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MIRCE MECHANICS ANALYSIS OF IN-SERVICE RELIABILITY OF NASA-CONTRACTED COMMERCIAL RE-SUPPLY SERVICES

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Abstract

The main purpose of this paper is to apply Mirce Mechanics to the analysis of in-service reliability of Space Exploration Technologies Corporation and Orbital Sciences Corporation, organizations that have been selected by NASA to participate in the Commercial Orbital Transportation Services, COTS. The reason for this is the fact that at the moment of writing this paper, both CRS Programmes are out of action due to catastrophic launch failures that took place on 28th June 2015 and 28th of October 2014, respectively. It is expected that analysis performed on the past missions, conducted by both corporations, based on the publicly available information, will get incites into their practices and experiences gained, as well as highlighting the areas of potential applications of the Mirce Mechanics based knowledge to increase in the probability of the successful continuations of NASA-contracted Commercial Resupply Services.

Keywords: *Mirce Mechanics, In-service Reliability, NASA, Contracting for in-service performance.*

1 INTRODUCTION

According to Einstein ***"****Everything that the human race has done and thought is concerned with the satisfaction of felt needs*". (Einstein, 1935)

Human needs for transporting, cooling, heating, communicating, navigating, sheltering and many others are continuously satisfied through the work done by transportation, ventilation, communication, refrigeration and other industrial systems. Their design-in performance in terms of speed, capacity, frequency, power and similar physically measurable quantities can be accurately predicted during the design process and tested at the delivery, as they are functioning in accordance to well understood laws of natural sciences, such as: Newton's laws of motion, Coulomb's law of solid friction, Hook's law of stress and strain, Maxwell's law of electrodynamics, Boltzmann's law of thermodynamics, to name a few, which are characterised by certainty, reversibility and independence of time, location and humans.

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However, the main concerns of the owners and users of industrial systems are related to how much of their "felt needs" will be satisfied during the life time of a system and how much maintenance and support efforts are expected from them to keep the system going[1]. This, property of industrial systems is known as functionality[2]. Regrettably, system producers/ constructors do not provide answers to these questions on the delivery day. Instead, years later the statistics for various functionality measures become available. The reason for this is the fact that in-service behaviour of industrial systems is governed by the complex processes that are governed by the laws of science, human rules and environmental impacts, which are characterised by irreversibility, inseparability, and dependence on time, location and humans. (Knezevic, Functionability in Motion, 2010)

To rationally address questions of the predictions of in-service performance of industrial systems, described through functionability measures, Dr Knezevic has established the MIRCE Akademy at Woodbury Park, Exeter, UK, in 1999. Staff, Fellows, Members and students of the Akademy have endeavoured to subject in-service behaviour of industrial systems to the laws of science and mathematics to:

- Determine the trajectory of the motion of functionability through life of a given industrial system, which is defined by the sequence of occurrences of positive and negative functionability events, resulting from the atomic, environmental and human actions.
- Understand mechanisms that lead to the occurrence of functionability events starting from atomic structure that drives the behaviour of matter, up to the solar system that drives the energy conversions (a physical scale ranging from 10^{-10} to 10^{10} metre). (Knezevic J. , Atoms and Molecules in Mirce Mechanics Approach to Reliability, 2012)
- Define a mathematical scheme for predicting expected in-service functionability measures of a given industrial system together with the expected work done on the system under a given maintenance policies and planned support strategy.

While in classical mechanics a force is said to do work if, when acting on a body, there is a displacement of the point of application in the direction of the force, in Mirce Mechanics a given industrial system is said to do work, if whenever required, there is a continuous provision of a measurable function through time.

In summary, the body of knowledge comprising of axioms, mathematical equations and computational methods that enable prediction of functionability measures, based on the on the scientific understanding of the processes that generate them, constitutes Mirce Mechanics. ((Zaczyk, 2010), (Zaczyk & Knezevic, Cosmic Phenomena in Mirce Mechanics Approach to Reliability and Safety, 2013), Baumann, R. (2005), Silberberg, R., Tsao, C. H. and Letaw, J. R. (1984).

