digital ones. This allowed to enhance the functional characteristics of launch vehicles (the placement accuracy, flight stability and controllability) and to use ballistic trajectories, which were unavailable earlier due to insufficient performance of analogue control systems. There is a tendency towards producing ecologically clean launch vehicles, reducing the environmental pollution while launching and in case of explosion (for example, after the Proton-M launch failure on 7 September 2007, its wreckages fell 40 km away from Jezkazgan city, spilling the highly toxic heptyl fuel over the vast area. There is a tendency towards close cooperation of many different companies and countries in manufacturing, production and launching of orbital carrier rockets and spacecrafts. A decade ago it was almost impossible to imagine that US orbital carrier rocket Atlas-V, produced and launched by the consortium Lockheed Martin and Boeing would use Russian propulsion system RD 180. The modern tendency of producing spacecraft control systems consists in an extensive use of computer operating system. In particular, VxWorks multitasking real-time operating system has become a de-facto standard for the spacecraft control systems. VxWorks was successfully used in NASA space missions Mars Pathfinder (1997), Mars Exploration Rover (2003), Deep Space One, Mars Odyssey, Stardust, in the spacecraft PROBA of European Space Agency and in the ISS's Lifeboat shuttle. As to programming languages used for developing control software for rocket-space complexes, Russian companies prefer Modula-2 and domestically developed Excelsior (XDS) compiler. Software of Russian launch vehicles and spacecrafts usually operates under control of Russian-made real-time operating system OS2000 or Canadian QNX 4.25D on microprocessors MIPS and Intel. Control software of Ariane-5 developed by European Space Agency is written in Ada-95 programming language which is also widely used in US military technologies.

Lessons Learnt. Extending number of software-implemented critical controlling functions of launch vehicles and spacecrafts, from the one hand, toughens requirements to the software reliability. From the other hand it increases number of defects introduced into software during its development and complicates verification and validation procedures due to enormous growth of software complexity especially in case of extensive use of operating systems and multitasking. Software malfunctions have caused number of rockets accidents and spacecraft failures, in particular, fatal launch failures of Zenit-2 on 9 September 1998 and Zenit-3SL on 12 March 2002, well-known Ariane-5 failure [21] during its maiden flight on 4 June 1996. The last one, in particular, has attracted a great attention on hazards and risks connected with the of software reusability as described in FAA Guide to Reusable Launch and Reentry Vehicle Software and Computing System Safety.[22] Another instructive example of one software fault occurred during Mars Pathfinder mission.[23] The software fault was connected with the well-known problem of priority inversion occurred in the mechanisms of access control to the Pathfinder' "information bus" synchronized with mutual exclusion locks in VxWorks operating system. Citing Glenn Reeves the problem was not eliminated before launch because it manifested itself only under combination of events assumed to be too rare and, therefore, not simulated during pre-flight testing. Besides, software engineers relied a lot on general recovery mechanism based on system reset (which failed to counter with this particular problem). Nevertheless, such failure arose as early as on the next day (!) after Mars Pathfinder had landed to Mars and caused repeated system resets, each resulting in losses of data. Moreover, there were a lot of software fault-tolerant and recovery mechanisms implemented to go through multiple resets, to recover from radiation induced errors in the memory or the processor, to recover the Mars Pathfinder activity after interruptions and other harmful events, most of which, seemingly, never happened during mission. Thus, a priory analysis of failure modes, their causes and effects, criticality and probability of occurrence is of a great importance during development of control systems and software for many critical application domains, including airspace technologies. This will improve cost-effectiveness of fault-tolerance means and recovery techniques and will enhance a correspondence of testing and verification profiles to the actual operational conditions. Besides, reliability and safety of aerospace systems can be improved by wide application of methods of formal development (e.g. B, Event-B, VDM, etc) and verifications (e.g. Model Checking).

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ANATOLIY GORBENKO – see CV on p. 158 of this volume.

VYACHESLAV KHARCHENKO – see CV on p. 51 of this volume.

OLGA TARASYUK – see CV on p. 158 of this volume.

SERGIY ZASUKHA was a head of National space complexes department. Since 5 August 2009 he is a vice-director of State Space Agency of Ukraine (www.nkau.gov.ua/nsau/nkau.nsf/indexE) leading rocket-space engineering branch. He is a head of committee for Sich-2 spacecraft development and launch preparation and also a president of HARTRON Corporation' supervisory board (www.hartron.com.ua). His main research interests are in developing prospective launch vehicles and spacecraft avionics.