## Publication of the MIRCE Akademy

# 2019 Annals of MIRCE Science

*"The goal of a scientist is to uncover new ideas, concepts and tools, practical or theoretical, that extend our understanding of the world around us and enable us to do new things. One must believe in what one is doing and stay the course. Now of course, in science one can ultimately prove the correctness of one's work by appeal to experiment and established theory. But even with this buttressing of one's ideas, acceptance can be a long and difficult road."*

**Richard F.W. Bader (1931 – 2012)**
**Grand Fellow of the MIRCE Akademy**

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# Content

## MIRCE Science

According to Knezevic [1] the purpose of existence of any functionable system[1] is to do functionability work, which is considered to be done when the expected measurable function is performed through time, like miles travelled, units produced, energy supplied and similar. However, experience teaches us that in-service life of functionable systems is frequently beset by undesirable negative functionability events, resulting from a variety of negative functionability actions (overstress, wear out, natural events, and human interventions). For the work to be continued, positive functionability actions, (servicing, repairing, testing, replacing, changing the mode of operation and similar) must be performed on the system. Thus, the complex interactions between positive and negative functionability actions govern the functionability performance of functionable systems, primarily measured through work done and resources consumed expressed through monetary values (functionability cost).

Regrettably the functionability performance becomes known only at the end of the life of functionable system[2], when nothing could be done to influence it. Hence, the ability to accurately and quantitatively predict functionability performance of the future functionable systems at the design stages, when all possible changes could be done, would be invaluable for all project: engineers, planners, managers and strategist. The mixture of technical systems and management methods chosen to govern the behaviour of functionability systems through time uniquely determine the expected: functionability work, cost and the expected return on the investment (profit, public benefit, reputation and so firth).

Five decades of research conducted by Knezevic [1] have generated a theoretical body of knowledge, named MIRCE Science, which comprises of axioms, system of formulas and methods that enable predictions of functionability performance of the future functionable systems to be done, by the modelling complex interactions between: physical properties of consisting components, operational rules, maintenance policies, support strategies and expected environmental conditions.

MIRCE Science is based on the scientific understanding of the mechanisms that generates the occurrences of functionability events, considered within a physical scale between $10^{-10}$ m (atomic scale) and $10^{10}$ m (solar system scale). [1] These mechanisms, together with the applied human rules, shape the expected pattern of the motion of a functionable system through MIRCE Space[3]. The “normalised” life-long pattern expected to be generated by each feasible type of functionable system is predictable, from the early stages of the design, by making use of the MIRCE Functionability Equation, which is the bedrock for the calculation of the expected functionability performance.

**Reference:** [1] Knezevic, J., The Origin of MIRCE Science, pp. 232, MIRCE Science, Exeter, UK, 2017, ISBN 978-1-904848-06-6

[1] Functionable system is a well defined collection of atomic, natural and human elements put together to do functionable work.[]1]

[2] Pan Am’s Boeing 747, registration number N747PA, during the 22 years of in-service life, has delivered 80,000 hours of positive work (transported 4,000,000 passengers, burned 271,000,000 gallons of fuel) while receiving 806,000 man-hours of maintenance work (consuming: 2,100 tyres, 350 brake systems, 125 engines, among other parts.

[3] MIRCE Space**:** a conceptual 3-dimentional space containing MIRCE Functionability Field, which is an infinite but countable set of all possible functionability states that a functionable system could be found in, and the probability of being in that state at each instance of calendar time. [1]

# Pitot Tube Blockage by Mud-dauber Wasp as a Mechanism of a Motion of an Aircraft through MIRCE Functionability Field

Dr Jezdimir Knezevic, MIRCE Akademy, Exeter, UK

**Abstract**

*MIRCE Mechanics is the discipline of MIRCE Science that focuses on the scientific understanding and description of the phenomena that govern the motion of functionable system types though the MIRCE Functionability field [1]. A full understanding of the mechanisms that generate the motion is essential for the accurate predictions of the functionability performance of functionable system types using MIRCE Science. According to the 2nd Axiom of MIRCE Science the motion of a functionable system type through MIRCE Space is a result of imposed natural phenomena or human activities, which are jointly called functionability actions. Thus, the main objective of this paper is to address pitot tube blockage by mud-dauber wasps as a mechanism that influences the motion of an aircraft through the MIRCE Functionability Field. Although it is not a frequent and globally realised phenomenon, it is a physically observable one, which is experienced by aircraft on the ground in areas where these types of insects are present. The paper also presents a set of a possible prevention and management actions regarding this specific phenomena.*

## 1. Introduction

MIRCE Mechanics is the discipline of MIRCE Science that focuses on the scientific understanding and description of the physical phenomena and human rules that govern the motion of functionable system types though the MIRCE Functionability Field[4]. A full understanding of the mechanisms that generate this motion is essential for the accurate predictions of the functionability performance of a functionable system type using the mathematical scheme of MIRCE Science. [1]

On 21 November 2013, after a flight from Singapore, Etihad Airways Airbus A330, registered A6-EYJ, landed at Brisbane (Australia) airport and was taxied to the terminal. Two hours and three minutes later, the aircraft was pushed-back from the gate for the return flight to Singapore. After observing airspeed indication failure on his display the captain rejected the initial take-off attempt. The aircraft taxied back to the terminal where a troubleshooting task was carried out, before being released back into service. During the second take-off roll, the crew became aware of an

[4] MIRCE Functionability Field is an infinite set of possible functionability points, each representing functionability states that a functionable system type could be found during the any instant of the calendar time [1]. It is defined by the following set:

$$MFF_S(t) = \left\{PFS_S^{i-1}(t), NFS_S^{i}(t),\ i = 1,2,.,\infty,\ t \geq 0\right\}$$

airspeed discrepancy after the $V_1$ decision speed and the take-off was continued. Once airborne, the crew declared a Mayday and decided to return to Brisbane where an overweight landing was carried out. [2]

Since 2008, four planes have returned to the airport after takeoff resulting from the same physical mechanism, with an additional three aborted takeoffs. In total, the Australian Transport Safety Bureau reported at least 15 scheduled flights were interrupted by the same physical mechanism on flights taking off from Brisbane Airport from 2008-2018 and more incidents in the previous years.

The main objective of this paper is to address the Pitot tube blockage by the mud-dauber wasp as a mechanism of the motion of the A6-EYJ through the MIRCE Functionability Field and the consequential functionability actions taken by humans in an attempt to continue with the scheduled flights. The paper also presents a set of a possible prevention and management actions regarding this specific phenomena.

## 2. MIRCE Science Fundamentals

According to the 2nd Axiom of MIRCE Science[5] the motion of a functionable system type through the MIRCE Functionability Field is a result of imposed natural phenomena or human activities, which are jointly called functionability actions [1]. At any instant of calendar time, a given functionable system type could be in one of the following two observable functionability states:

- Positive Functionability State (PFS), a generic name for a state in which a functionable system type is able to deliver the expected measurable function(s),
- Negative Functionability State (NFS), a generic name for a state in which a functionable system type is unable to deliver the expected measurable function(s), resulting from any reasons whatsoever.

The sequential motion of a functionable system type through the functionability states, in the direction of calendar time, is generated by functionability actions, which are classified as:

- Positive Functionability Action (PFA), a generic name for any natural process or human activity that compels a system to move to a PFS,
- Negative Functionability Action (NFA), a generic name for any natural process or human activity that compels a system to move to a NFS.

To scientifically understand the mechanisms that generate functionability events, positive and negative, analysis of the in-service behaviour of several thousands of components, modules and assemblies of functionable systems in defence, aerospace, nuclear, transportation, motorsport, communication and other industries have been conducted at MIRCE Akademy, by members of staff, students and science fellows.

[5] MIRCE Science comprises axioms, laws, mathematical equations and calculation methods that enable accurate predictions of the functionability performance of a given “future” system to be calculated. [1]

In MIRCE Science all negative functionability actions are categorised as following [1]:

- Component-internal actions that consist of:
    - Inherent actions that are introduced into components prior to their introduction into service through the activities associated with the design, manufacturing, handling, transportation, maintenance, storage and similar processes.
    - Cumulative continuous actions that are an inevitable part of the components in-service life resulting from natural decay processes such as: corrosion, fatigue, creep, wear and similar.
- Component-external actions, which are originated by:
    - Environmental phenomena that cause discrete overload, like foreign object damage; birds strike (domestic and wild animals), weather (hail, rain, snow, lightening, solar radiation, etc.,) and so forth.
    - Human activities:
        - Errors that are related to phenomena that cause overload, for example use and abuse by operators, (pilots, driver and other users), maintainers (maintenance induced errors) and logistics support personnel (bogus parts, shelf life, etc.)
        - Rules that are related to organisational policies, legal requirements, national and international, best practices or any other human imposed functionability related actions (scheduled and condition based maintenance tasks).
- System-internal actions: resulting from processes that are taking place within a system, like a change from passive to active state for certain components and modules, a change in functionability states of some of its constituent components that impact the functionability of the system.
- System-external actions: which are generated by:
    - Discrete environmental phenomena related to weather (hail, rain, snow, lightening, volcanic eruptions, wind, fog, solar radiation, etc.) and other causes that impact on the functionability of a functionable system type.
    - Human activities:
        - Errors, which are related to the phenomena of use and abuse by: operators, maintainers or supply chain personnel.
        - Rules, which are related to organisational policies, legal requirements, national and international, best practices or any other human imposed functionability actions that cause the occurrence of NFEs for the functionable systems.

This paper discusses the Pitot tube blockage by mud-dauber wasps, as one of many component-external actions generated mechanisms, that govern a motion of an aircraft from a PFS to a NFS of the MIRCE Functionability Field and the consequential functionability actions taken by humans to return an aircraft into subsequent PFS state.

## 3. Pitot Static System

In aviation, a pitot-static system is used to determine an aircraft's: airspeed, Mach number, altitude, and altitude trend. It consists of a pitot tube, a static port, and the pitot-static instruments. Other instruments that might be connected are: air data computers, flight data recorders, altitude encoders, cabin pressurisation controllers, and various airspeed switches.

Errors in the pitot-static system readings can be extremely dangerous as the information obtained from the pitot static system, such as altitude, is potentially safety-critical. Several commercial airline disasters have been traced to a failure of the pitot-static system.

### 3.1 Pitot Tube[6]

The Pitot probe consists of a tube pointing directly into the air flow and is used in measuring the stagnation pressure called total pressure or Pitot pressure ($P_T$). It is the sum of the static and kinetic pressures and is detected as the flowing stream impacts on the pitot opening. To measure impact pressure, most pitot tubes use a small, sometimes L-shaped tube, with the opening directly facing the oncoming airflow (from the perspective of normal forward movement of the aircraft). The point velocity of approach ($V_P$) can be calculated by taking the square root of the difference between the total pressure and the static pressure ($P_S$) and multiplying that by the C/D ratio, where C is a dimensional constant and D is air density:

$$Vp = \frac{\mathrm{C}}{\mathrm{D}}\sqrt{(P_T - P_S)}$$

The flow rate is obtained by multiplying the point velocity by the cross-sectional area of the pipe or duct. It is critical that the velocity measurement be made at an insertion depth which corresponds to the average velocity. As the flow velocity rises, the velocity profile in the pipe changes from laminar to turbulent.

Static pressure is obtained through a static port, which is most often a flush-mounted hole on the fuselage of an aircraft, and is located where it can access the airflow in a relatively undisturbed area. Some aircraft may have a single static port, while others may have more than one. In situations where an aircraft has more than one static port, there is usually one located on each side of the fuselage. With this positioning, an average pressure can be taken that allows for more accurate readings in specific flight situations. A pitot-static tube effectively integrates the static ports into the pitot probe. It incorporates a second coaxial tube (or tubes) with pressure sampling holes on the sides of the probe, outside the direct airflow, to measure the static pressure. When the aircraft climbs, static pressure will decrease.

The Pitot tube is most often located on the wing or front section of an aircraft, facing forward, where its opening is exposed to the relative wind. By situating the Pitot tube in such a location, the ram air pressure is more accurately measured since it will be less distorted by the aircraft's structure.

### 3.2 Airspeed indicator

[6] Henri Pitot, in 1732, invented Pitot tubes to measure the velocity of a flowing liquid or air.

The airspeed indicator is connected to both the pitot and static pressure sources. The difference between the pitot pressure and the static pressure is called dynamic pressure. The greater the dynamic pressure, the higher the airspeed reported.

A traditional mechanical airspeed indicator contains a pressure diaphragm that is connected to the Pitot tube. The case around the diaphragm is airtight and is vented to the static port. The higher the speed, the higher the ram pressure, the more pressure exerted on the diaphragm, and the larger the needle movement through the mechanical linkage.

**3.3 Altimeter**

The pressure altimeter, also known as the barometric altimeter, is used to determine changes in air pressure that occur as the aircraft's altitude changes. Pressure altimeters must be calibrated prior to flight to register the pressure as an altitude above sea level.

The instrument case of the altimeter is airtight and has a vent to the static port. Inside the instrument, there is a sealed aneroid barometer. As pressure in the case decreases, the internal barometer expands, which is mechanically translated into a determination of altitude. The reverse is true when descending from higher to lower altitudes.

**3.4 Machmeter**

Aircraft designed to operate at transonic or supersonic speeds will incorporate a Machmeter. The Machmeter is used to show the ratio of true airspeed in relation to the speed of sound.

Most supersonic aircraft are limited as to the maximum Mach number they can fly, which is known as the "Mach limit". The Mach number is displayed on a Machmeter as a decimal fraction.

**3.5 Variometer**

The variometer, also known as the vertical speed indicator (VSI) or the vertical velocity indicator (VVI), is the pitot-static instrument used to determine whether or not an aircraft is flying in level flight.

**4.0 Airspeed Measurement on Airbus A330**

The A330 has three independent systems for calculating and displaying airspeed information: (1) captain, (2) first officer, and (3) standby systems. All three located on the underside of the fuselage near the nose. Each of them has its own pitot probe, static ports, air data modules (ADMs), air data inertial reference unit (ADIRU), and airspeed indicator. Each ADIRU comprises two parts, an air data reference (ADR) part and an inertial reference (IR) part which are integrated into a single unit. One part can be switched off while the other part can still operate.

Airspeed is measured by comparing total air pressure (Pt) and static air pressure (Ps). On the A330, this is measured using a pitot probe, and Ps is measured using two static ports. A separate ADM is connected to each pitot probe and each static port, and it converts the air pressure from the probe or port into digital electronic signals.

Each pitot probe consisted of a tube that projected several centimetres out from the fuselage, with the opening of the tube pointed forward into the airflow. The tube has drain holes to remove moisture, and it is electrically heated to prevent ice accumulation during flight.

Normally, the airspeed displayed to the captain uses the captain’s pitot probe and ADIRU 1, but the source can be manually switched by the crew to the standby system (standby pitot probe and ADIRU 3) if required. Similarly, the airspeed displayed to the first officer (FO) normally uses the first officer’s pitot probe and ADIRU 2, but the source can be manually switched by the crew to the standby system if required

**5. Flight Control System on Airbus A330**

The Airbus A330 has fly-by-wire flight controls, which means that the aircraft’s flight control surfaces are electrically controlled and hydraulically activated in accordance with the flight control computers that process pilot and autopilot inputs to direct the movements of the control surfaces.

A330 has three flight control primary computers (FCPCs) and two flight control secondary computers (FCSCs) that continuously monitored outputs from the three ADIRUs. The median (voted) value of each parameter is compared to each individual value. If the difference is above a predetermined threshold for a predetermined confirmation time, then the associated part of that ADIRU (IR or ADR) is rejected and the two remaining sources are used for flight control purposes.

The flight control system operates according to normal, alternate or direct control laws. Under normal law, the computers prevent the exceedance of a predefined safe flight envelope. If various types of aircraft system problems are detected the control law reverted to alternate law, under which some of the protections were not provided or were provided with alternate logic. Under direct law, no protections are provided and control surface deflection is proportional to sidestick and pedal movement by the flight crew.