The main purpose of this paper is to apply Mirce Mechanics to the analysis of in-service reliability of Space Exploration Technologies Corporation and Orbital Sciences Corporation, organizations that have been selected by NASA to participate in the Commercial Orbital Transportation Services, COTS. The reason for this is the fact that at the moment of writing this paper, both CRS Programmes are out of action due to catastrophic launch failures that took place on 28th June 2015 and 28th of October 2014, respectively. (Carreau, 2015) It is expected that analysis performed on the past missions, conducted by both corporations, based on the publicly available information, will get incites into their practices and experiences gained, as well as highlighting the areas of potential applications of the Mirce Mechanics

[1] Boeing 747, registration number N747PA, which belonged to Pan Am transportation system, have delivered the work of 80,000 flying hours and received 806,000 maintenance man-hours, during the 22 years of in-service life. (Knezevic, 1997)

[2] Functionability, n, defined as the ability of being functional through life, in the book (Knezevic, Reliability, Maintainability and Supportability – A probabilistic Approach, 1993)

based knowledge to increase in the probability[3] of the successful continuations of NASA-contracted Commercial Re-supply Services.

2 NASA-CONTRACTED RE-SUPPLY SERVICES

In 1958 the United States government created the National Aeronautics and Space Administration (NASA) with a specific responsibility to develop the civilian space program as well as aeronautics and aerospace research. Since that time, NASA has lead large number of space exploration efforts, including the Apollo moon-landing missions, the Skylab space station, and later the Space Shuttle. In early 1990s NASA was directed to pursue commercial options for launching spaceflight missions, whenever such commercial offerings are available.

The development of the Commercial Resupply Services, CRS, vehicles began in 2006 with the purpose of creating American commercially operated uncrewed cargo vehicles to service the International Space Station, ISS. The development of these vehicles was under a fixed price milestone-based program, meaning that each company that received a funded award had a list of milestones with a dollar value attached to them that they didn't receive until after they had successful completed the milestone.

On 23rd December, 2008 NASA awarded Commercial Re-supply Services contracts to:

– Space Exploration Technologies Corporation, which is an American aerospace manufacturer and space transport services provider, with headquarters in Hawthorne, California, USA, which uses its Falcon 9 rocket and Dragon spacecraft. This, $1.6 billion contract was for 12 cargo transport missions to ISS with spacecraft SpaceX.

– Orbital Sciences Corporation, which is also American company, specialising in the design, manufacture and launch of small- and medium- class space and rocket systems for commercial, military and other government customers, based in Dulles, Virginia, USA, which uses its Antares rocket and Cygnus spacecraft. This contract was worth $1.9 billion for 8 missions to ISS using Cygnus cargo spacecraft, covering deliveries to 2016.

As NASA has contracted all the missions, the primary payload, date and time of launch, and orbital parameters for each mission are determined by NASA.

3 MIRCE MECHANICS ANALYSIS OF IN-SERVICE RELIABILITY OF ORBITAL SCIENCES

Orbital Science Corporation plan for the commenced regular ISS cargo missions to ISS under the Commercial Resupply Services contract was to deliver approximately 20,000 kg, or 20 metric tons, of cargo to the space station over the course of eight missions by using the Antares launch vehicle and Cygnus spacecraft. Antares is a two-stage launch vehicle designed to deliver medium-class payloads weighing up to 6120 kg into space. Antares utilises refurbished Russian-built engines which were originally manufactured in the 1960s and 1970s for the Soviet space programme. Cygnus spacecraft is capable of delivering 2000 kg of pressurised cargo to the ISS. It was planned that an enhanced version to be flown in later CRS missions will be able to deliver 2700 kg of pressurised cargo. The first of the eight contracted Cygnus missions to the ISS was expected to be completed during 2013.

According to the planned sequence of in-service events, 10 minutes from the liftoff of the Antares the Cygnus space craft would separate, deploy its solar arrays and enter in its initial orbit. When it arrives to the orbiting laboratory four days later, after a series of checks, ground controllers command began to increase the altitude of Cygnus, until it matched that of the space station. At that point NASA was to make go/no-go decision for Cygnus to berth with the station. Cygnus would autonomously approach within 12 metres below the space station, where it would stay. Astronauts aboard the station would then command Cygnus

[3] Mirce Mechanics Axiom 2: Probability of in-service failure in any interval of time is greater than zero.

to a “free drift” mode, when the space stations robotic arm would take hold of the spacecraft. At that moment the Ground commands would send command, from mission control in Houston, for the station’s arm to rotate Cygnus around and install it on the bottom side of the station’s Harmony module, enabling it to be bolted in place for its stay at the ISS.

In the preparation for an on-pad hot-fire test of the rocket scheduled for the early November 2012, Orbital Sciences rolled out its Antares rocket to the launch pad at the Mid-Atlantic Regional Spaceport in October 2012. The rocket successfully made its initial launch with a test payload on 21st April, 2013, from Wallops Flight Facility in Virginia. Orbital Sciences' first COTS demonstration mission was successfully carried out on the 29th September, 2013, a week behind schedule due to a software malfunction.

3.1 Orb-1

This was the first of eight contracted flights by Orbital Sciences under NASA's Commercial Re-supply Services program. The launch of Orb-1 was scheduled for November 2013, but a series of delays pushed the date to 20th December UTC.

The Antares launch vehicle left the Wallops Horizontal Integration Facility, HIF, on the morning of 17th December, and was later erected at Launch Pad 0A. However, later that day, due to the need for a series of spacewalks to fix a faulty coolant system on the ISS, NASA directed Orbital to stand down the Antares rocket. It was rolled back to the HIF where the time-sensitive cargo was removed. The launch date was rescheduled for no earlier than 13th January 2014.

However, after a scheduling conflict was resolved, at Wallops, the launched was moved forward to 7th of January. The launch was delayed one extra day due to cold temperatures at the launch site. Then on the 8th of January, NASA Wallops and Orbital Sciences announced that the launch attempt was scrubbed due to "an unusually high level of space radiation that exceeded by a considerable margin the constraints imposed on the mission to ensure the rocket's electronic systems are not impacted by a harsh radiation environment. Later, Orbital revised this, stating that a more extensive review of the radiation environment found it to be "within acceptable limits" of the Antares program, and that a launch would be attempted on 9th January.

In the fourth attempt, on the 9th of January the Orb-1 mission successfully started at 18:07:05 UTC from the Mid-Atlantic Regional Spaceport Launch Pad 0A. Cygnus was filled with 1261 kg of supplies for the ISS, crew provisions and spare parts, together with hardware to expand the research capability of the station. This included 12 experiments flying as part of the Student Spaceflight Experiments Program, selected from 1466 entrants and involving 7200 North American students. The Cygnus spacecraft arrived at the International Space Station early on 12th January, where it was successfully docked with the assistance of Canadarm2, as originally planned.

On 18th February 2014 at 10:25 UTC, Canadarm2 unberthed the Cygnus spacecraft from the nadir port of the Harmony module on. The spacecraft was then maneuvered to a position below the station, where it was released from the RMS at 11:41 UTC. It followed by a series of separation maneuvers that moved it away from the ISS. The spacecraft re-entered the atmosphere and burned up on 19th February 2014 over the southern Pacific Ocean, disposing of approximately 1470 kg of trash.

3.2 Orb-2

This was the second of eight scheduled flights by Orbital Sciences under the Commercial Resupply Services contract with NASA. It was the third flight of the Orbital Sciences' un-manned re-supply spacecraft Cygnus and the fourth launch of the company's Antares launch vehicle.

The mission was scheduled for the 1st May 2014. The Cygnus is expected to deliver 1650 kg of cargo to ISS and dispose of about 1470 kg of trash through destructive re-entry. However, the original launch date was delayed to no sooner than 6th May, which followed by the following sequence of estimated times, 17th June, 10th July and again to NET on 11th July, due to test stand failure of an AJ-26 engine. On the 12th the local weather conditions prevented the launch.

Finally, the second mission of the Orbital Science Corporation was launched from the Mid-Atlantic Regional Spaceport on 13th July, 2014.

During the Flight Days, 36 through 41 Cygnus was detached from the station and maneuvered a safe distance away. Engineering tests were performed for up to 15 days before a series of engine burns are conducted to slow the spacecraft for re-entry over the South Pacific Ocean, where it and the cargo inside were destroyed. Total weight of cargo was 1494 kg (Crew supplies, 764 kg; Hardware: 355 kg, Science and research, 327 kg, Computer supplies, 8.2 kg; Spacewalk tools: 39 kg).

3.3 Orb-3

Orbital Sciences CRS Flight 3 was the first attempted flight of the Antares 130, which uses a more powerful Castor 30XL second stage, and the last flight of the standard-sized Cygnus Pressurised Cargo Module.

Orb-3 carried a variety of NASA-determined payloads, some of which were finalised very close to the launch day. The cargo module from the rocket carried 2300 kg of supplies and experiments meant for the International Space Station. In addition, the Arkyd-3 satellite would have been transported to the ISS on this flight and 34 of the Planet Labs small “Dove” Earth-observation spacecrafts.

The mission was scheduled to launch on 27th October, 2014, at 22:45 UTC from the Mid-Atlantic Regional Spaceport at the Wallops Flight Facility in Wallops Island, Virginia, with rendezvous and berthing with the ISS early in the morning on 2nd November. This was the first night-time launch for both the Antares launcher and Cygnus spacecraft. The launch was scrubbed due to safety concerns of a sailboat entering the exclusion zone less than ten minutes before launch. A 24-hour delay was put in place.