**6. Aircraft Maintenance Manual Parking Procedure for Airbus A330**

Parking procedures for Airbus A330 is described in the Aircraft Maintenance Manual (AMM) requests that approved protective covers are installed on each of the air data probes or devices, including Pitot probes. However, experience teaches us that many operators do not apply the AMM parking procedure, if the aircraft only has a short turn-around time or remains on the flight line.

Using the approved Pitot probe covers is important as the covers for other manufacturer's aircraft may not be the correct fit or offer complete protection for the Pitot probes of Airbus aircraft. The same Pitot probe cover can be used on Airbus A310, A320, A330, and A340 aircraft families. Airbus A380 and A350 aircraft have Multi-Function Probes (MFP) and a standby Pitot probe that use two different covers. Pitot probe and MFP covers are part of the flight kit for each aircraft.

It is necessary to point out that protective covers can be installed 30 minutes after engines shut down as the probe heating is deactivated when engines are turned off. After a period of 15 minutes for the probe tip to cool to 70°C, it can take an additional 15 minutes to reach ambient temperature.

## 7. The Observed Motion of A6-EYJ through the MIRCE Functionability Field

The sequence of observed functionability events that took place during attempting take off by Etihad Airways Airbus A330, from Brisbane (Australia) to Singapore on 21 November 2013, is briefly presented below.

### 7.1 First Negative Functionability Action

A red "speed flag" display on the avionics, as the aircraft accelerated through 50 kt (50 knots[7]) on the first takeoff attempt, initiated the functionability action. [2]

According to the standard operating procedures (SOP), the captain rejected the takeoff and in doing so, compelled the change of functionability state of the aircraft, from positive to negative.

### 7.2 Positive Functionability Actions after the First Rejected Take-off

To return the aircraft into a PFS, maintenance engineer performed the troubleshooting procedures for an 'ADIRU1 fault message, in accordance to the Airbus provided Troubleshooting Manual (TSM). The aircraft maintenance engineer also performed a Built-In Test Equipment (BITE) test of the Electronic Flight Control System (EFCS) 1 and 2. The units tested with normal indications and no faults were identified. The TSM procedure did not specifically identify the Pitot probe as a possible cause.

Although no 'hard' (permanent) faults had been identified, the maintenance engineer, in consultation with the Operator's Maintenance Control Centre, considered that the best resolution would be to make ADIRU 1 inoperative. However, this was not permitted under the Minimum Equipment List (MEL) requirements for Extended Operation (ETOPS) dispatch. Hence, the engineer exchanged ADIRU 1 and 2 and performed a BITE test of both units. The aircraft was dispatched with the ADR part of ADIRU 2 inoperative (switched off) in accordance with the MEL. The flying officer's air data source was switched to ADIRU 3 and the captain's air data source remained switched to the normal

[7] The knot is a unit of speed equal to one nautical mile per hour. [exactly 1.852 km/h (approximately 1.15078 mph)].

(ADIRU 1) position. As a result of this positive functionability action the aircraft have been returned to a PFS and ready for the second take off.

### 7.3 Second Negative Functionability Action

And so, the Airworthiness declared A330 was cleared for departure. However, during the second takeoff run the captain’s airspeed indicators failed again, but this time at a speed where the SOPs call for continuing the takeoff. The Australian Transport Safety Bureau (ATSB) questioned the captain’s recollection that the airspeed failed after “V1” (151 kt.), the speed at which crews are advised to continue the takeoff, noting that the flight data recorder information showed that the failure flag should have appeared after reaching 50 kt. [2]

The incorrect captain airspeed associated with ADIRU 2 inoperative caused the A330’s auto-thrust and flight directors to disengage, the flight controls mode reverted from normal law to alternate law (for 8 seconds) then back to normal law (4 seconds) and finally back to alternate law. The second reversion to alternate law was latched for the remainder of the flight, which meant that the autopilot was unavailable. The pilots declared an emergency and landed at Brisbane at an aircraft weight of approximately 200 metric tons, which was 18 metric tons heavier that the A330s maximum landing weight.

### 7.4 Positive Functionability Actions after the Second NFE

The captain’s probe was removed from the aircraft and sent to the probe manufacturer in the US for examination. In consultation with the participants in the investigation, a test plan was developed prior to examination and testing of the probe.

The probe had been on the aircraft since new (just over 7 years of continuous operation). Its condition was consistent with its time-in-service with the probe inlet showing wear, but within the component maintenance manual (CMM) limits. Visual inspection showed that there was no evidence of obstruction of the drain holes. A borescope examination was performed through the pitot inlet and also through the pneumatic port. The examination showed that the interior of the probe was occluded by an incomplete insect’s nest and the nest material was consistent with that of the mud-dauber wasp. Compressed air was applied to the probe and none of the material was dislodged. The base of the nest was broken away with a sharp instrument and was fully removed by flushing with hot water.

After removal of the obstruction, the probe was tested and, according to the CMM, it could be re-certified and returned to in service use. [2]

## 8. Mud-dauber Wasps (*Sphecidae*)

Solitary wasps differ from the social wasps in nesting habits and life cycle. As they do not have any workers, the queens care for their own young. Hence, they usually only have a single nest. After building cells within the nest, the female wasp captures several spiders. The captured prey are stung and paralysed before being placed in the nest (usually 6-15 per nest), and then a single egg is deposited on the prey within each cell. The wasp then seals the cell with a thick mud plug. After finishing a series of cells, she leaves and does not return. The larva spins a cocoon and pupates. Eventually, the hatching larva will eat the prey and emerge from the nest. They have a low reproductive rate.

The Mud-dauber wasps[8] are medium to large sized and are either shiny black or metallic blue-black with slender abdomens. They get their name from building their nests out of mud balls that are collected at puddle and pool edges. The finger-like nests are attached to flat or vertical surfaces. The mud is moulded into cells by the wasps' mandibles. Their nests are usually built in sheds, barns and other structures. This species is found in a wide variety of habitats, such as rock ledges, man-made structures, puddles and other water edges, cypress domes, in long leaf pines and in turkey oaks.

Mud-dauber wasps are widespread in Canada, the United States, Central America, South Africa and the West Indies, and has been introduced to many Pacific Islands (including Australia, Hawaii and Japan), Peru and Europe, where it has become established in some countries of the western Mediterranean Basin (Austria, Croatia, France, Italy, Cyprus, Ukraine).

## 9. Pitot Tube Blockage Hazard Management at Brisbane Airport

Mud-dauber wasp activity at Brisbane Airport has been investigated previously by the ATSB15 and continuing reports and incidents indicate that it is an ongoing hazard. As the wasps cannot be completely eradicated, it is necessary to have control measures in place to minimise the chance of a pitot probe becoming obstructed. [2]

Following the incident addressed in this paper, the Brisbane Airport Corporation (BAC) reviewed their Wildlife Hazard Management Plan (which includes wasp activity). The relevant part of management activities related to Pitot tube blockage by mud-dauber wasp is presented below:

- The aircraft operator has changed its policy on the use of pitot covers. They are now required to be used on all transits at Brisbane Airport, regardless of ground time.
- The aircraft manufacturer has amended its maintenance troubleshooting manual to increase the likelihood that a blocked pitot probe will be detected.
- The airport operator has extended its wasp inspection and eradication program and reviewed and updated its Wildlife Hazard Management Plan.
- In addition, CASA[9] has drawn attention to the safety implications of mud wasp activity through several publications.

[8] https://animalcorner.co.uk/animals/mud-dauber-wasp/

[9] **Civil Aviation Safety Authority** (CASA) is the Australian national authority for the regulation of civil aviation.

Reporting any occurrences of Pitot probe obstruction to the local airport authorities and Airbus will help to monitor for adverse trends, put specific measures in place and communicate this information to the benefit of all airlines and operators

## 10. Conclusions

The main objective of this paper is to address pitot rube blockage by mud-dauber wasps as a physically observed mechanism of the motion of an aircraft through the MIRCE Functionability Field.

Although not a frequently occurring phenomenon, it has been experienced by several aircraft on the ground in areas where these types of insects are present. Even further in a few occasions it caused fatalities. For example, all 189 people on board died of Birgenair Flight 301 from Puerto Plata in the Dominican Republic to Frankfurt, Germany, on 6 February 1996. The B757-200 operating the route crashed shortly after take-off. The cause of crash was pilot error after receiving incorrect airspeed information from one of the pitot tubes, which investigators believe was blocked by a wasp nest built inside it. The aircraft had been sitting unused for two days without the Pitot tube covers in place. [3]

The paper has clearly demonstrated that airlines and operators should assess and monitor the risk of any obstruction to their aircraft's Pitot probes at the airports where they are based or operating to. Airports should an active role by collaborating with their operators to manage airport hazards and communicate on any of the mitigations in place.

Finally, where there is an identified risk of Pitot obstruction due to sand, dirt, dust or insect nesting activity, the operator should be obliged applying a specific policy to use Pitot covers for aircraft on the ground regardless of the lengths of turn-around times.

## 11. References

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# Glare as a Mechanism of the Motion of an Aircraft through the MIRCE Functionability Field

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Abstract

*MIRCE Mechanics is the discipline of MIRCE Science that focuses on the scientific understanding and description of the phenomena that govern the motion of functionable system types though the MIRCE Functionability Field [1]. A full understanding of the mechanisms that generate the motion is essential for the accurate predictions of the functionability performance of functionable system type. According to the 2nd Axiom of MIRCE Science the motion of a functionable system type through MIRCE Space is a result of imposed natural phenomena or human activities, which are jointly called functionability actions. Thus, the main objective of this paper is to address glare as an observed physical phenomenon in aviation that can contribute to fatigue, due to the frequency with which the pilot's eyes must adapt from cockpit to exterior, from near to far, from dark to light. Although it is not a frequently manifested catastrophic event, direct or reflected glare is a physically observable phenomenon, which has been attributed to impact directly on the performance of humans involved in flying aircraft and operating them on the ground. The paper also presents a set of possible preventions and management actions that could be taken to reduce the consequences of glare on the safety of flying.*

## 1. Introduction

MIRCE Mechanics is the discipline of MIRCE Science that focuses on the scientific understanding and description of the physical phenomena and human rules that govern the motion of functionable system type[10] though the MIRCE Functionability Field[11]. A full understanding of the mechanisms that generate this motion is essential for the accurate predictions of the functionability performance of a functionable system type using the mathematical scheme of MIRCE Science. [1]

[10] Functionable system type is a well defined set of physical entities whose purpose of existence is to do a functionable work in accordance to natural laws and human rules.

[11] MIRCE Functionability Field is an infinite two dimensional set of discrete functionability points, each representing a possible functionability state that a functionable system type could be found at any instant of the calendar time [1]. It is defined as:

$$MFF_S(t) = \left\{PFS_S^{i-1}(t), NFS_S^{i}(t),\ i = 1, 2, ., \infty,\ t \geq 0\right\}$$

 

Nakagawara at el [2] searched 25,226 accidents[12] in the USA National Transportation and Safety Board's (NTSB)'s database for terms including "sun," "glare," "vision," "blinded" and "reflections." They found 130 accidents in which direct or reflected glare was a contributing factor.  Of those, 110 occurred during optimal visual and atmospheric conditions, since glare is hardly a risk factor on a cloudy day. Even further, 107 occurrences took place during the daytime hours rather than early morning or evening when the sun is lower in the sky. Further analysis shown that 72 of the accidents considered were associated with landing or departure phases, and of those 52 resulted in a collision with an object or terrain. Finally, 39 of the collisions were due to under- or over-shooting the runway or failing to maintain alignment with the runway. Eight glare related events occurred during taxiing.

Glare was also cited as a contributing factor in seven midair collisions. The study concluded that, "Exposure to glare from natural sunlight has contributed to aviation accidents, primarily under otherwise optimal visual conditions at low altitude in congested airspace." [3]

Ground and Air Traffic Control (ATC) personnel can also be affected by glare. A tragic example of this occurred on Feb. 1, 1991, at Los Angeles International Airport (LAX). A USAir Boeing 737 had been cleared to land, but the pilots were unaware that a SkyWest Metroliner was holding on the same runway awaiting takeoff clearance. The Boeing landed on top of the commuter and 34 people died as a result. The NTSB's findings included the following statement: "The ability of the Los Angeles Air Traffic Control tower personnel to distinguish aircraft on the runways and other airport traffic movement areas, including the accident site, was complicated by some of the Terminal II apron lights, which produced glare." [3]

It is worth pointed out that in many instances the accident report noted that the glare effects were intensified by inadequately maintained windscreens. Dirt, scratches and pitting on the windscreen, scattered the sunlight and further reducing the pilot's ability to see the external environment clearly.

The main objective of this paper is to address the glare as a physical mechanism of the motion of an aircraft through the MIRCE Functionability Field and to presents a set of possible prevention and management actions that can be taken by humans in an attempt to minimise the impact to a functionable system from glare and thus continue with the scheduled flights.

## 2. MIRCE Science Fundamentals

According to the 2$^{nd}$ Axiom of MIRCE Science[13] the motion of a functionable system type through the MIRCE Functionability Field is a result of imposed natural

[12] The NTSB database is the official repository of aviation accident data, causal factors, and selected incident data, whereas the FAA Accident/Incident Data System contains accident and incident data records for all categories of civil aviation.

[13] MIRCE Science comprises axioms, laws, mathematical equations and calculation methods that enable accurate predictions of the functionability performance of a given "future" system to be calculated. [1]

phenomena or human activities, which are jointly called functionability actions [1]. At any instant of calendar time, a given functionable system type could be in one of the following two observable functionability states:

- Positive Functionability State (PFS), a generic name for a state in which a functionable system type is able to deliver the expected measurable function(s),
- Negative Functionability State (NFS), a generic name for a state in which a functionable system type is unable to deliver the expected measurable function(s), resulting from any reasons whatsoever.

The sequential motion of a functionable system type through the functionability states in the direction of calendar time is generated by functionability actions, which are classified as:

- Positive Functionability Action (PFA), a generic name for any natural process or human activity that compels a system to move to a PFS,
- Negative Functionability Action (NFA), a generic name for any natural process or human activity that compels a system to move to a NFS.

To scientifically understand the mechanisms that generate functionability events, positive and negative, analysis of the in-service behaviour of several thousands of components, modules and assemblies of functionable systems in defence, aerospace, nuclear, transportation, motorsport, communication and other industries have been conducted at MIRCE Akademy, by members of staff, students and science fellows.

In MIRCE Science all negative functionability actions are categorised as following [1]:

- Component-internal actions that consist of:
  - Inherent actions that are introduced into components prior to their introduction into service through the activities associated with the design, manufacturing, handling, transportation, maintenance, storage and similar processes.
  - Cumulative continuous actions that are an inevitable part of the components in-service life resulting from natural decay processes such as: corrosion, fatigue, creep, wear and similar.
- Component-external actions, which are originated by:
  - Environmental phenomena that cause discrete overload, like foreign object damage; birds strike (domestic and wild animals), weather (hail, rain, snow, lightening, solar radiation, etc.,) and so forth.
  - Human activities:
    - Errors that are related to phenomena that cause overload, for example use and abuse by operators, (pilots, driver and other users), maintainers (maintenance induced errors) and logistics support personnel (bogus parts, shelf life, etc.)
    - Rules that are related to organisational policies, legal requirements, national and international, best practices or any other human imposed functionability related actions (scheduled and condition based maintenance tasks).

- System-internal actions: resulting from processes that are taking place within a system, like a change from passive to active state for certain components and modules, a change in functionability states of some of its constituent components that impact the functionability of the system.
- System-external actions: which are generated by:
    - Discrete environmental phenomena related to weather (hail, rain, snow, lightening, volcanic eruptions, wind, fog, solar radiation, etc.) and other causes that impact on the functionability of a functionable system type.
    - Human activities:
        - Errors, which are related to the phenomena of use and abuse by: operators, maintainers or supply chain personnel.
        - Rules, which are related to organisational policies, legal requirements, national and international, best practices or any other human imposed functionability actions that cause the occurrence of NFEs for the functionable systems.