The Antares rocket carrying the Orb-3 Cygnus was launched, from Launch Pad 0A on 28th October, 2014, at 6:22 p.m. (EDT). Fifteen seconds after liftoff a failure of propulsion occurred in the first stage and the vehicle began falling back to the launch pad. Before reaching the ground, the vehicle was destroyed by its flight termination system, which was engaged by a command from the Wallops Range Control Center. According to NASA’s emergency operations officials, there were no casualties and property damage was limited to the south end of Wallops Island.

The resulting explosion was felt in Pocomoke City, Maryland, 32 km away. The fire at the site was quickly contained and allowed to burn itself out overnight. Initial review of telemetry data found no abnormalities in the pre-launch, the launch sequence, and the flight, until the time of the failure. According to the NASA press release, there were no known issues prior to launch and that no personnel were injured or missing but that the entire payload was lost and there was significant damage to the launch pad and site fuel tanks.

On 29th October, 2014, teams of investigators began examining debris at the crash site. With some preliminary investigation completed, Orbital Science Corporation cited the cause of the Orb-3 launch failure is likely to be a turbo pump malfunction in one of the AeroJet Rocketdyne AJ-26 engines (refurbished Russian NK-33 engine).

Repairs of the damage caused to Wallops Flight Facility, by the launch exploration, started in January 2015.

By the time on writing this paper there was not an official report regarding the cause of the failure of the Orb-3.

3.4 Orbital Science’s CRS Plan

To meet its Commercial Re-supply Services obligations to NASA, Orbital is planning to launch at least one enhanced Cygnus cargo spacecraft via an Atlas V launch vehicle in 2015. Orbital has yet to officially announce which engine may replace the AJ-26, but evaluation of other engines such as the RD-181 and RD-193 were being conducted as an AJ-26 replacement prior to the incident. The re-designed Antares launch vehicle is expected to fly again sometime in 2016.

4 MIRCE MECHANICS ANALYSIS OF IN-SERVICE RELIABILITY OF SPACEX

Under the NASA COTS contract it is expected that SpaceX will make 12 deliveries of cargo to ISS, with each flight carrying up to 3300 kg of internal and external cargo to the space station and return up to 2500 kg of equipment to Earth.

The space agency paid SpaceX $396 million in instalments as the company accomplished design, testing and flight milestones, including two test launches and demo missions of the Falcon 9 rocket and Dragon capsule.

4.1 SpaceX CRS-1

SpaceX CRS-1 was the third flight for Space Exploration Technologies Corporation's uncrewed Dragon cargo spacecraft, the fourth overall flight for the company's two-stage Falcon 9 launch vehicle, and the first SpaceX operational mission under their Commercial Resupply Services contract with NASA. The launch occurred in accordance to the plan on 8th October 2012 (UTC) and successfully placed the Dragon spacecraft into the proper orbit for arriving at the International Space Station with cargo re-supply several days later.

During the launch, one of the nine engines suffered a sudden loss of pressure about 80 seconds into the flight, which was followed by its immediate shutdown. The remaining eight engines continued to fire, while the flight control software adjusted the trajectory to insert Dragon into required orbit.

At launch the CRS-1 Dragon was carrying approximately 905 kg of cargo, 400 kg without packaging (120 kg of crew supplies and 180 kg of critical materials to support the 166 experiments on board the station and 66 new experiments) and 105 kg of hardware for the station as well as other miscellaneous items. It was also planned to launch a 150 kg prototype of the second-generation Orbcomm satellite, as a secondary payload from Falcon 9's second stage.

4.1.1 Falcon 9 Engine Anomaly

During the ascent, an engine anomaly occurred with one of the nine engines on the Falcon 9 first stage. SpaceX has emphasized for several years that the Falcon 9 first stage is designed for "engine out" capability, with the capability to shut down one or more malfunctioning engines and still make a successful ascent. In this event, the SpaceX CRS-1's first stage shut down engine no.1 and as a result continued the first-stage burn on the remaining eight engines longer than usual at a reduced thrust to insert the Dragon spacecraft into the proper orbit. SpaceX referred to the event as a "Rapid unscheduled disassembly" which, although unintended, was the first in-flight demonstration of Falcon 9's "engine out" design and "provides a clear demonstration of the engine out capability."

4.1.2 Post Flight Investigations

In response to the anomaly, NASA and SpaceX jointly formed the CRS-1 Post-Flight Investigation Board. Preliminary information from the post-flight review board indicates that the Engine no.1 fuel dome, above the nozzle, ruptured but did not explode. The burning fuel that existed before the engine was shut down caused the fairing rupture, as seen in the flight video recordings. Subsequent investigations revealed in a Congressional hearing pinpointed the issue as a result of an undetected material flaw in the engine chamber jacket, likely introduced during engine production. During flight, the data suggests this material flaw ultimately developed into a breach in the main combustion chamber. This breach released a jet of hot gas and fuel in the direction of the main fuel line, causing a secondary leak and ultimately a rapid drop in engine pressure. As a result, the flight computer commanded shutdown of engine 1 and Falcon 9 continued on its path to ensure Dragon’s entry into orbit for subsequent rendezvous and berthing with the ISS.

The primary payload contractor, NASA, requires a probability of 0, 99 that the stage of any secondary payload on a similar orbital inclination to the International Space Station will reach their orbital altitude goal above the station. Due to the one engine failure, the Falcon 9 used more propellant than intended, reducing the success probability estimate to approximately 0.95. Consequently, the second stage did not attempt a second burn, and Orbcomm-G2 was left in an unusable orbit and burned up in Earth's atmosphere within 4 days after the launch.

Video of the launch shows debris falling from the rocket as it speeds to orbit, though SpaceX indicates that the engine did not explode, as they continued to receive data from it.

4.2 SpaceX CRS-2

The second CRS mission from Space Exploration Technologies Corporation took place on 1st March, 2013. A minor technical issue on the Dragon spacecraft involving the RCS thruster pods occurred upon reaching the orbit, which was recoverable.

When launched the CRS-2 Dragon was filled with 6 77 kg of cargo, 575 kg without packaging (81 kg of crew supplies, 347 kg of scientific experiments and experiment hardware, 135 kg of hardware for the station) and other miscellaneous items. The two Heat Rejection Subsystem Grapple Fixtures (HRSGFs) had a combined weight of 221 kg and were transported to the ISS inside the unpressurised Dragon trunk as external cargo.

The vehicle was released from the station on March 26th, 2013, at 10:56 GMT, and splashed down in the Pacific Ocean at 16:34 GMT.

The Dragon returned 1370 kg of cargo, 1210 kg without packaging. Included is 95 kg of crew supplies, 660 kg of scientific experiments and experiment hardware, 401 kg of space station hardware 38 kg of spacesuit equipment and other miscellaneous items.

4.3 SpaceX CRS-3

There were several delays between the nominal December 2013 date that had been planned since early 2013, mostly due to limited berthing windows in the ISS Visiting Vehicle schedule, and delays to Programmes, Orbital's Cygnus and SpaceX's Dragon, resulted from the December 2013 cooling issue on the ISS which required several spacewalks to mitigate.

The launch planned for 12th March 2014 was rescheduled to 30th March and then for 2nd April 2014 due to a variety of reasons, including data buffering issues, some operational issues with the new Dragon design and some contamination of the impact shielding blanket. SpaceX ultimately decided to move forward and use the shielding blanket with the minor contamination problems, believing it would not impact the optical payloads being carried in the Dragon trunk

However, a further delay was announced on 26th March, which was related to a fire at one of the radar facilities on the Eastern Range. There is mandatory radar coverage for any launches from Cape Canaveral, and the fire forced a delay until that section of the launch trajectory could be covered, possibly by alternative means that would have telemetry communication capability to the Air Force facility responsible for launch safety.

By April 4th the Eastern Range radars were repaired and back online to support launch and the CRS-3 launch was slated for no earlier than 14th April with a backup date of 18th April, contingent upon a ULA Atlas V flight scheduled for 10th April.

On 11th April, the International Space Station suffered a failure of an external computer known as a Multiplexer/Demultiplexer (MDM), which required a spacewalk on 22nd April to replace it, in order to restore vital redundancy to the station. Despite the challenges, the CRS-3 mission, which could have been impacted by the MDM failure, was still on for Monday, 14th April, with ISS berthing scheduled to take place two days later on 16th April.

However, during the launch attempt on 14th April, a primary helium supply valve used in the stage separation system failed a pre-launch diagnostic test approximately one hour prior to the scheduled launch, so the SpaceX launch manager scrubbed the mission. In ground tests following the scrub, the redundant backup helium supply valve tested okay so the mission would likely have succeeded.

The launch was immediately rescheduled for no earlier than the backup date, 18th April. That date was confirmed two days later, following replacement of the defective valve, but it was noted that weather constraints may prevent the launch on 18th April from occurring. If the launch had been scrubbed on 18th April, the next launch window would have been, 19th April at 3:02 pm ET. However, on Friday, 18th April 2014 at 7:25:21 p.m. UTC, the vehicle was successfully launched.