This paper discusses the glare, as one of many external functionability actions generated mechanisms that govern a motion of an aircraft from PFS to ma NFS of the MIRCE Functionability Field.

## 3. The Mechanics of Human Vision

Human eyes need light[14] to work, and it is essential for colour vision. Light reflects off the objects and it is this reflected light that we observe and interpret as an image of the world. Different objects reflect different amounts and frequency of light. Reflected light entering eyes is collected by retina, which is located at the back of the eye. It is a light-sensitive layer of cells, which are of the following type:

- Cone cells, which are concentrated in the centre of retina where the light is focused by the cornea and lens. This area is called the macula. Cone cells give detailed vision that is used when reading, watching and looking at people's faces. They are also responsible for most of colour vision.

- Rod cells, which are concentrated around the edge of retina. They help to see things that aren't directly in front of a person giving a rough idea of what is around. They help with mobility and getting around by not bumping into things. They also enable to see things in dim light and to see movement.

Photons passing through the iris are focused by the lens and collected by the retina, which converts them into electrical signals that are send by the optic nerve to the brain. Finally, the brain processes these signals and enables a person to "see" the world around.

Although light is an essential part of this process, sometimes it can have a negative impact on human vision. For example, there are times when the amount of light or

[14] According to quantum theory a light is a type of energy. It is a form of electromagnetic radiation of a wavelength which can be detected by the human eye. It consists of discrete packets of energy called photons.

the quality of that light can affect our ability to see. Many people with impaired vision need more light than is typical to read. However, too much light can cause problems with glare[15]. Some eye conditions can exacerbate glare, including: ocular albinism, cataract, macular degeneration, uveitis and some conditions which affect the front surface of the eye such as conjunctivitis, dry eye or corneal problems. There are also some other conditions such as meningitis which cause light to be very painful quite quickly.

## 4. Glare as a Physical Phenomenon

Glare is usually defined as a temporary sensation produced by luminance within the visual field that is significantly greater than that to which the eyes can readily respond to and is not associated with biological damage. It is a vision impairment produced by intense light, and it can occur either directly or by reflection. It occurs whenever there is a high contrast between a light source and the particular object(s) a person is trying to focus on.

Unified Glare Rating (UGR) is a unit of measurement of glare in accordance to the International Commission on Illumination (CIE). The UGR is a ratio of light source illuminance and background luminance, and can take values from 5 to 40. Glare becomes more drastic as the UGR rises.

It’s necessary to stress that there is a range of light sensitivity among humans, as some are just more sensitive to light than others. Also as human grow older they can become more sensitive to light; this is because the eye changes even though there is no underlying eye condition.

### 4.1 Types of Glare

Glare can be divided into three types:

- Blinding or Reflected Glare can be described as glare that is caused by, for example, staring directly into the sun. While reflected glare can be described as light which is reflected off surfaces which are smooth and shiny such as sand, snow and water.

- Disability Glare can be best described as being blinded by surrounding light sources. Similar to blinding glare, disability glare also has the ability to block vision or a significant reduction in vision capabilities. This is due to a reduction in contrast. For example, driving under the rain in a two-way street causes the light from cars coming in the opposite direction to get scattered by raindrops, impairing vision. In this scenario glare interferes with the task at hand, but without reaching the point of causing pain or physical discomfort.

[15] Light Sensitivity (photophobia), Eye Conditions Fact Sheets, pp 11, Royal National Institute of Blond People, London, UK, 2016.

- Discomfort Glare can be best described as a sensation that humans are unable to tolerate it and instinctively look away. A drastic example of discomfort glare would be the experience if a High-intensity discharge lamp is turned on and pointed directly at eyes from only a few meters away. The same thing happens whenever humans look directly at the sun by accident. Light sources capable of causing discomfort glare are normally also able to damage human eyes**,** hence the instinctive reaction to look away

**4.2 Sources of Glare**

Although essential to life on Earth, sunlight could cause a problem for those humans who traverse the skies above Earth. Sunlight is a portion of the electromagnetic radiation given off by the Sun, in particular infrared, visible, and ultraviolet light. On Earth, sunlight is filtered through Earth's atmosphere, and is obvious as daylight when the Sun is above the horizon. When the direct solar radiation is not blocked by clouds, it is experienced as sunshine, a combination of bright light and radiant heat. When it is blocked by clouds or reflects off other objects, it is experienced as diffused light.
Flash-blindness is a visual interference effect that persists even after the source of illumination has been removed. After image occurs when a transient image is left in the visual field after exposure to a bright light. These can temporarily impair vision as the spots appear to be burned into one’s vision. Even if the spots are small and not in the centre of the eye, they can still be distracting. Glare affects the ability to maintain visual awareness and therefore can impair flight safety and is a frequent factor in all air operations.

Glare can come directly from the light source or can take the form of veiling glare, reflected from crazing or dirt on the windscreen. The visual phenomenon affects a pilot’s ability to accurately detect objects, especially when they are in the same direction as the glare. For example, Air Traffic Control (ATC) issues a traffic alert for an aircraft straight ahead and it happens to be flying with the sun in that same direction. Hawkins [7] states that when the source of the glare is only 5 deg. away from the direction of view, the loss of visual effectiveness is an astounding 84%. When glare is 40 deg. from the line of sight, the loss of visual effectiveness drops 42%.

**4.3 Night Time Glare**

For pilots operating an aircraft at night preservation of optimal night vision is of vital importance. When the eyes have adapted to low-light levels, exposure to bright light can result in temporary visual impairment due to glare, flash-blindness, and afterimages.

Nakagawara at el [4, 5] also examined the role of glare at night. Their study revealed that the eye is much more sensitive to light at night because it relies primarily on the rods for night vision. In order for eyes to adapt to low light they undergo a chemical reaction using photoreceptor pigments. Intense light decomposes the photoreceptor pigments reducing sensitivity to dim light. Regeneration of the photo pigment occurs during night adaptation. The regeneration of these pigments can take 30 to 60 minutes after exposure to bright light. This is a serious problem in flight for obvious reasons.

Pilots commented that they lost depth perception after experiencing glare or from being flash-blinded by approach or runway lights, which caused them to land long or short, resulting in a collision with terrain. The FAA study cited an incident in which a pilot asked the control tower to turn up the intensity of the approach lights to aid visually acquiring the runway on approach but then reported experiencing excessive glare in contact lenses on short-final. Consequently that resulted in a collision with the approach light structure.

Pilots also reported visual difficulties when their landing lights reflected back into the cockpit due to dust, fog, rain, snow or ice. Other sources of glare were taxiway/apron lighting, aircraft lights, lasers and emergency vehicles, among other things. Ineffective lighting configurations in the airport environment appear to be the root cause of these visual difficulties while taxiing.

The majority of the taxiing incidents involved pilots straying off ramps, taxiways, runways, hitting obstacles or other aircraft. Undoubtedly, many pilots have experienced the problem with poorly positioned ramp or apron lighting that hampers the ability to distinguish runway markings or to determine exactly where the taxi surface begins and ends. Coincident with these conditions were inadequate taxiway markings. The study's authors highlight the increased risk of runway incursions, collisions and excursions from aircraft movement areas when pilots cannot adapt to the dark. [6]

**4.4 Human Made Glare**

Solar power is a growing source of “clean” energy for many communities. While solar power panels provide a useful means to generate revenue and to provide energy locally, nobody expected that it will pose a potential hazard in the form of glare.

Airplane pilots reported that they were blinded by the intense sunlight reflecting off some of the 340,000 mirrors at the Ivanpah Solar Electric Generating System on the California-Nevada border. The Ivanpah power plant is about 40 miles from the Las Vegas airport. [8] The mirrors, called heliostats, focus the sun on 140 metre towers that contain water-filled boilers. The concentrated sunlight boils the water to create steam, driving turbines that generate 377 MW of carbon-free electricity. The heat is so blistering that it has melted the feathers of birds in mid-flight. [6]

Planes fly far too high to be affected by the heat, but not by the light[16]. According to Air traffic controller at an Federal Aviation Administration (FAA) centre that monitors the airspace in southern California Daily, during the late morning and

[16] “From the pilot's seat of my aircraft the brightness was like looking into the sun,” reported one pilot as his small plane climbed from 6,000 to 12,000 feet after taking off from the Boulder City, Nevada, airport. In a report he filed with the Aviation Safety Reporting System (ASRS), the pilot wrote that, “In my opinion the reflection from these mirrors was a hazard to flight because for a brief time I could not scan the sky in that direction to look for other aircraft.” [8]

early afternoon hours there are numerous reports from pilots[17] of aircraft flying from the northeast to the southwest about the brightness of this solar farm,

In USA the Aviation Safety Reporting System (ASRS), receives more than 1,300 reports weekly from pilots, air traffic controllers and other aviation personnel, according to the organisation's website. If the reports identify a hazardous situation, the ASRS issues an alert to the appropriate government agency in USA. [8]

Aviation officials have long been concerned about the impact of huge solar power plants, and in recent years the US military has vetoed the construction of projects near bases in the California and Nevada deserts.

## 5. Impact of Glare on Pilots Vision

The most significant feature of glare encountered in flight is its variable nature. It is variable in intensity and in direction, and while the pilot may be subjected to these variations very quickly within the space of seconds, s/he may on the other hand be exposed to glare from one direction for a period of several hours. Also, the frequency, with which the pilot's eyes must alternate from cockpit to exterior, from near to far, from dark to light, combines with all these factors to produce a visual environment that most readily results in fatigue and difficulty in seeing.

When operating below clouds, and at lower altitudes, the light comes from above. However, at high altitude there is a reversal of light distribution, particularly when flying above a layer of clouds. Once an aircraft climbs above a cloud deck most of the light reflected back into the aircraft comes from the cloud layer below. It is estimated the clouds underneath effectively reflect 80% of the sunlight. Some light does come from the sky above, but the amount of scattered light that comes from the sky becomes progressively less as the aircraft flies at higher altitudes. This altered light distribution results in more light reaching the upper part of the cockpit and in less reaching the lower part, which is therefore darker than it would be at a lower altitude.

At high altitudes the change in the light spectrum causes a visual illusion in the pilot's ability to see contrasting shades of colour. When a dark and a bright area are adjacent to each other, the bright area appears brighter and the dark area darker. Human anatomy plays an interesting role in accommodating this visual phenomenon. A light source below eye level can actually flood one's vision and cast a troublesome haze over the entire visual field. Sunglasses reduce the luminance of the outside scene, bringing it to a comfortable level, but they also reduce the luminance of the already dark interior of the cockpit.

Humans have different tolerances for illumination from high intensity light sources. Age is one of significant factors. Older eyes have less tolerance for high-intensity light. In addition, eye pigment, which is the colour of retina, influences an individual's tolerance for glare and people with a lighter pigment have less tolerance than those with darker pigment.

[17] "In my opinion the reflection from these mirrors was a hazard to flight because for a brief time I could not scan the sky in that direction to look for other aircraft." [8]

Abnormal eye conditions can also increase glare sensitivity as can contact lenses. Cataracts will cause a person to see halos around lights. While modern medical procedures such as lens implants, cataract surgery, radial keratotomy and laser refractive surgery offer visual sight improvement, they can result in discomfort or disability glare, according to abundant references cited in [2].

## 6. Glare Protecting Methods

When possible, pilots could consider alternative flight routes and takeoff and landing directions. However, as a practical matter, it may not be possible to choose a different route or an alternate runway to avoid glare.

The FAA's "Natural Sunlight" study [2] recommends the following actions could have a positive impact on the poetical negative consequences of a glare effects on pilots and safety of flights, thus:

- Enlisting a co-pilot or passenger to help read important instruments and/or printed flight documents including checklists and approach plates so the pilot-flying can focus attention on overcoming glare conditions.
- The aircraft's sun visor or a brimmed hat can provide shielding to the pilot's eyes from glare.
- Avoiding light-coloured clothing as it creates a reflection on the windscreen.
- Light-coloured or reflective materials should not be place on the glare shield since they can reflect light off the windscreen.
- Preventive maintenance on the windscreen is necessary when scratches or pits cause unacceptable light scatter.
- Periodic windscreen polishing prevents additional light scatter as well.
- Cleaning the windscreen thoroughly during the pre-flight check
- Use of appropriate sunglasses can minimise the effects of glare by establishing a proper balance between visibility of objects inside and outside of the cockpit environment.
- Use of larger lenses and wrap-around frame styles can prevent sunlight from entering peripherally and affect the wearer's vision[18].

## 7. Conclusions

The main objective of this paper was to address glare as a physical mechanism of the motion of an aircraft through the MIRCE Functionability Field. [1] Although it is not a frequently manifested catastrophic phenomenon, glare is a physically observable event, which has been attributed to impact directly on the performance of humans involved in flying aircraft and operating them on the ground [2, 3, 4, 5].

Glare as a physical mechanism is briefly explained in the paper together with all three types of its manifestation, namely: blinding (or reflected), disability and discomfort, considering their main characteristics and potencial impact on pilots

[18] The Civil Aviation Authorities of UK, guidance on the type of spectacle frame and lenses recommended for use in the aviation environment could be found in www.caa.co.uk

and air traffic controller. These effects can result in prolonged visual impairment and be extremely hazardous to pilots in flight who require optimum vision all the time.

Pilots are exposed to various meteorological conditions while in-flight that may increase glare and limit visibility and contrast. They are often subjected to direct and indirect sunlight, which can act as an intense source of glare. Furthermore, while flying at high altitude pilots may be exposed to darkened skies above and bright reflected light from the clouds beneath. Physiologically the contours of the human face serve to protect the eyes from bright light coming from above, but not from below.

It has been pointed out in the paper that in many instances the accident report concluded that the glare effects were intensified by inadequately maintained windscreens. Dirt, scratches and pitting in a windscreen scatter the sunlight and further reduce a pilot’s ability to see the external environment clearly.

While solar power panels provide a useful means to generate a “clean” energy for many communities nobody expected that it will pose a potential hazard in the form of glare to the aviation community. In USA the Aviation Safety Reporting System (ASRS), receives more than thousand reports weekly from pilots flying from the northeast to the southwest about the brightness of this solar farm, according to the organisation’s website.

This paper clearly confirms that glare from natural sunlight and other sources has caused visual impairment of pilots while operating aircraft and has contributed to the transition of an aircraft from positive to negative functionability state, resulting in the reduction or potentially cessation of the functionability work done.

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# Emergency Oxygen Provision as a Mechanism of the Motion of an Aircraft Through MIRCE Functionability Field

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*MIRCE Mechanics is the discipline of MIRCE Science that focuses on the scientific understanding and description of the functionability actions that govern the motion of functionable system types though the MIRCE Functionability Field (MFF) [1]. A full understanding of the mechanisms of these actions is essential for the accurate predictions of the functionability performance of functionable system types using MIRCE Functionability Equation. Thus, the main objective of this paper is to address a provisioning of emergency oxygen as a mechanism of a motion of an aircraft through MFF generated by the observed physical phenomena or human activities. Some of them are briefly described and analysed in the paper. Based on the evidence available recommendations for the reduction of the probability of occurrence of negative functionability events of the emergency oxygen provision are presented.*

## 1. Introduction

Oxygen is vital for the human body. As the altitude increases, the consequent decrease in pressure reduces the amount of oxygen the human body can absorb when breathing. To enable flight at high altitudes, which significantly reduces fuel consumption, either the aircraft cabin has to be pressurised, to replicate the pressure at a lower altitude, or the occupants of the aircraft have to be given supplemental oxygen. A healthy person at sea level has a bodily oxygen saturation of 97 percent. Medical officials consider that an oxygen saturation of 93 percent is to be the lower limit of normal functioning. At an altitude of 10,000 ft, saturation drops to almost 90 percent, at 15,000 ft it is at 80 percent and at 25,000 ft it is a mere 55 percent leading to incapacitation. The higher the altitude, the lower the time of useful consciousness, as shown by Figure 1.