During this flight the CRS-3 booster made history by being the first liquid-rocket-engine orbital booster that successfully performed the controlled ocean soft touchdown. The booster included landing legs for the first time which were extended for the simulated "landing", and the test utilised more powerful gaseous nitrogen control thrusters than had been used in the previous test to better control aerodynamic-induced rotation. The booster stage successfully approached the water surface with no spin and at zero vertical velocity, as designed. The SpaceX team was able to receive video from cameras placed on the first-stage booster during soft landing test, as well as vehicle telemetry recorded by aircraft, but swells of 4.6–6.1 m were reported in the anticipated recovery area. The first stage successfully hovered over the ocean surface, but heavy waves destroyed the stage before boats were able to retrieve it.

Two days after splashdown, the 1600 kilograms of down-mass cargo, from the mission was returned to the Port of Long Beach by a marine vessel. Time-sensitive cargos are unloaded in California and flown to NASA receiving locations. The remainder of the cargo was unloaded and transferred to NASA at the SpaceX McGregor test facility in Texas, where the Dragon capsule was fully decommissioned and defueled. Although water was found inside the Dragon capsule, the preliminary checks indicated that no scientific equipment had been damaged. The source of the water has not been confirmed and will be investigated during the decommissioning of the capsule.

4.4 SpaceX CRS-4,

SpaceX's fourth CRS mission was scheduled for launch on September 20th, 2014, but was delayed due to adverse weather conditions. The launch took place on 21st September, 2014 at 1:52 a.m. EDT from Cape Canaveral Air Force Station in Florida.

As contracted, the CRS-4 mission the payload consisted of 2216 kg of cargo (1627 kg of pressurised and 589 kg of unpressurised.

The CRS-4 mission, which lasted 31 days, 22 hours and 41 minutes, was successfully completed on the 25th October 2014.

4.5 SpaceX CRS-5,

By July 2014, NASA scheduled this for "no earlier than" December 2014, with docking to the station projected to occur two days after launch.

This mission, was scheduled for launch on December 9th, 2014, but was delayed over several dates in December due to manifest adjustments for items lost from the Cygnus CRS Orb-3 launch failure (described in 4.3), technical issues found from a static fire test, the U.S. holiday season and staff scheduling, as well as a beta angle period during late December where thermal and operational constraints would make a Dragon berthing prohibited.

On 6th January 2015, the launch attempt was placed on hold at 1 minute 21 seconds prior to scheduled lift-off after a member of the launch team noticed actuator drift on one of two thrust vector control systems of the Falcon 9 second stage engine. As this launch had an instantaneous launch window, meaning no delays are possible in the launch sequence, the flight was postponed to 9th January 2015. On 7th January, the flight was rescheduled for 10th January 2015.

The Falcon 9 rocket carrying the CRS-5 Dragon spacecraft successfully launched on 10th January 2015 at 9:47 UTC. Dragon reached the station on 12th January. It was grappled by the Space Station Remote Manipulator System at 10:54 UTC and berthed to the Harmony module at 13:56 UTC.

The Dragon spacecraft for CRS-5 carried 2317 kg of cargo to the ISS. Included in this was 490 kg of provisions and equipment for the crew, 717 kg of station hardware, 577 kg of science equipment and experiments, and the 494 kg Cloud Aerosol Transport System (CATS).

In this flight, SpaceX attempted an unprecedented operation, which was to return the nearly-empty first stage of the Falcon 9 through the atmosphere and land it on a 90x50-meter floating platform called the autonomous spaceport drone ship. In October 2014, SpaceX had revealed that the ship was being built for SpaceX in Louisiana, and by mid-December, the ship was docked in Jacksonville, Florida, ready to go to sea to support the test flight landing attempt.

SpaceX attempted a landing on the drone ship on 10th January. Many of the test objectives were achieved, including precision control of the rocket's descent to land on the platform at a specific point in the South Atlantic Ocean and a large amount of test data was obtained from the first use of grid fin control surfaces used for more precise re-entry positioning. The SpaceX webcast indicated that the boost-back burn and re-entry burns for the descending first stage occurred, and that the descending rocket then went "below the horizon," as expected, which prevented the live telemetry signal. Shortly after that, the information released by SpaceX stated that the rocket did get to the drone spaceport ship as planned, but it had “hard landing”, while ship itself is fine, although some of the support equipment on the deck will need to be replaced. Full details of what happened to the rocket are not yet publicly known (one of the possible problems was the grid fins running out of hydraulic fluid).

4.6 SpaceX CRS-6

As of July 2014, this mission was tentatively scheduled by NASA for February 2015, with expected berthing to the station occurring two days later. However, as a result of delays in the launch of the SpaceX CRS-5 mission, in late March 2015, the tentative launch of this mission was scheduled for 13th April 13, 2015.