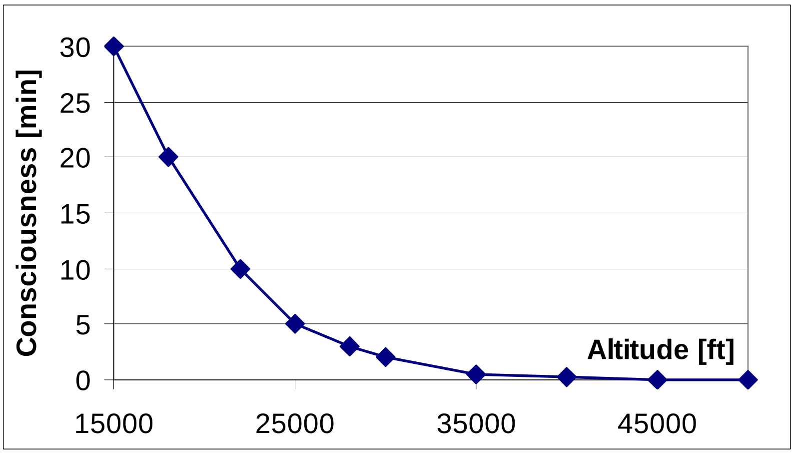


Figure1: The relationship between the altitude and the time of useful consciousness

Consequently, commercial aircraft are pressurised to the cabin equivalent of 8,000 ft, meaning that someone sitting in an aircraft cruising at 35,000 ft is experiencing the same concentration of oxygen that they would experience at an altitude of 8,000 ft. Today, this is a routine process. The basics of pressurised aircraft date back to the mid-1930s. Thus, on most pressurised aircraft, if cabin pressurisation is lost when the cabin altitude is above 14,000 feet, emergency oxygen will be automatically provided. The supply of emergency oxygen typically provides enough air to last 12 to 20 minutes, which gives the pilot sufficient time to descend a safe altitude where masks are not needed anymore.

Combustion is the exothermic chemical reaction between oxygen and a fuel, producing a flame and smoke. Thus, oxygen-generating equipment on aircraft presents a significant fire hazard and has contributed to several aircraft fires, both on the ground and in flight. For example:

- In 1996 ValuJet Flight 592 expired chemical oxygen generators were improperly prepared and labelled as company material and without being designated as HAZMAT and placed in the cargo hold of a passenger aircraft, where they caught fire in flight resulting in a crash that killed all 110 persons onboard
- In 2008 ABX Air Flight 1611 cockpit fire in a Boeing 767 on the ground before departure caused by an unexpected electrical current in the anti-kink spring of the pilot's oxygen mask hose. This ignited the hose due to the presence of oxygen inside the hose that remained from pre-flight checks although there was no indication that the oxygen supply was breached. Both pilots safely evacuated the cockpit, but the aircraft was declared a total loss.
- In 2008, a Boeing 747-438 aircraft carrying 369 passengers and crew, on Qantas Flight 30[19], rapidly depressurised following the forceful rupture of one of the aircraft's emergency oxygen cylinders in the forward cargo hold. The aircraft was cruising at 29,000 ft and was 55 minutes into a flight between Hong Kong and Melbourne. Following an emergency descent to 10,000 ft, the flight crew diverted the aircraft to Ninoy Aquino International Airport, Manila, Philippines, where it landed safely. None of the passengers or crew sustained any physical injury. The aircraft was repaired and returned to service in 2009.
- In 2011 EgyptAir Flight 667 an electrical spark in the presence of the supplemental oxygen system turned the flight deck of a Boeing 777-200 into a conflagration, at Cairo International Airport (CAI). The captain attempted to extinguish the fire with the cockpit fire extinguisher but was unsuccessful. As the aircraft was on the ground at the time, the captain ordered an emergency evacuation and all passengers and crewmembers were able to escape without serious injury. Due to the growing fire in the cockpit the first officer was unable to use a radio to summon emergency services. So, after exiting the Boeing he stopped a car on a service road to call the fire department. Although there were no fatalities, the aircraft was damaged beyond repair.

[19] http://news.bbc.co.uk/1/hi/world/asia-pacific/7532357.stm

The main objective of this paper is to examine the emergency oxygen provisioning actions as a mechanism of the motion of an aircraft through MIRCE Functionability Field, which impacts the functionability work done by an aircraft and resources consumed during a given interval of calendar time.

## 2. MIRCE Science Fundamentals

According to MIRCE Science[20], at any instant of calendar time, a given functionable system type[21] could be in one of the following two states [1]:

- Positive Functionability State (PFS), a generic name for a state in which a functionable system type is able to deliver the expected measurable function(s),
- Negative Functionability State (NFS), a generic name for a state in which a functionable system type is unable to deliver the expected measurable function(s), resulting from any reason whatsoever.

In MIRCE Science a life of a functionable system type is defined by the MIRCE Functionability Field (MFF), which is mathematically described[22] as a two dimensional countable infinite set of possible functionability points, each representing functionability state that a functionable system type could be found in, at any instant of the calendar time.

The motion of a functionable system type through the MFF is generated by functionability actions, which are classified as:

- Positive Functionability Action (PFA), a generic name for any human activity or physical phenomena that compels a system to move to a PFS.
- Negative Functionability Action (NFA), a generic name for any physical phenomena or human activity that compels a system to move to a NFS.

The motion of a functionable system type through the MFF is physically manifested through the occurrences of functionability events, which are classified as:

- Positive Functionability Event (PFE), a generic name for any physically observable occurrence in the calendar time that signifies the transition of a functionable system type from a NFS to a PFS.
- Negative Functionability Event (NFE), a generic name for any physically observable occurrence in the calendar time that signifies the transition of a functionable system type from a PFS to a NFS.

[20] MIRCE Science comprises of mathematical axioms, equations and methods that enable predictions of expected functionability performance of each feasible option of the future functionability system type to be done, based on the complex, time-dependent, interactions between: physical properties of consisting components and applied functionability rules regarding operation, maintenance and support processes.

[21] According to Knezevic [1], functionable system type is “a set of mutually related entities put together to do a functionability work in accordance to physical laws and given functionability rules.”

[22] $MFF_S(t) = \left\{PFS_S^{i-1}(t), NFS_S^{i}(t),\ t > 0,\ i = 1, 2, ., \infty\right\}$ [1]

MIRCE Mechanics is a part of MIRCE Science that focuses on the scientific understanding of the mechanisms that generate functionability actions that govern the motion of functionable system types though MFF [1]. A full understanding of these mechanisms is essential for accurately predicting the expected functionability work done and the cost of resources consumed by a given functionable system type using MIRCE Science Equations.

## 3. Aircraft Emergency Oxygen System

Brief description of the certification regulations related to the aircraft emergency oxygen system is presented here together with the description of their main parts.

### 3.1 Regulations

National regulations for the provision and use of supplemental or emergency oxygen systems are based on the guidance provided in Annex 6 of the International Civil Aviation Organisation (ICAO) Standards and Recommended Practices (SARPS) [23]. The most significant items found in the guidance on oxygen are following:

- All Aircraft: An operator shall ensure that passengers are made familiar with the location and use of: oxygen dispensing equipment, if the provision of oxygen for the use of passengers is prescribed.
- Non-pressurised Aircraft
    - An aeroplane intended to be operated at flight altitudes at which the atmospheric pressure is less than 700 hPa in personnel compartments shall be equipped with oxygen storage and dispensing apparatus
    - A flight to be operated at flight altitudes at which the atmospheric pressure in personnel compartments will be less than 700 hPa shall not be commenced unless sufficient stored breathing oxygen is carried to supply:
        - all crew members and 10 per cent of the passengers for any period in excess of 30 minutes that the pressure in areas occupied by them will be between 700 hPa and 620 hPa
        - the crew and passengers for any period that the atmospheric pressure in areas occupied by them will be less than 620 hPa
- Pressurised Aircraft
    - An aeroplane intended to be operated at flight altitudes at which the atmospheric pressure is less than 376 hPa or which, if operated at flight altitudes at which the atmospheric pressure is more than 376 hPa, cannot descend safely within four minutes to a flight altitude at which the atmospheric pressure is equal to 620 hPa shall be provided with automatically deployable oxygen equipment. The total number of oxygen dispensing units shall exceed the number of passenger and cabin crew seats by at least 10 per cent.
    - All flight crew members of pressurised aeroplanes operating above an altitude where the atmospheric pressure is less than 376 hPa shall

[23] https://www.skybrary.aero/index.php/Aircraft_Oxygen_Systems (accessed on 07.02.2019)

have available at the flight duty station a quick-donning type of oxygen mask which will readily supply oxygen upon demand.

### 3.2 Equipment

Due to the different requirements of the equipment used on the flight deck and that used in the passenger cabin their design and functionality methods differ.

#### 3.2.1 Flight Deck

Oxygen for the use of the flight deck occupants is normally stored as pressurised gas in one or more tanks or cylinders. In certain aircraft types, oxygen is stored as a liquid.

The total oxygen capacity must be sufficient to supply all flight deck occupants with adequate oxygen for a defined period of time at an altitude profile specified in the applicable National Aviation Authority regulations. Commonly, the altitude profile will incorporate an emergency descent segment and followed by a period in level flight at a defined altitude.

A quantity gauge or other means of determining the amount of available oxygen will be incorporated.

A regulator is installed to reduce storage cylinder pressure to a usable level. Depending upon the aircraft type, regulators can be:

- Constant flow type, that provides the same output pressure or flow regardless of altitude. The regulator is therefore optimized for a specific altitude. At altitudes lower than the designed optimum altitude, it will provide more oxygen than is actually required. This type of regulator is most often found in non-pressurized aircraft and on portable oxygen systems. A single constant flow regulator is able to control the oxygen flow to all users.
- Diluter-demand type that provides oxygen at each crew position. Depending upon user selection, the diluter-demand regulator can provide 100% oxygen, 100% oxygen under positive pressure or a mixture of oxygen "diluted" with cabin air on a specific, altitude-based schedule.

#### 3.2.2 Passenger Compartment

In non-pressurised aircraft that routinely fly above 10,000 ft, passenger oxygen is typically provided by:

- Fixed systems that draw their oxygen supply from a pressurised cylinder of gaseous oxygen. This can be a dedicated cylinder or it might be the same cylinder that is used to supply the flight deck occupants. An oxygen manifold runs from the cylinder into the passenger compartment via a single regulator. Attachment ports allow passenger oxygen masks to be connected to the manifold. A shutoff valve capable of isolating the passenger compartment is normally incorporated.
- Portable systems that consist of a storage tank, a regulator and one or more passenger masks. These will be distributed to the passengers when required.

Pressurised aircraft which have a certified maximum altitude of 25,000 ft or less do not require passenger oxygen systems subject to the aircraft being able to descend to 13,000 ft or below within 4 minutes of loss of pressurisation. If the aircraft is not capable of achieving the descent profile or the route structure does not allow the descent due to terrain, an oxygen system must be fitted in the aircraft as per the provisions which apply to aircraft which are certified to fly at higher altitudes (above 25,000 ft).

For pressurised aircraft which are certified to operate above 25,000 ft, emergency oxygen equipment must be available. Some aircraft utilise cylinders of pressurised oxygen to meet this requirement but most types are fitted with chemical oxygen generators. The emergency oxygen supply must last a minimum of 10 minutes. Provisions must be provided in the system to automatically deploy the emergency oxygen masks when the cabin altitude exceeds a pre-determined level (typically 14,000 ft). Sufficient masks must be provided for at least 10% more passengers than there are seats in the passenger compartment.

### 3.3 Oxygen Mask

Due to different functionality oxygen mask used in the flight deck are different from those that are available to passenger cabin.

#### 3.3.1 Flight Deck

An oxygen mask is provided at each flight deck station. The mask could be of the "full face" variety incorporating smoke goggles or a "mouth and nose" type mask with smoke goggles available separately.

The masks at the pilot stations will incorporate microphones to allow internal and external communications.

Masks are fitted to the face utilising various suspension harnesses. For aircraft which routinely fly above 25,000 ft, masks are generally of the "quick-donning" variety, which allow them to be put on in 5 seconds or less using only one hand.

For diluter-demand systems, selectors for normal, 100% and positive pressure maybe incorporated into the mask itself. If not, they will be found on the associated regulator. Diluter-demand oxygen masks are stowed with the selector in the 100% oxygen position and should be reselected to the normal (or diluting) position when mask utilization is required for other than a smoke or fume event.

#### 3.3.2. Passenger Compartment

The most typical passenger oxygen masks consist of a soft, yellow, silicone cup fitted with elastic bands for securing the mask to the face. The bands are adjustable to accommodate passengers of different sizes. The mask may also have a clear concentrator or re-breather bag. Depending upon the cabin altitude, the concentrator bag may or may not inflate. Airlines make a point during their safety presentation of pointing out that the bag may not inflate as, in the past, lack of bag inflation has lead some passengers to believe that their mask was not working and to remove it resulting in hypoxia.

The bag is attached to a tube, connected to the oxygen source in the compartment, allowing for it to drop down and hang in front of the passengers. To operate on all aircraft except the L-1011 and B787, they must be pulled sharply toward the passenger who needs it to un-clip the flow pin and start the process of transporting the oxygen to the passenger. Passenger oxygen masks cannot deliver enough oxygen for sustained periods at high altitudes. This is why the flight crew needs to place the aircraft in a controlled emergency descent to a lower altitude where it is possible to breathe without emergency oxygen.

While the masks are being used, passengers are not allowed to leave their seat for any reason until it is safe to breathe without the emergency oxygen. If there is a fire on board the aircraft, masks are not deployed, as the production of oxygen may further fuel the fire.

### 3.4 Oxygen Generating Mechanisms

There are two systems that are typically found on commercial aircraft, namely:

- A chemical oxygen generator system that is connected to all masks in the compartment. Pulling down on one oxygen mask removes the firing pin of the generator igniting a mixture of sodium chlorate and iron powder, opening the oxygen supply for all the masks in the compartment. During the short period of oxygen production, the generator becomes extremely hot and should not be touched. A burning smell may be noted and cause alarm among passengers, but this smell is a normal part of the chemical reaction. For any aircraft which carries more than a very few passengers, the weight, complexity and maintenance issues associated with a compressed gas system would be prohibitive. Hence, the commercial aviation industry relies on chemical oxygen generators.

- A gaseous manifold system that connects all oxygen masks to a central oxygen supply usually is in the cargo hold area. Pulling down on one oxygen mask starts the oxygen supply for that mask only. The entire system can usually be reset in the cockpit or in some other location in the aircraft.

## 4. Emergency Oxygen Provisioning Related Negative Functionability Actions

Veillette [2] conducted a search of 100 recent NASA Aviation Safety Reporting System (ASRS) records regarding involving incidents in which oxygen masks were employed, submitted in 2016 and 2017. Out of the records analysed 71 are related to a loss of pressurisation or suspected smoke or fumes. In all of these cases emergency oxygen systems operated as designed, enabling the flight crews to breathe and they safely got the aircraft and their passengers on the ground.

 

However, the remaining 29 reports draw attention to the serious risk posed for a flight crew being without supplemental oxygen as well as other serious problems with masks use when needed. The following cases are extracted from Veillette [2]

**Case 1:** NASA ASRS Report 1498858, published in November 2017, contains the following statement by flight crew whose oxygen masks and hoses physically failed: "In cruise flight, I went to put on quick-donning mask as first officer was going to leave the flight deck for physiological needs. I pulled the mask out of the box and it came apart in my hands. It was useless had there been an emergency. Where the hose attaches with the microphone to the main rubber face area was broken and dangling. The full mask section was intact but the hose/microphone area was detached and hanging by a wire, no ability to breathe oxygen from the mask."

**Case 2:** NASA ASRS Report 1462284, published in July 2017, contains the following statement "While out on the lavatory break a co-pilot heard a loud whoosh noise from up in the flight deck. So he immediately returned to the flight deck to request entry back in. When arrived to his seat he saw the captain holding the oxygen hose and mask together in his hands, accomplished with a hissing sound. The captain explained that the oxygen hose for his crew mask would not stay attached to the mask. The captain made several attempts to re-secure the oxygen hose to the mask but did not succeed. Due to the positive pressure of oxygen coming from the hose, neither of them was successful at securing the oxygen hose. After several minutes they became unable to even hold the oxygen hose to the mask. At this point there was nothing to even slow the flow of the crew oxygen and they began to lose crew oxygen at an extremely fast rate."

**Case 3:** A UPS Boeing 747 departed Dubai International Airport (DXB) on a cargo flight to Cologne, Germany (CGN), on 3 September 2010. Twenty minutes into the flight, at approximately 32,000 ft., the crew advised ATC that there was an indication of an onboard fire and declared an emergency. Both pilots had donned their oxygen masks approximately 90 sec. after the fire bell sounded. Less than 90 sec. later, the fire caused severe damage to the flight control system and filled the cockpit with continuous smoke. During the emergency descent the cabin reached a pressure altitude of 21,000 ft., followed almost immediately by the rapid failure of the captain's oxygen supply without any indication of trouble. Unknown to the flight pilots, the fire had severely damaged many significant systems on the aircraft, including the crew supplementary oxygen system supply. The damage caused a cessation of oxygen flow to the captain's mask and reduced capacity for the remainder of the flight to the F/O's mask. To obtain the portable oxygen bottle, the captain left his seat, but did not return due to incapacitation from toxic gases. As the F/O could not view outside the cockpit, or see the primary flight displays, the aircraft subsequently entered an uncontrolled descent into terrain, killing both pilots in the crash.

During the investigation, several UPS line pilots commented on the use of the oxygen mask and goggle sets during their training. They reported receiving little hands-on instruction for the actual use of the set and smoke vent, and what they did receive occurred during initial training for the aircraft in the form of computer-based text and images. They also stated that they were never taught about the relationship between the emergency selector on the regulator and the need to simultaneously open the smoke vent to clear contaminants from inside the goggles or how to locate the switches on the oxygen regulator after the oxygen mask was donned. Further more, they were never required to practice these actions in the presence of an instructor or check airman.

**Case 4**: United Airlines Flight 949 departed London Heathrow Airport (LHR) for Chicago O'Hare International Airport (KORD), on 20 July 2009. At 37,000 ft. the flight crew encountered smoke in the cockpit and diverted to Keflavik International Airport (KEF) in Iceland. During the event, the flight crew donned their oxygen sets and attempted, with difficulty, to establish and maintain crew communications. The following statement the pilot provided to the Icelandic Aircraft Accident Investigation Board, "We struggled with the audio panels to communicate with the masks on." Thus, he removed the oxygen mask to communicate with the Flight officer (F/O) and relief pilot in the cockpit. The F/O said, "The entire process of donning goggles, the use of the oxygen mask, pushing all the different buttons and toggles to communicate with all the people involved was very frustrating at times. Between the goggles scratching my glasses and the smoke film in front of them too, it was hard to see at times. Too many items have to come together for this setup to work." Also, the pilot added that "Crew communications with oxygen masks on was non-effective and increased crew workload significantly. It was made worse with three crewmembers plus ATC all trying to communicate."[24]

**Case 5:** NASA ASRS Report 1486360, October 2017 contains the following statement: "After arriving to the aircraft, we began our pre-flight duties and flows. Upon checking my oxygen mask, I ran the oxygen via the test button for 5 sec. and made sure the microphone worked. However, I immediately saw the $O_2$ psi go from 1,600 to 100 instantly and stay there. I suspected the valve on the bottle itself was in the off position. I told the captain and he agreed. We made an electronic logbook write-up and backed it up with a call to maintenance. They came to the plane and the mechanic was shocked."

**Case 6:** Bob Bostick Jr, retired FedEx pilot, commented on the Veillette's article [2] with a following words[25], "Years ago I was the right seater in the 727, my habit pattern for checking the oxygen mask was to pull the mask off the spring loaded strap it was hanging from, test for flow without putting it on, and reinstall the mask on the strap. Yup, I was not doing a full check and that was my habit pattern until I got an education. Just by chance, during one pre-flight I decided to take the mask off the strap, put it on, and give it a full test, along with taking out the smoke goggles and seeing how well it all worked with my glasses on. Had a simulator ride the next day and knew using the mask would be part of the drill. Donned the mask, flipped the switch on, took a breath…and something came out of the mask and lodged in my throat. That something was moving. After ripping off the mask and doing some very dramatic coughing and heaving, while the Captain and Flight Engineer were watching and wondering what the heck was wrong, I finally spit out a fairly good sized live moth! Wow. How did that happen? Didn't take long to

[24] In response to these events the NTSB issued Safety Recommendation A-11-089, to require airline, charter and fractional operators "to include, during initial and recurrent training, aircraft-specific training on establishing and maintaining internal cockpit communications when the oxygen masks are donned."
[25] a300bob (accessed 28 January 2019)

figure it out, the mask hangs from the top left corner of the Flight Engineer panel, and just above the attach point is one of the flood lights for the panel. Hmmm. Light attracts bug, bug gets tired, bug falls into mask. A good lesson, from that point on in my flying career I made it my habit to pull the mask out of wherever it was, clean it with a mask wipe, put some pressure to it, check it, then put it on and check for function and communication. And yes, on several occasions there was another moth in the mask. Can imagine how bad things could go with smoke/fumes/loss of pressurisation and inhaling a moth with that first deep breath."

**Case 7**: On 25 October 1999, a chartered Learjet 35 was scheduled to fly from Orlando, Florida, to Dallas, Texas. Early in the flight, the aircraft, which was climbing to its assigned altitude on autopilot, quickly lost cabin pressure and all six on board were incapacitated due to hypoxia (a lack of oxygen). The aircraft continued climbing past its assigned altitude, then failed to make the westward turn toward Dallas over north Florida and continued on its north-western course, flying for almost four hours (1,500 miles). The plane ran out of fuel over South Dakota and crashed into a field near Aberdeen after an uncontrolled descent. The NTSB has several levels of investigation, but the final conclusion was; "The probable cause of this accident was incapacitation of the flight crew members as a result of their failure to receive supplemental oxygen following a loss of cabin pressurization, for undetermined reasons. [26]"

However, the crash investigation has highlighted that in Learjet model 35/36, the oxygen bottle regulator/shutoff valve is located in the nose cone of the airplane and therefore inaccessible to flight crewmembers during flight. It was further discovered that pilots may have difficulty visually verifying the position of this valve during a pre-flight inspection because of the way it is installed in the airplane. The Safety Board noted that it is critical that the valve position indicators are clearly visible and easily understandable during pre-flight check. Oxygen bottle supply pressure is indicated on a gauge in the cockpit of the Learjet 35/36. Since a visual check of the oxygen bottle supply may not provide information about the position of the oxygen bottle regulator/shutoff valve, the pilots' only sure indication in the cockpit that the oxygen bottle regulator/shutoff valve is in the OFF position would be the failure of the oxygen mask to deliver oxygen.

## 5. Oxygen Masks Related Negative Functionability Actions

Although emergency oxygen masks and connecting lines are used very infrequently they are not protected from "wear out". The most common components which fail are around valves, fittings, and connections involving rubber seals, tubing and hoses. Other possible negative functionability action that affects oxygen system components is a "dry rot", which occurs when rubber or plastic surfaces are exposed for long periods to alternative heating and cooling temperature swings in dry air (which is an apt description of an aircraft cockpit.) Moisture within the rubber or plastic is wicked away, degrading its flexibility and elasticity over time. Cracking, tearing, and breakage are common indications of dry rot.

[26] https://en.wikipedia.org/wiki/1999_South_Dakota_Learjet_crash (accessed 11 February 2019)

The Australian Civil Aviation Safety Authority (CASA) issued Airworthiness Bulletin 35-004 (Nov. 29, 2012) noting service difficulty trends with oxygen systems service during maintenance identified by their Service Difficult Report database. The observed phenomena that cause the transition of emergency oxygen provisioning system from PFS to NFS include [3]:

- Lines and fittings disconnected or blanked during inspections.
- Worn or damaged components and fittings.
- Kinked oxygen lines and hoses.
- Passenger service unit doors not closed properly.
- Passenger service unit doors glued at hinges.
- Unserviceable oxygen masks.
- Incorrectly packed oxygen masks.
- Discharged oxygen generators.
- Overstrained oxygen hoses.
- Oxygen fill line nuts cracked.
- Cracked in-line oxygen flow indicators.
- Missing information on part number identification labels.
- Contaminated oxygen masks.
- Contaminated oxygen fittings.
- Incorrect oxygen cylinder configuration.
- Bent oxygen generator firing pins.
- Leaking pilot oxygen regulators

**6. Functionability Improving Actions for Emergency Oxygen Provisioning**

The analysis of ASRS reports performed by Veillette [2] lead to the deduction of the following recommendations for the reduction of the probability of malfunctioning of emergency oxygen provisioning process, thus:

- The pressure-demand masks must be properly stowed in their containers to qualify as quick-donning equipment. Each mask has two red harness inflation levers that, when squeezed, allowing the mask to be removed from the storage box. Releasing the levers after placing the mask over the head fits it securely to the head and face. Although, it can be ”challenging” stowing the oxygen mask after completing pre-flight checks, it is imperative to do so correctly as it could help safely resolve a dangerous in-service situation!

- The frequent pre-flight inspections could cause undetected wear and tear on the mask and hose connections. The pilots expressed concern that some mask designs are not sturdy enough for repeated extraction and re-stowing. These reports were submitted by regional airline crews whose aircraft can be operated by a dozen different pilots within a handful of days, each necessitating a full inspection of the oxygen system during an aircraft acceptance check. In addition, the ASRS submitters were concerned that many of the facemasks are getting scratched to the point that they would be difficult to see through in a real event.

- Aircraft cabin that has become cold-soaked, it may require the cabin to be warm sufficiently to ensure the proper deployment and operation of passenger oxygen masks. For example, the Cessna Encore manual, stipulates that cabin temperature must be held at or above 32° F for a minimum of 15 minutes prior to takeoff after a prolonged ground cold soak.

- It is vital that all flight crewmembers to personally make sure that during the pre-flight checks that their oxygen equipment is: functioning, fitted properly and connected to appropriate supply terminals, the oxygen supply and pressure are adequate, and the oxygen buttons are selected for optimum performance in case of emergency.

- All pilots of high-performance aircraft should receive appropriate, hands-on instruction regarding the use of oxygen mask/goggle sets, including the regulator's emergency selector and smoke goggle venting, and practice communications using the mask microphones during initial and recurrent training.

**7. Conclusions**

The main objective of this paper was to address the emergency oxygen provisioning as a physical mechanism of the motion of an aircraft through MIRCE Functionability Field. [1] Although the malfunctioning of this process is not frequently observed NFE, their occurrences could cause significant consequences to airline and flying pubic, impacting the functionability performance of commercial aircraft in the air and on the ground [2].

Emergency oxygen provisioning systems have been briefly described in the paper considering their main characteristics and potencial negative impact on crew and flying passengers. Timely response by a flight crew to a loss of cabin pressurisation or to smoke or fumes is critical for the safe operation of an aircraft and certainly not the time to discover that emergency oxygen provisioning system is in NFS.

It has been pointed out in the paper that in many instances the accident report concluded that the deterioration of the condition of emergency oxygen provisioning systems were intensified by inadequately maintained oxygen masks, their attachments to the rest of the system and frequent inspections by flight deck crew.

This paper clearly confirms that malfunctions of emergency oxygen provisioning system have caused considerable contributions to the transition of an aircraft from positive to negative functionability state, resulting in the reduction of the functionability work done and occasional destruction of the aircraft or human fatalities.

Recommendations provided in the paper, based on the observed in-service functionability events should be used for the design of the future emergency oxygen provisioning systems as well as the planning of their maintenance programmes and cabin crew training.

**8. References**

[1] Knezevic, J., The Origin of MIRCE science, pp 232, MIRCE Science, Exeter, UK

[2] Veillette, P.R., A n Emergency Is Not When To Discover Your Oxygen Masks Don't Work, Business & Commercial Aviation, 28 January 2019 http://aviationweek.com/business-aviation/emergency-not-when-discover-your-oxygen-masks-don-t-work (accessed 28.01.2019)

[3] "Oxygen Mask Failures" feature in the February 2019 issue of *Business & Commercial Aviation*. The original title is "Weak Points That Are Failing." http://aviationweek.com/business-aviation/weak-points-oxygen-masks-are-failing (accessed 12.02.2019)

 

# Fireless, Burning Smell Driven, Mayday Landings of Commercial Aircraft as a Mechanisms of Motion in MIRCE Mechanics

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*According to Knezevic the purpose for the existence of any functionable system[27] is to do functionability work. The work is done when the expected measurable function is performed through time. [1] However, experience teaches us that expected work is frequently beset by the occurrences of undesirable interruptions like component failures, natural phenomena or human actions, some of which result in hazardous consequences. MIRCE Mechanics is a body of knowledge that focuses on the scientific understanding and description of the mechanisms that generate undesirable in-service interruptions. Thus, the main objective of this paper is to examine the mechanism that generated undesirable in-service interruption to 32 flights, on 16th October 2017, within UK airspace. After fireless burning smoke/fumes were felt in their cockpits the flight crew went to oxygen and declared either a PAN-PAN or a MAYDAY landing. The first event took place around 0622 during departure from Liverpool causing the aircraft to declare mayday landing and return back to land. It was followed by clusters of affected aircraft in the Channel Islands, Liverpool, Manchester and London, later in the day. Although this is one of an extremely rear observed event, its mechanism had to be understood, as if repeated, it will generate the motion of an aircraft through MIRCE Functionability Field and impact its functionability work done and resources consumed. Inspections of aircraft involved and the analysis of the meteorological conditions in Europe have revealed that the burning smell did not result from a failure of any component, but it was as a result of smoke and dust carried in the atmosphere from North Africa and Iberia. Satellite imagery from the European Organisation for the Exploitation of Meteorological Satellites[28] (EUMETSAT) verified this theory. Potencial actions for reducing the impact of this functionability mechanism are presented.*

## 1.0 Introduction

The philosophy of MIRCE Science is based on the premise that the purpose for the existence of any functionable system is to do functionability work. The work is done when the expected measurable function is performed through time. [1] However, experience teaches us that expected work is frequently beset by the occurrences of undesirable interruptions like component failures,

[27] According to Knezevic [1], functionable system type is “a set of mutually related entities put together to do a functionability work in accordance to physical laws and given functionability rules.”
[28] EUMWTSAT in an intergovernmental organisation created through an international convention agreed by a current total of 30 European Member States,

natural phenomena or human actions, some of which result in hazardous consequences.

“Mayday” is the word used around the globe to make a distress call via radio communications. Mayday signals a life-threatening emergency, usually on a ship or an aircraft, although it may be used in a variety of other situations. It originated as an international distress call in 1923 and was made official in 1948. “Mayday” was the idea of Frederick Mockford, who was a senior radio officer at Croydon Airport in London, England. He came up with the idea for “mayday" because it sounded like the French word “*m'aide*r”, which means “help me."

A typical international distress call starts with the word “mayday” repeated three times, not to be mistaken for another word or phrase that sounds similar under noisy and stressful conditions. It is followed by all the relevant information that potential rescuers would need, including type and identity of craft involved, nature of the emergency, location or last known location, current weather, fuel remaining, what type of help is needed and number of people in danger.

A mayday call is not something to be taken lightly. In the United States, it is illegal to make a fake distress call. Unjustified use carries a jail sentence for up to six years and is subject to a $250,000 fine!

For situations that are less than life-threatening, one of several other urgent messages can be conveyed. For example, “Pan-Pan", from the French word “*panne*”, which means “breakdown", can be used to signal an urgent situation involving a mechanical or medical issue.

Thus, the main objective of this paper is to examine the mechanisms that generated undesirable in-service interruption to 32 flights, on 16$^{th}$ October 2017, within UK airspace. After fireless burning smoke/fumes were felt in a cockpit the flight crew went on oxygen and declared either a PAN-PAN or a MAYDAY landing. The first event took place around 0622 during departure from Liverpool causing the aircraft to declare mayday landing and return back to land. It followed by clusters of affected aircraft in the Channel Islands, Liverpool, Manchester and London, later in the day.