Due to bad weather conditions 13th April launch was postponed. Finally, the sixth SpaceX mission was successfully launched on 14th April 2015, at 20:10:41 UTC from Cape Canaveral Air Force Station in Florida. It was the eighth flight for SpaceX's uncrewed Dragon cargo spacecraft and the sixth SpaceX operational mission contracted to NASA under a Commercial Re-supply Services contract. It was docked to the International Space Station from 17th April to 21st May 2015.

The Dragon spacecraft was filled with more than 2000 kg of supplies and payloads, including critical materials to directly support about 40 of the more than 250 science and research investigations carried out at the ISS.

Planetary Resources will transport Arkyd 3 to the ISS aboard Dragon on CRS-6, which was the attempt to validate and mature the technology of its Arkyd series of spacecraft, (the first Arkyd 3 satellite was destroyed on launch in the explosion of the Orbital Sciences Antares launch vehicle carrying it aboard the third Cygnus cargo resupply flight to the ISS, as was described in 4.3).

SpaceX has the primary control over manifesting, scheduling and loading secondary payloads. However there are certain restrictions included in their contract with NASA that preclude specified hazards on the secondary payloads, and also require contract-specified probabilities of success and safety margins for any SpaceX reboosts of the secondary satellites once the Falcon 9 second stage has achieved its initial low-Earth orbit.

CRS-6 included science payloads for studying new ways to possibly counteract the microgravity-induced cell damage seen during spaceflight, the effects of microgravity on the most common cells in bones, gather new insight that could lead to treatments for osteoporosis and muscle wasting conditions, continued studies into astronaut vision changes and test a new material that could one day be used as a synthetic muscle for robotics explorers of the future. Also making the trip was a new espresso machine for space station crews!

After the separation of the second stage, SpaceX conducted a flight test and attempted to return the nearly-empty first stage of the Falcon 9 through the atmosphere and land it on a 90x50-meter floating platform called the autonomous spaceport drone ship. Although the unmanned rocket technically landed on the floating platform, as it came down with too much lateral velocity, it tipped over and was destroyed. According to SpaceX, as the bipropellant valve was stuck the control system could not react rapidly enough for a successful landing.

The sixth mission was successfully completed on 21st May 2015, at 16:42 UTC.

4.7 SpaceX CRS-7

In January 2015, the launch of the seventh SpaceX CRS mission was tentatively scheduled by NASA for no earlier than 13th June, 2015. This was adjusted to 22nd June, then moved forward to 19th June and adjusted again to 26th June, 2015. Subsequently, the launch had been rescheduled to 28th June, 2015 at 14:21:11 UTC, from Cape Canaveral LC-40.

A full listing of the cargo aboard the failed mission included the following items:

690 kilograms of Crew Supplies related cargo and 573 kg of the cargo required for the operation, 36 kg of Computer Resources, 462 kg of Vehicle Hardware, 167 kg of Hardware for Extra vehicular activities (including Russian Cargo, Russian Segment Torque Wrench) and International Docking Adapter # 1 weighing 526 kg.

As of July 2013, the first International Docking Adapter, IDA-1 was scheduled to be delivered to the International Space Station on this mission in order to be attached to one of the existing Pressurised Mating Adapters and convert the existing docking interface to the new NASA Docking System (NDS). The new adapter is intended to facilitate future docking of new U.S. human-transport spacecraft. Previous United States cargo missions since the retirement of the Space Shuttle have been berthed, rather than docked, while docking is considered the safer and preferred method for spacecraft carrying humans.

The spacecraft was planned to stay in orbit for five weeks before returning to Earth with approximately 640 kg of supplies and waste.

4.7.1 Planned Landing on Floating Platform

The launch was scheduled to be the third controlled-descent and landing test for the Falcon 9's first stage. It was planned that after the second stage separation, SpaceX planned to conduct a flight test and attempt to return the Falcon 9's nearly-empty first stage through the atmosphere and land it on a 90x50-meter floating platform barge. SpaceX calls the barge an autonomous spaceport drone ship (ASDS), and this particular mission's ASDS was named “Of Course I Still Love You”.

4.7.2 Launch Failure

The vehicle's second stage failed with a measured overpressure at T+02:19, well after max Q (at T+01:26) and before first stage engine shutdown (MECO, scheduled at T+02:45). The second stage developed a very large Liquid Oxygen Tank leak, releasing large clouds of vapour while the first stage continued to thrust stably on course for about 9 seconds, until it disintegrated at T+02:28.