Although this is one of an extremely rare observed event, its mechanism had to be understood, as it generate the motion of an aircraft through MIRCE Functionability Field and impacts the functionability work done by an aircraft and resources consumed during its in-service life. The final analysis confirmed that the burning smell was not resulting from a failure of components of aircraft involved, but from smoke and dust carried in the atmosphere from North Africa and Iberia.

## 2. MIRCE Science Fundamentals

Undoubtedly, the ability to accurately and quantitatively predict the probability of occurrences of in-service undesirable interruptions, especially those with hazardous consequences, early in the design stage would be invaluable for all decision makers.

Regardless of whether engineering solutions or management methods are chosen to control the occurrences of in-service undesirable interruptions, they will have a direct impact on the business plan that should deliver the expected work, within the expected budget and generate the expected return on their investment (e.g. profit, reputation, loyalty, public benefit and similar).

Consequently, Dr Knezevic [1] has created the body of knowledge, named MIRCE Science[29], that can be used for the quantitative prediction of the probability of occurrences of undesirable interruptions during the expected in-service life of any given functionability system type. According to MIRCE Science, at any instant of calendar time, a given functionable system type could be in one of the following two states [1]:

- Positive Functionability State (PFS), a generic name for a state in which a functionable system type is able to deliver the expected measurable function(s),
- Negative Functionability State (NFS), a generic name for a state in which a functionable system type is unable to deliver the expected measurable function(s), resulting from any reason whatsoever.

In MIRCE Science functionability work done by a functionable system type is uniquely defined by the trajectory generated by its motion through the MIRCE Functionability Field[30] (MFF). The motion of a functionable system type through the MFF is driven by functionability actions, which are classified as:

- Positive Functionability Action (PFA), a generic name for any human activity or physical phenomena that compels a system to move to a PFS.
- Negative Functionability Action (NFA), a generic name for any physical phenomena or human activity that compels a system to move to a NFS.

The motion of a functionable system type through the MFF is physically manifested through the occurrences of functionability events, which are classified as:

- Positive Functionability Event (PFE), a generic name for any physically observable occurrence in the calendar time that signifies the transition of a functionable system type from a NFS to a PFS.
- Negative Functionability Event (NFE), a generic name for any physically observable occurrence in the calendar time that signifies the transition of a functionable system type from a PFS to a NFS.

MIRCE Mechanics is a part of MIRCE Science that focuses on the scientific understanding of the mechanisms that generate functionability action, which

[29] MIRCE Science comprises of mathematical axioms, equations and methods that enable predictions of expected functionability performance of each feasible option of the future functionability system type to be done, based on the complex, time-dependent, interactions between: physical properties of consisting components and applied functionability rules regarding operation, maintenance and support processes.

[30] MFF is mathematically described as a two dimensional countable infinite set of possible functionability points, each representing functionability state that a functionable system type could be found in, at any instant of the calendar time. $MFF_S(t) = \left\{PFS_S^{i-1}(t), NFS_S^i(t),\ t>0,\ i=1,2,.,\infty\right\}$ [1]

govern the motion of functionable system types though MFF [1]. The occurrences of undesirable interruptions are considered within a physical scale between $10^{-10}$ (atomic system) and $10^{10}$ (solar system) of a metre. These mechanisms, together with the corresponding functionability rules imposed by humans shape the pattern of the occurrences of these undesirable interruptions through MIRCE Functionability Field. The life-long pattern expected to be generated by each future functionability system type is predictable, from the early stages of the design, by making use of the MIRCE Functionability, Operability, Maintainability and Supportability Equations [2, 3].

## 3. Monday 16 October 2017

### 3.1 Dublin Airport, Ireland

An Embraer 190 passenger aircraft, G-FBEM, took off from Cardiff Airport (EGFF) in Wales at 0614 for a scheduled passenger flight to Dublin Airport (EIDW) in Ireland with 75 passengers and a crew of five. The climb, en-route and initial descent flight phases were routine. [4]

At 0635, the aircraft was cleared for landing on Runway 10. Due to a low-visibility weather conditions the crew were instructed to hold at FL 090. At 0706, Air Traffic Control (ATC) cleared the aircraft to leave the holding pattern and continue on to Runway 10. Weather at Dublin included light rain and drizzle with scattered clouds at 100 ft. and a broken layer at 200 ft. Visibility was 3,500 meters.

As the aircraft departed the holding pattern, it entered the top of a cloud layer and the flight crew noticed a burning smell, which they described as "sulphurous" and similar to that of "burning wood or paper." As the captain had experienced similar odours before his first thought was that it might be originating from the aircraft oven. He contacted the senior cabin crewmember to check if "everything was OK" in the cabin. In response he was told that that the ovens were not the source but the attendants could detect a burning smell in the rear of the cabin. The captain informed the co-pilot that there was a "smell of smoke in the cabin" and both pilots noted that the smell appeared to be getting more intense in the cockpit, although no crewmember saw smoke at any time during the flight.

Without any hesitation, both pilots donned their oxygen masks and at 0713, and declared a PAN-PAN[31]. ATC immediately gave priority to the flight and cleared it directly to the final approach to Runway 10. At 0714, the aircraft was cleared to descend to 4,000 ft. and the captain conducted the ILS[32] approach to Runway 10 with the autopilot engaged. He acquired the runway visual references at approximately 300 ft. AGL[33] and took over manual control for landing. The aircraft

[31] The radiotelephony message ***PAN-PAN*** is the international standard urgency signal that someone aboard a boat, ship, aircraft, or other vehicle uses to declare that they have a situation that is urgent, but for the time being, does not pose an immediate danger to anyone's life or to the vessel itself

[32] Instrument Landing System (ILS) is defined as a precision runway approach aid based on two radio beams which together provide pilots vertical and horizontal guidance during an approach to land.

[33] In aviation, atmospheric sciences and broadcasting, a height above ground level (AGL) is a height measured with respect to the underlying ground surface. This is as opposed to altitude/elevation above mean sea level (AMSL), or (in broadcast engineering) height above average terrain (HAAT).

rolled out at 0723 and was met by the airport fire services after it cleared the active runway. The emergency crew informed the captain that there appeared to be no signs of fire or damage on the exterior of the aircraft.
The flight crew removed their oxygen masks and noted that the smell of smoke had been reduced. The captain then asked the cabin crew for an assessment of conditions in the cabin and was told that the smell of smoke had lessened. With no obvious threat to safety, at 0731, the flight crew requested taxi clearance to their parking position and disembarked their passengers normally. [4]

## 3.2 Manchester Airport, England

### 3.2.1 EasyJet

#### 3.2.1.1 Alicante – Manchester Flight

An EasyJet flight that was heading towards Manchester Airport from Alicante, Spain, had been forced to declare Mayday emergency landing because of the smoke smells coming from the cockpit. After landing at Manchester Airport the aircraft was surrounded by fire engines as it reached Terminal 1, while airport train services were temporarily stopped for safety reasons. [6]

The aircraft landed safely. One of the passengers said, “There was a definite smell of smoke.” [6]

#### 3.2.1.2 Manchester – Hamburg Flight

EasyJet flight EZY1841 was scheduled to fly from Manchester Airport to Hamburg at 12:25. The flight was airborne for about 20 minutes when the captain detected "smoke in the cockpit” and decided to return to Manchester. [8]

Passengers in the cabin also caught a whiff of the smoke, which "smelled like a firework". They were escorted away from the plane by fire crews, before being put back on the same plane for departure. [8]

### 3.2.2 Flybe

A scheduled passenger flight from Cardiff to Dublin took "precautionary action" and landed at Manchester airport after the crew detected the smell of fumes.

Flyby also confirmed that a scheduled flight from Manchester to Paris was returned due to a "fume-like smell", felt by the flying crew in the cockpit. [7]

### 3.2.3 Jet2

Jet2, a British low cost charter and scheduled airline, aircraft was unable to land at Leeds Airport due to foggy conditions. After circling several times over Leeds the crew decided to land at Manchester Airport instead.

The landing was safe and “unadventurous”.

### 3.3. Liverpool Airport, England

The EasyJet flight EZY 7159 from Liverpool John Lennon (LPL) to Zakynthos took off on time towards the scheduled destination that was International Dionysios Solomos (ZTH) in Greece. [7]

Soon after take off the flight crew noticed a “burning smell” in the cockpit. Immediately, the pilot turned the plane around and requested an emergency landing at John Lennon airport. ATC provided the crew with all information necessary for an emergency landing. After the safe landing the aircraft examination showed no signs of any possible source of “burning smell”.

Another EasyJet flight declared “full emergency” landing at Liverpool Airport. All flights landed normally to LPL without the assistance of emergency services which were just a precautionary measure.

A spokesman for EasyJet said: “EasyJet can confirm that four of its flights flying in the west of the UK had reported smoke smells in the cockpit that day! [7]

### 3.4 Guernsey Airport

Aurigny Air Services aircraft that was travelling from Guernsey to Bristol had to head back to the Channel Island due to a smell detected by the cockpit crew. It was returned to service after post-flight checks by engineers. [10]

### 3.5 Jersey Airport

Emergency services were called to a British Airways aircraft landing in Jersey "as a precaution" due to the conditions. [10]

### 3.6 Hawarden Airport, Chester, England

During a descent of Jetstream 4100, G-MAJC, into Hawarden Airport, at around FL150, the flight crew noticed a burning smell. Oxygen masks were donned, a Mayday was declared and an expedited approach was carried out to land on Runway 22. The crew experienced some difficulty in communication, both internal and external, while using their oxygen masks. [5]

After landing the aircraft was taxied clear of the runway, brought to a stop, and an emergency evacuation was carried out. [5]

### 3.7 At the End of the Day

NATS, formerly National Air Traffic Services[34], is the UK's leading provider of air traffic control services that handles 2.4 million flights and 250 million passengers in UK airspace, each year. In addition to providing services to 14 UK airports, and

[34] Established in 1962 to bring together responsibility for the UK's existing military and civil Air Traffic Control services.

managing all upper airspace in the UK, NATS provides services around the world spanning Europe, the Middle East, Asia and North America.

On 16th October 2017 NATS facilitated "a number" of diversions from aircraft reporting fumes being detected in the cockpit. All of these flights had landed safely. It came following reports of an "unusual" reddish sky across parts of England, which experts are attributing to the remnants of Hurricane Ophelia dragging in tropical air and dust from the Sahara.

### 4.0 The Source of Fireless Burning Smell

The investigators of the Embraer SA, G-FBEM, were informed by the UK Air Accident Investigation Board (AAIB) that the smoke/fumes were detected from between 2,000 ft. and FL 200, and that most of the aircraft either returned to land at the point of departure or expedited their existing approaches. [4]

It turned out that, between Oct. 13 and 18, up to 8,000 ft wildfires were burning across northern Portugal and north-western Spain. Hurricane Ophelia[35] was passing by offshore, fanning the fires and pushing the smoke northward along with its own path.

Ireland’s weather service said later that “the sheer scale of the wildfires in that area meant that the air quickly became highly concentrated with dense smoke. With this being the source area for the air mass over Dublin at 0700z and the strong winds dragging this air quickly northward, it is not surprising that the smoke was dense enough to register in the cockpits of commercial aircraft flying at the time.”

Based on the above information the Irish air safety investigators concluded “it is clear that the detection of smoke on numerous commercial aircraft on that date can be attributed to the rapid advection of air laden with particulates from Iberian wildfires northward over Ireland and the UK by Ophelia.” [3, 7, 8]

#### 4.1 UK Met office Report on 17th October 2017

The Met Office[36] on 17th October 2017 reported that, the same southerly winds that had brought the current warmth had also drawn dust from the Sahara and smoke from wildfires occurring over northern Iberia (Spain/Portugal) to our latitudes. [10] Ophelia originated in the Azores where it was a hurricane and as it tracked its way northwards it dragged in tropical air from the Sahara. The dust gets picked up into the air and goes high up into the atmosphere, and that dust has been dragged high up in the atmosphere above the UK. The particles in the air cause blue light to scatter, leaving longer-wavelength red light to shine through. [11]

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[35] Hurricane Ophelia was regarded as the worst storm to affect Ireland in 50 years, and was also the easternmost Atlantic major hurricane on record. Total fatalities: 54, Highest wind speed: 185 km/h Date: 9 October 2017 – 18 October 2017, Start date: 16 October 2017, 1:28 pm BST, estimated damage over $65.3 million (2017 USD). Affected areas: France, United Kingdom, Spain, Portugal, Ireland, Sweden, Finland, Azores, Scandinavia

[36] The Met Office was established in 1854 as a small department within the Board of Trade under Vice Admiral Robert FitzRoy as a service to mariners.

### 4.2 EUMETSAT Confirmation

Satellite imagery from the European Organisation for the Exploitation of Meteorological Satellites[37] (EUMETSAT) verified this theory. [9]

## 5.0 What Could Be Done?

Although the same smoke from wildfires on the Iberian Peninsula drawn toward Ireland and the UK caused all emergency landings in very short interval of time the participating cabin crew and ATC of the affected airports were not informed about the existing atmospheric conditions. Hence, it is reasonable to ask should any formal system be established to notify flight crew of the presence of smoke in the atmosphere from ground fires.

### 5.1 Pilots Demand New Cabin Air Filters on Commercial Aircraft

Following "Fireless, Burning Smell Driven, Mayday Landings of Commercial Aircraft" on 16th October 2017, the British Airline Pilots Association (BALPA) wrote to regulators to ask that "effective filters are developed and are then required to be fitted." [12]

Dr Hunter, head of flight safety of BALPA said: "Today we have seen high levels of contaminants in the air, which experts are attributing to the remnants of Hurricane Ophelia dragging tropical air and dust from the Sahara, as well as debris from forest fires in Portugal and Spain. A vulnerability of the way in which cabin air is supplied in most airliners is that there is no direct filtration of the outside air before it enters the cabin, so if the outside air is contaminated, this contaminated air is drawn into the aircraft. This most commonly happens when an aircraft is taxiing on the ground close to the jet exhaust of another aircraft and it is rare for the atmosphere to be contaminated at cruising altitude. However, contamination can occur when there are high levels of atmospheric pollution, when volcanic ash and volcanic gasses are in the atmosphere and when dusts from storms or soot from fires on the ground are drawn in to the air." [12]

As of now, March 2019, the author could not find any information regarding the response from the Aviation authorities to the BALPA's request for "the effective filters are developed and are then required to be fitted."

### 5.2. Inclusion of Information to flight crews on the presence of smoke in the atmosphere from ground fires in SIGNET[38]

The Irish Air Accident Investigation Unit (AAIU) investigators pointed out that ICAO[39] standards and recommendations for SIGMETs list thunderstorms, cyclones,

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[37] EUMWTSAT in an intergovernmental organisation created through an international convention agreed by a current total of 30 European Member States,

[38] **Sig**nificant **Met**eorological Information is a weather advisory that contains meteorological information concerning the safety of all aircraft.

[39] The **International Civil Aviation Organization** (**ICAO**; French: *Organisation de l'aviation civile internationale*) is a specialised agency of the United Nations. It codifies the principles and

severe turbulence, severe icing, severe mountain waves, dust or sand storms, and volcanic ash, but there is no requirement to include the presence of large quantities of smoke in the atmosphere. [4]

### 5.2.1 *SIGMET*

A SIGMET provides concise information issued by a Meteorological Watch Office (MWO) concerning the occurrence or expected occurrence of specific en-route weather and other phenomena in the atmosphere that may affect the safety of aircraft operations.

There three types of SIGMET, as shown in the table below.

| SIGMET (WS) | SIGMET (WV) | SIGMET (WC) |
|---|---|---|
| TS : Thunderstorm | VA : Volcanic ash | TC : Tropical cyclone |
| TURB : Turbulence | | |
| ICE : Icing | | |
| MTW : Mountain wave | | |
| DS : Duststorm | | |
| SS : Sandstorm | | |

SIGMETs (WSs) are inflight advisories concerning non-convective weather that is potentially hazardous to all aircraft. They report weather forecasts that include severe icing not associated with thunderstorms, severe or extreme turbulence or clear air turbulence not associated with thunderstorms, dust storms or sandstorms that lower surface or inflight visibilities to below three miles, and volcanic ash. SIGMETs are unscheduled forecasts that are valid for 4 hours, but if the SIGMET relates to hurricanes, it is valid for 6 hours.

Phenomena reported by SIGNET (WS) are shown in the table below.

| Code | Description |
|---|---|
| OBSC TS | Obscured thunderstorms |
| EMBD TS | Embedded thunderstorms |
| FRQ TS | Frequent thunderstorms |
| SQL TS | Squall line thunderstorms |
| OBSC TSGR | Obscured thunderstorms with hail |
| EMBD TSGR | Embedded thunderstorms with hail |
| FRQ TSGR | Frequent thunderstorms with hail |
| SQL TSGR | Squall line thunderstorms with hail |
| SEV TURB | Severe turbulence |
| SEV ICE | Severe icing |
| SEV ICE (FZRA) | Severe icing due to freezing rain |
| SEV MTW | Severe mountain wave |
| HVY DS | Heavy duststorm |
| HVY SS | Heavy sandstorm |
| RDOACT CLD | Radioactive cloud |

techniques of international air navigation and fosters the planning and development of international air transport to ensure safe and orderly growth. Its headquarters is located in Montreal, Canada.

The SIGMET (VC) provides information on volcanic ash phenomena and the SIGNET (WC) informs the tropical cyclones.

### 5.2.2 The Recommendation to ICAO

As of March 2019, the author could not find any information regarding the Irish Air Accident Investigation Unit‘s recommendation to ICAO to consider the provision of including the information to flight crews of the presence of smoke in the atmosphere from ground fires and prevent all of those unnecessary Mayday calls and use of safety resources associated with each emergency landings.

## 6. Conclusions

Thus, the main objective of this paper is to examine the physical mechanism of an undesirable flight interruption that had been experienced and recorded by 32 commercial flights on 16th October 2017, by a number of airlines, within UK airspace. When burning smoke/fumes were smelt in cockpits of affected flights flight crews went on oxygen and declared either a “pan-pan” or “mayday” landing. The first event had been experienced around 0622 during departure from Liverpool causing the aircraft to declare mayday landing and return back to land. It was followed by clusters of affected aircraft in the Channel Islands, Liverpool, Manchester and London, later in the day.

Although this was an extremely rare event, its mechanism had to be understood, as its occurrence generates the motion of an aircraft through MIRCE Functionability Field, which impacts the functionability work done and resources consumed during its in-service life. The fireless burning smell in cockpits of aircraft affected was not as a result of a failure of any component within aircraft, but by the smoke and dust carried in the atmosphere from North Africa and Iberia. Thus, this paper makes a clear distinction between the aircraft reliability widely covered in literature during the last 60 years and the aircraft functionability introduced and studied by MIRCE Science. While the former deals with probabilities of not having components and system failures within a given interval of time, the latter is dealing with a work done by a functionable system during its in-service life. Hence, the reliability performance of a system are a subset of the of the functionability performance of a system.

In response to the occurrence of this NFE the British Airline Pilots Association wrote to regulators to ask that ”the effective filters are developed and are then required to be fitted,” while the Irish Air Accident Investigation Unit‘s recommended to ICAO to consider the provision of including the information to flight crews of the presence of smoke in the atmosphere from ground fires and prevent all of those unnecessary mayday calls and use of safety resources associated with each emergency landing. However, the author was unable to fine any evidence of the implementation of either recommendation.

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# Impact of High Altitude Ultraviolet Radiation on Functionability of Flight Crews

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Abstract

*The philosophy of MIRCE Science is based on the premise that the purpose for the existence of any functionable system is to do functionability work. The work is done when the expected measurable function is performed through time. In MIRCE Science a flight crew is considered as an element of a flying system type. MIRCE Mechanics is a part of MIRCE Science that focuses on the scientific understanding of the mechanisms of the interactions between functionability elements and the consequences on functionability performance. The research performed shown that pilots and flight crews on aircraft is twice as likely as the general population to develop life-threatening melanoma skin cancer. On average, those who developed melanoma were 42% more likely to die compared with the general population. With progress in aviation technology, aircraft will fly longer and at higher altitudes attracting more and more passengers demanding more and more flights. Hence, the main objective of this paper is to investigate the mechanism of interactions between the high altitude ultraviolet radiation on functionability of flight crew.*

## 1. Introduction

The philosophy of MIRCE Science is based on the premise that the purpose for the existence of any functionable system[40] is to do functionability work. The work is done when the expected measurable function is performed through time. [1] Thus, in MIRCE Science a flight crew is considered to be an element of a functionable system type whose work is done when passengers and cargo are transported through the air between given destinations.

MIRCE Mechanics is a part of MIRCE Science that focuses on the scientific understanding of the mechanisms of the interactions between functionability elements and the consequential impacts on functionability performance. For example, total ultraviolet (UV) radiation is twice as intense at an altitude of 30,000 feet (10,000 metres), the cruising height of passenger planes, than it is at ground level. The research performed shows that pilots and flight crews on aircraft are twice as likely as the general population to develop life-threatening melanoma skin

[40] According to Knezevic, functionable system type is “a set of functionability elements brought together to do a functionability work in accordance to physical laws and functionability rules.” [1]

cancer. On average, pilots and cabin crew who developed melanoma were 42% more likely to die compared with the general population. [2]

With continuous progress in aviation technology, aircraft will be flying longer and at higher altitudes attracting more and more passengers demanding more and more flights. Hence, the main objective of this paper is to investigate the impact of the high altitude ultraviolet radiation on functionability of flight crews in commercial aviation.

## 2. Ultraviolet Radiation

Ultraviolet radiation is a type of electromagnetic radiation that comes from the sun and transmitted in waves or particles at different wavelengths and frequencies. This broad range of wavelengths is known as the electromagnetic (EM) spectrum. The spectrum is generally divided into seven regions in order of decreasing wavelength and increasing energy and frequency. The common designations are: radio waves, microwaves, infrared (IR), visible light, ultraviolet, X-rays and gamma rays.

The word "ultraviolet" means "beyond violet". The German physicist Johann Wilhelm Ritter discovered ultraviolet radiation in 1801. He noticed invisible light beyond the violet portion of the visible spectrum darkened silver chloride treated paper more quickly than violet light. Ritter called the invisible light "oxidising rays", referring to the chemical activity of the radiation. Most people used the phrase "chemical rays" until the end of the 19th century, when "heat rays" became known as infrared radiation and "chemical rays" became ultraviolet radiation.

Ultraviolet light falls in the range of the EM spectrum between the visible light and X-rays. It has frequencies of about $8\times10^{14}$ to $3\times10^{16}$ cycles per second, or hertz (Hz), and wavelengths of about 380 nanometers to about 10 nm. UV is generally divided into three sub-bands:

- UVA, or near UV (315–380 nm)
- UVB, or middle UV (280–315 nm)
- UVC, or far UV (180–280 nm)

Radiations with wavelengths from 10 nm to 180 nm are usually referred to as “vacuum or extreme UV." These wavelengths only propagate in a vacuum, as they are blocked by earth’s atmosphere.

Besides the sun, there are numerous celestial sources of UV radiation. Very large young stars shine most of their light in ultraviolet wavelengths. Because Earth's atmosphere blocks much of this UV radiation, particularly at shorter wavelengths, observations are conducted using high-altitude balloons and orbiting telescopes equipped with specialised imaging sensors and filters for observing in the UV region of the EM spectrum.

Most observations are conducted using charge-coupled devices (CCD), detectors designed to be sensitive to short-wavelength photons. These observations can determine the surface temperatures of the hottest stars and reveal the presence of intervening gas clouds between the Earth and quasars.

### 2.1 Ionisation

Ultraviolet radiation has enough energy to break chemical bonds. Due to their higher energies, ultraviolet photons can cause ionisation, which is a process in which electrons break away from atoms. The resulting vacancy affects the chemical properties of the atoms and causes them to form or break chemical bonds that they otherwise would not. This can be useful for chemical processing, or it can be damaging to materials and living tissues. This damage can be beneficial, for instance, in disinfecting surfaces. However, ionisation can also be harmful, particularly to skin and eyes, which are most adversely affected by higher-energy UVB and UVC radiation.

### 2.2 Ultraviolet Effects

Most of the natural ultraviolet light humans encounter comes from the sun. However, only about 10% of sunlight is UV, and only about one-third of this penetrates the atmosphere to reach the ground. Of the solar UV energy that reaches the equator, 95% is UVA and 5% percent is UVB. No measurable UVC from solar radiation reaches the Earth's surface, because ozone, molecular oxygen and water vapour in the upper atmosphere completely absorb the shortest UV wavelengths.[10]  Nevertheless, broad-spectrum ultraviolet radiation (UVA and UVB) is the strongest and most damaging to living things.

## 2.3 Environmental factors that influence the UV level

The amount of UV radiation reaching the Earth’s surface varies widely around the globe and through time. Several factors contribute to this variation at any given location. They are addressed below in order of importance, together with brief explanations [3]:

- Cloud cover:  it plays a highly influential role in the amount of both UVA and UVB radiation reaching the ground. Each water droplet in a cloud scatters some incoming UV radiation back into space, so a thick cover of clouds protects organisms and materials from almost all UV. The larger the percentage of the sky that is covered by clouds, the less UV reaches the ground. The more opaque the cloud, the less UVB. However, thin or broken cloud cover can be deceiving to people who are sunbathing, and the result can be unexpected and severe sunburn.

- Ozone in the stratosphere: it is a gas composed of three oxygen atoms combined in a single molecule ($O_3$). It is a naturally generated in the stratosphere where it strongly absorbs incoming UV radiation. However, as stratospheric ozone decreases, UV radiation is allowed to pass through, and exposure at the Earth’s surface increases. Exposure to shorter wavelengths increases by a larger percentage than exposure to longer wavelengths.

- Oblique angle of sunlight reaching the surface: at any given time, sunlight strikes most of the Earth at an oblique angle. In this way, the number of UV photons is spread over a wider surface area, lowering the amount of incoming radiation at any given spot, compared to its intensity when the sun is directly overhead. In addition, the amount of atmosphere crossed by sunlight is greater at oblique angles than when the sun is directly overhead. Thus, the light travels through more ozone before reaching the Earth's surface, thereby increasing the amount of UVB that is absorbed by molecules of ozone and reducing UVB exposure at the surface. When the sun is directly overhead, forming a 90° angle with the surface, sunlight is spread over the minimum area. Also, the light only has to pass through the atmosphere directly above the surface. An increased angle between the sun and the surface, due to latitude, time of day, and season, spreads the same amount of energy over a wider area, and the sunlight passes through more atmosphere, diffusing the light. Thus, UVB radiation is stronger at the equator than the poles, stronger at noon than evening and stronger in summer than winter.

- Aerosols: unlike clouds, aerosols in the troposphere, such as dust and smoke, not only scatter but also absorb UVB radiation. Usually the UV reduction by aerosols is only a few percent, but in regions of heavy smoke or dust, aerosol particles can absorb more than 50 % of the radiation. While the presence of aerosols anywhere in the atmosphere will always scatter some UV radiation back to space, in some circumstances, aerosols can contribute to an increase in UV exposure at the surface. For example, over Antarctica, cold temperatures cause ice particles to form in the stratosphere (Polar Stratospheric Clouds). The nuclei for these particles are thought to be sulphuric acid aerosol, possibly of volcanic origin. The ice particles provide the surfaces that allow complex chemical reactions to take place in a manner than can deplete stratospheric ozone. [5] The eruption of an active volcano Mt. Pinatubo, Philippines, in 1991 injected sulphate aerosols into the stratosphere, significantly though temporarily depleting stratospheric ozone and resulting in an increase of UVB reaching the Earth's surface. Over millions of years, the biosphere has evolved to deal with temporary increases in UV from reductions in stratospheric ozone by natural causes such as volcanic eruptions.

- Elevation: Living organisms at high elevations are generally exposed to more solar radiation and with it, more UVB than organisms at low elevations. This is because at high elevations UVB radiation travels through less atmosphere before it reaches the ground, and so it has fewer chances of encountering radiation-absorbing aerosols or chemical substances (such as ozone and sulphur dioxide) than it does at lower elevations.

- Reflectivity of the Earth's Surface: as a highly reflective substance, snow dramatically increases UVB exposure near the Earth's surface as it reflects most of the radiation back into the atmosphere, where it is then scattered back toward the surface by aerosols and air molecules. Fresh snow can reflect much as 94 percent of the incoming UV radiation. In contrast, snow-free lands typically reflect only 2-4 % of UV and ocean surfaces reflect about 5-8 %.

### 2.4 Ozone depletion and UV radiation level

Depletion of the ozone layer is likely to aggravate existing health effects caused by exposure to UV radiation, as stratospheric ozone is a particularly effective UV radiation absorber. As the ozone layer becomes thinner, the protective filter provided by the atmosphere is progressively reduced.

Higher UV radiation levels, and especially higher UVB levels will have the greatest impact on humans, animals, marine organisms and plant life.

**3. Impact of UV radiation on life on earth**

UV radiation from the sun has always played important roles in earth's environment, and affects most living organisms. Biological actions of many species have evolved to deal with it. However, as UV radiations at different wavelengths have different effects living organisms have to cope with the harmful effects as well as the beneficial ones. The UVA plays a helpful and essential role in formation of Vitamin D by the skin, and plays a harmful role in that it causes sunburn on human skin and cataracts in human eyes. The incoming UVB part of the electromagnetic spectrum causes damage at the molecular level to the fundamental building block of life, deoxyribonucleic acid (DNA).

DNA readily absorbs UVB radiation, which commonly changes the shape of the molecule in one of several ways. Changes in the DNA molecule often mean that protein-building enzymes cannot "read" the DNA code at that point on the molecule, resulting in either creation of distorted proteins or death of cells.

However, during the millions of years of evolution, in the presence of UVB radiation, cells have developed the ability to repair DNA. A special enzyme arrives at the damage site, removes the damaged section of DNA, and replaces it with the proper components; govern by the information elsewhere on the DNA molecule. This makes DNA somewhat resilient to damage by UVB.

**3.1 Some effects of UVB radiation on the biosphere**

Biological scientists would like to be able to demonstrate a direct correlation between the amount of exposure to UVB radiation and the harm it causes. This is an enormously complicated question that depends on many different variables, such as varying degrees of susceptibility among different species, and most of these variables are not yet completely understood. For example, the same organism in different bodies of water in different parts of the ocean may respond differently to UVB increases. Furthermore, stress to organisms and ecosystems from increased exposure to UVB are modified by interactions among many other stresses, such as lack of water or nutrients.

It is know that increased exposure to UVB radiation has specific effects on crops, terrestrial ecosystems, aquatic ecosystems, and biogeochemical cycles[41]. UVB impairs photosynthesis in many species. Overexposure to UVB reduces size, productivity, and quality in many of the crop plant species that have been studied

[41] Biogeochemical cycles" refers to the cycling of chemicals such as carbon and energy throughout the Earth system

(among them, many varieties of rice, soybeans, winter wheat, cotton, and corn). Similarly, overexposure to UVB impairs the productivity of phytoplankton in aquatic ecosystems. UVB increases plants’ susceptibility to disease. Since some species are more vulnerable to UVB than others, an increase in UVB exposure has the potential to cause a shift in species composition and diversity in various ecosystems. Because UVB affects organisms that move nutrients and energy through the biosphere, it is to be expected that changes in their activities will alter biogeochemical cycles. For example, reducing populations of phytoplankton would significantly impact the world’s carbon cycle, because phytoplankton stores huge amounts of carbon in the ocean.

Overexposure to ultraviolet radiation can change the flowering times of some kinds of plants and therefore will affect the animals that depend on them.