It was the first Falcon 9 failure in the 19 launches of the rocket type. According to SpaceX, the launch vehicle experienced a problem shortly before first stage shutdown due to an overpressure event in the upper stage liquid oxygen tank.

It is not clear if the destruction of the first stage was due to the flight termination system, which would have been activated automatically by on-board sensors. The Eastern Range's range safety officer did transmit a remote destruct signal, but only as a formality, 70 seconds after the event when there was nothing left to be destroyed.

5 CURRENT STATUS OF NASA-CONTRACTED COMMERCIAL RE-SUPPLY SERVICES

At the time that this paper was written (July 2015) NASA-contracted Commercial Resupply Services had no capabilities of supporting the ISS, due to catastrophic launch failures that took place on 28th June 2015 and 28th of October 2014, respectively. Consequently, NASA was without spares for the water filtration system of ISS.

The first opportunity to improve the water filtration system of ISS will be in mid-August 2015 when the planned launch of a Japanese ISS re-supply mission will take place. It is expected that Japan’s HTV will be loaded with water containers and other supplies that should help to ensure six-crewmember operations until late this year.

6 THE FUTURE OF NASA-CONTRACTED COMMERCIAL RE-SUPPLY SERVICES

On February 21st, 2014 NASA posted Request for Information, RFI, about a possible follow on options to the current Commercial Re-supply Services to the International Space Station.

The anticipated contract regarding the future flights will include:

- delivery of pressurised and unpressurised cargo,
- return and disposal of pressurised cargo,
- disposal of unpressurised cargo,
- ground support services for the end-to-end re-supply mission

and will include: delivery of approximately 14000 to 17000 kg per year, 55 to 70 m^3 of pressurised cargo in four or five transport trips delivery of 24–30 powered lockers per year, requiring continuous power of up to 120 Watts at 28 Volts,.

The draft Request for Proposal, RFP, was released in May 2014 with a final RFP in June 2014.

Five companies are known to have submitted proposals to NASA, namely: SpaceX, Orbital ATK, Boeing, Sierra Nevada, and Lockheed Martin. Although the contract awards were originally anticipated by NASA in April 2015, they moved back to a June target date, and in April, delayed again to a contract award target date of September 2015.

In 2015, NASA extended the contract by ordering another three re-supply flights from SpaceX and one from Orbital Sciences. It is expected that the second round of contracts, CRS2, will cover deliveries from 2017 until 2024 and are expected to be awarded in 2015.

In summary NASA through its Commercial Re-supply Services to the International Space Station is attempting to establish a scheme for risk management of these processes, in similar way as the passenger air transport community is achieving through well-established international standards and procedures (Kyselova, 2013).

7 CONCLUSIONS

The factual results of the analysis of NASA-contracted Commercial Re-supply Services presented in this paper are another confirmation of the uncertainty of the in-service behaviour of industrial systems. Hence, this is another confirmation of the validity of the Mirce Mechanics Axiom related to the probability of occurrence of in-service failures. Even further, it is also confirmed that causes of mission failures are not due to the failures of their consisting components only. Several launches have been postponed due to unsatisfactory environmental conditions during the attempted launches on one hand and high level of space radiation on the other. (Knezevic & Papic, 2015)

Both catastrophic launches are still under investigations, which only confirm the complexity of the processes taking place in the launch process, and even more the complexity of the interactions between internal components of the launch system, as well as the interactions between the launch system and the surrounding natural environment.

Finally it is necessary to stress that all processes from the conceptions of both the launch systems, Space Exploration Technologies Corporation and Orbital Sciences Corporation, through their design, production, testing, launches, space flights, berthing with the ISS, return flight to the Earth and finally post failure analysis are performed by humans that despite all creative, scientific, motivational and similar positive qualities also have proven abilities to make errors on the execution of tasks required to be performed by them, to the level that the 3rd Axiom of Mirce Mechanics states "*The probability of a human error in the execution of any functionability action is greater than zero".*

In summary this paper provides further confirmation that in-service reliability and safety considerations of a large number of modern industrial systems, including NASA-contracted Commercial Re-supply Services, are complex properties whose full understanding requires scientific approach towards understanding intricate mechanisms that lead to the occurrence of in-service failures, starting from atomic structure that drives the behaviour of matter, up to the solar system that drives the energy conversions (a physical scale ranging from 10^{-10} to 10^{10} metre). Then and only then, can accurate and meaningful reliability and safety predictions become possible, enabling the ultimate goal of reducing the probability of the occurrence of in-service failures during the life of industrial systems like power networks, aviation, satellite services, pipelines, digital control sand many others, including NASA-contracted Commercial Re-supply Services of today and of the future

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