**3.2 Impact of UV radiation on human skin**

A suntan is a reaction to exposure to harmful UVB rays resulting from the body's natural defence mechanism govern by a pigment called melanin, which is produced by cells in the skin called melanocytes. Melanin absorbs UV light and dissipates it as heat. When the body senses sun damage, it sends melanin into surrounding cells and tries to protect them from sustaining more damage. The pigment causes the skin to darken.

Melanin is a natural sunscreen. However, continued exposure to UV radiation can overwhelm the body's defences. When this happens, a toxic reaction occurs, resulting in sunburn. Ultraviolet rays can damage the DNA in the body's cells. The body senses this destruction and floods the area with blood to help with the healing process. Painful inflammation occurs as well. Sometimes the cells with DNA mutated by the sun's rays turn into problem cells that don't die but keep proliferating as cancers. The UV radiation causes random damages in the DNA and DNA repair process such that cells acquire the ability to avoid dying. People who get sunburned repeatedly are at much higher risk. The risk for the deadliest form of skin cancer, called melanoma, doubles for someone who has received five or more sunburns.

The effects of UVB radiation on human skin are varied and widespread. UVB induces skin cancer by causing mutation in DNA and suppressing certain activities of the immune system. The United Nations Environment Program estimates that a sustained 1 % depletion of ozone will ultimately lead to a 2-3 % increase in the incidence of non-melanoma skin cancer. UVB may also suppress the body’s immune response to Herpes simplex virus and to skin lesion development, and may similarly harm the spleen.

3.3 **Molecular mechanisms of ultraviolet radiation carcinogenesis**
UV radiation is a potent DNA damaging agent and a known inducer of skin cancer in experimental animals. According to Ananthaswamy [12] there is excellent scientific evidence to indicate that most non-melanoma human skin cancers are induced by repeated exposure to sunlight. UV radiation is unique in that it induces DNA damage that differs from the lesions induced by any other carcinogen. The prevalence of skin cancer on sun-exposed body sites in individuals with the

inherited disorder XP[42] suggests that defective repair of UV-induced DNA damage can lead to cancer induction. Carcinogenesis in the skin, as elsewhere, is a multistep process in which a series of genetic and epigenetic events leads to the emergence of a clone of cells that have escaped normal growth control mechanisms. The principal candidates that are involved in these events are oncogenes and tumour suppressor genes. Oncogenes display a positive effect on transformation, whereas tumour suppressor genes have an essentially negative effect, blocking transformation. Activated ras oncogenes have been identified in human skin cancers. In most cases, the mutations in the ras oncogenes have been localized to pyrimidine-rich sequences, which indicates that these sites are probably the targets for UV-induced DNA damage and subsequent mutation and transformation. The finding that activation of ras oncogenes in benign and self-regressing keratoacanthomas in both humans and in animals indicates that they play a role in the early stages of carcinogenesis (Corominas et al., 1989; Kumar et al., 1990). Since cancers do not arise immediately after exposure to physical or chemical carcinogens, ras oncogenes must remain latent for long periods of time. Tumor growth and progression into the more malignant stages may require additional events involving activation of other oncogenes or deletion of growth suppressor genes. In addition, amplification of proto-oncogenes or other genes may also be involved in tumor induction or progression. In contrast to the few studies that implicate the involvement of oncogenes in UV carcinogenesis, the role of tumor suppressor genes in UV carcinogenesis is unknown. Since cancer-prone individuals, particularly XP patients, lack one or more repair pathways, one can speculate that DNA repair enzymes would confer susceptibility to both spontaneous and environmentally induced cancers. Another potential candidate that can function as a tumour suppressor gene is the normal c-Ha-ras gene. Spandidos and Wilkie (1988) have shown that the normal c-Ha-ras gene can suppress transformation induced by the mutated ras gene

### 3.4 Impact of UV radiation on human vision

Human body hair and clothing protect them from UVB, but eyes are vulnerable. Common eye problems resulting from over-exposure to UVB include cataracts, snow blindness, and other ailments, both in humans and animals. While many modern sunglasses offer some UV protection, a significant amount of UV can still reach our eyes in a high exposure situation.

## 4. Impact of UV radiation of flight crew

The National Council on Radiation Protection and Measurements reports that among those U.S. workers exposed to radiation while on the job, flight crews get the largest annual effective dose.

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[42] Xeroderma pigmentosum is a genetic disorder in which there is a decreased ability to repair DNA damage such as that caused by ultraviolet light. It is autosomal recessive with at least nine specific mutations able to result in the condition. Many people with XP die at an early age from skin cancer if they are untreated and unprotected from sunlight. However, if a person is diagnosed early, has no severe neurological problems, is protected from UV light, and followed carefully for early cancer detection, a normal life span is expected.

Flight crews of high altitude flying aircraft are exposed to elevated levels of UV radiation as a result of their operations in the upper reaches of the troposphere and lower stratosphere. The air density in that portion of the earth's atmosphere is thinner than at sea level and therefore filters less of the dangerous solar radiation. UV radiation increases at about 6-10% with every 1,000 ft. of altitude. Between 31,000 and 41,000 ft., where most jet aircraft cruise, UV radiation exposure doubles. Additionally, the destruction of stratospheric ozone, by chlorofluorocarbons and other pollutants, may increase UV radiation exposure. This is especially true close to the equator and both poles due to the thinning of the ozone layer in these regions. According to Meerkotter[43], the occupational UV radiation exposure for pilots depends on numerous factors, including:

- the entire time a pilot spent in a cockpit,
- the number of flights along specific routes,
- the specific windscreen properties of the aircraft,
- the individual skin type of a pilot,
- sun position during flight from takeoff to landing,
- the day of the year.

However, the most impactful factor is the incidence angle of the sun with the aircraft's windscreen. The intensity of UV radiation inside the cockpit strongly depends on whether direct sun is entering or not. Without direct sun, the diffuse UV radiation inside the cockpit amounts to about 5% of the ambient UV irradiance outside the aircraft. In cases of low sun when direct radiation can reach the pilot, percentages grow from 50 to 100%.

## 5. UV radiation and aircraft windscreen

The amount of UV radiation absorbed by aircraft windscreens depends on the material used and the general design. In a study conducted by Meerkotter[44], released in 2007, the transmittance properties of aircraft windscreens were measured for both visible and invisible optical radiation. Transmission measurements were performed on eight aircraft windscreens. Three windscreens were from large commercial jets (MD-88, Airbus A320 and Boeing 727/737); two from commercial, propeller-driven passenger planes (Fokker 27 and ATR 42); one from a small private jet (Raytheon Hawker Horizon); and two from small general aviation, single-engine, propeller-driven planes (Beech Bonanza and Cessna 182).

The general aviation aircraft windscreens were plastic (polycarbonate); the others were multilayer (laminated) composite glass. UV transmittance for both glass and plastic windscreens was less than 1% for UVB radiation. In the UVA portion of the spectrum, transmittance differences increased from 0.41% to 53.5%, with plastic attenuating more UV radiation than glass. Hence, the plastic windscreens outperform glass by protecting the pilot's eyes from UV radiation[45].

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[43] Ralf Meerkotter, director of the German Aerospace Center's Institute of Atmospheric Physics
[44] U.S. Federal Aviation Administration's (FAA) Civil Aerospace Medical Institute (CAMI)
[45] According to the study, "Optical Radiation Transmittance of Aircraft Windscreens and Pilot Vision

Dr. A. Chorley of Britain's Civil Aviation Authority and London South Bank University's Department of Primary Care and Public Health, conducted research in optometry and ophthalmology. It focussed on ocular UV exposure of pilots in airline and offshore helicopter operations on different aircraft types. Inflight data were captured on five return-sector European airline flights and one transatlantic flight from London Gatwick Airport in addition to four helicopter flights from Aberdeen Dyce Airport.

The study found a wide variation in ocular UVA doses during flights. The main factor influencing exposure was the UV transmission of the windscreen, which fell into two distinct profile types. In an aircraft with good UVA blocking properties, ocular exposure was found to be equivalent to that of office exposure and did not exceed international guideline limits regardless of external conditions or flight time. Most aircraft assessed had poor UVA blocking windscreens, which resulted in an ocular exposure to the unprotected eye in excess of international guideline limits. No significant UVB dose was found.

A research team led by Dr. M. Sanlorenzo[46], measured UV radiation through the acrylic plastic windscreen, 160 mm thick, in front of the pilot seat of a TBM 850[47] at ground level, 2,500 ft., 6,000 ft., 10,000 ft., 15,000 ft., 20,000 ft., 25,000 ft. and 30,000 ft. around midday during April at San Jose, California, and Las Vegas. Published in 2015, the study [6] determined that aircraft occupants flying for 57 min. at 30,000 ft. got the same amount of UVA radiation as from a 20 min. tanning bed session.

Sanlorenzo concluded, "Airplane windscreens do not completely block UVA radiation and therefore not enough to protect pilots. UVA transmission inside airplanes can play a role in pilots' increased risk of melanoma. . . . We believe that better UV protection on aircraft windscreens is necessary to offer cabin crew a hazard-free work environment. We strongly recommend the use of sunscreens and periodical skin checks for pilots and cabin crew." [6]

In addition, Sanlorenzo led another team of medical researchers who reviewed more than 3,527 citations from 19 previous studies on melanoma published between 1990 and 2013, reported data from 1943 to 2008 from 11 countries, and included over 266,431 participants. The results of this study, "The Risk of Melanoma in Airline Pilots and Cabin Crew: A Meta-Analysis," published in 2015, indicated that participants in flight-based occupations are twice as likely to contract melanoma than the general public. Furthermore, pilots specifically have a 42% higher mortality rate from melanoma compared with the general population. Researchers believe that the culprit is likely UV radiation, which can penetrate glass; even the specialty glass used in aircraft windscreens.

## 6. Impact of long term UV exposure on the eyes of the flight crew

A long-term exposure to solar UV radiation is another significant hazard to pilots due to the damage done to retinal photoreceptors. Research conducted by Chorley

[46] The Department of Dermatology at the University of California San Francisco, USA.
[47] High performance single-engine turboprop, light business and utility aircraft.

between 2008 and 2015 found no ill effects to the eyes caused by UVB and UVC, since these types of UV radiation are filtered out by the upper atmosphere and the windscreens of most aircraft. However, the study showed that UVA, the least energetic form of UV radiation, is the most harmful to a pilot's eyes and eyesight because a higher percentage of it penetrates the cockpit and cabin of an aircraft. [10]
Chorley found that, although rare, short, intense exposure to UVA might lead to conditions such as snow blindness and damage to the cornea. He concluded, "There is good evidence that long-term exposure to solar radiation, especially the ultraviolet and blue light components, is a risk factor for cataracts and, to a lesser extent, age-related degeneration of the retina." [7]

**7. Sunglasses as Eyesight Damage Prevention**

To prevent eyesight damage a pilot can use sunglasses with sufficient UV protection. In an evaluation of 38 sunglasses used by commercial pilots, Chorley found that all conformed to international standards for UV radiation transmittance, offered sufficient UV radiation protection and against the increase in blue light exposure that pilots experience at altitude. However, it is necessary to stress that used sunglasses with scratched lenses were less effective.

The study concluded that lenses manufactured to minimally comply with standards for UV radiation transmittance could result in excess UV radiation to a pilot based on inflight irradiance data. The study recommended an additional requirement of less than 10% transmittance in the wavelength of 380 nm.

An online survey conducted by Chorley of nearly 3,000 pilots in the UK regarding the use of sunglasses and other onboard protective devices to block sunlight revealed that pilots were critical of standard aircraft protection systems such as visors (and other commonly employed devices) to manage bright light. Sunglass use was found to be surprisingly variable. A quarter of those questioned wore sunglasses less than 10% of the time or not at all. The most common reasons for sunglasses not being used was the sunglass tint interfering with instrument legibility and discomfort from frames, particularly when used in conjunction with required headsets.

According to an FAA study[48], flying over a thick cloud layer or a snowfield with the sun at its zenith increases the exposure to naturally occurring UV. Snow reflects 85% of visible and UV radiation, while clouds can reflect up to 80%. In such conditions, sunglasses with a closely fitting wraparound frame design are best since UV blocking lenses are useless if radiation is allowed to enter the eye from the sides of the frame. A gray, neutral density filter to block 70-85% of all visible light is recommended to preserve colour discrimination and enhance the ability to quickly adapt to lower light levels.

People often equate sunglasses with UV radiation protection. The FAA's study pointed out that lens tints or colour are not indicative of the UV blocking ability of a lens. While there are no UV radiation standards for clear prescription lens

[48] "Optical Radiation Transmittance of Aircraft Windscreens and Pilot Vision,"

materials, the American Optometric Association recommends that sunglasses block at least 99% of solar UV radiation below 400 nm. Without UV treatments, clear glass and CR-39 lenses fall short of this mark. Therefore, it is important when purchasing non-prescription, sunglasses to be sure they are accompanied by proper labelling and/or documentation describing their UV protection properties.

## 8. Conclusions

The philosophy of MIRCE Science is based on the premise that the purpose for the existence of any functionable system is to do functionability work. The work is done when the expected measurable function is performed through time. In MIRCE Science a flight crew is considered as an element of a flying system type. MIRCE Mechanics is a part of MIRCE Science that focuses on the scientific understanding of the mechanisms of the interactions between functionability elements and the consequences on functionability performance.

The information presented in the paper has shown that ultraviolet radiation is an invisible enemy, to human eyes, that can cause long-lasting and potentially deadly consequences for pilots and crewmembers who are repeatedly exposed to higher levels of both UVA and UVB and for longer periods than those working on the ground. These exposure time risks will, for some flight crew, shorten their career span, requiring more pilots to be trained by the operators and potentially lead to future compensation claims for workplace induced illness. Pilots, especially those operating aircraft at high altitudes, need to have suitable protection to mitigate these risks, which have been shown, based in the information obtained from the literature available that pilots and flight crews on aircraft are twice as likely as the general population to develop life-threatening melanoma skin cancer. On average, those who developed melanoma were 42% more likely to die compared with the general population.

With continuous progress in aviation technology, aircraft will be flying longer and at higher altitudes attracting more and more passengers demanding more and more flights. Hence, the main objective of this paper was to highlight the potential impact of high altitude ultraviolet radiation exposure and the increasing risk factors on the functionability of flight crews in commercial aviation over the lifetime of the flight crew.

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# Troubleshooting as a Mechanism of Motion of Functionable System through MIRCE Functionability Filed

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**Abstract**

*The purpose of a paper is to address the troubleshooting, an activity performed by maintainers to identify failed component or module, as a mechanism of the motion of a functionable system through the MIRCE Functionability Field. For effective maintenance troubleshooting, as one of the main drivers of the "speed" of moving through negative functionability state, is essential element of any corrective maintenance task. To successfully perform troubleshooting tasks maintainers must possess both the knowledge and skills to find and fix problems efficiently. Many years of research have demonstrated that it is much easier to and learn manual skills than troubleshooting skills. The paper clearly demonstrates that troubleshooting is a complex subject as it is driven by both sides of equation, namely system designers that conceive troubleshooting processes and maintenance managers that manage them during the in-service life of functionable systems.*

## 1. Introduction

The philosophy of MIRCE Science is based on the premise that the purpose for the existence of any functionable system type[49] is to do functionability work. The work is done when the expected measurable function is performed through time. [1] Thus, a functionable system type is doing work while in Positive Functionable State (PFS) only, not in Negative Functionable State (NFS) undergoing maintenance.

MIRCE Mechanics is a part of MIRCE Science that focuses on the scientific understanding of the mechanisms of the interactions between functionability elements and the consequential impacts on functionability performance.

The human constituents of a maintenance process, either as a decision maker or as a task executor, bear the ultimate responsibility for recognising, interpreting, compensating for, and correcting or mitigating the consequences of deficiencies and faults of a maintenance process. [1] Full understanding of these phenomena's is only possible by understanding physical mechanisms that lead to the successful execution of maintenance tasks.

In general, troubleshooting is the identification of diagnosis of "trouble" in the operation of a system caused by any Negative Functinability Action (NFA) whatsoever. The problem is initially described as symptoms of malfunction, and

[49] According to Knezevic, functionable system type is "a set of functionability elements brought together to do a functionability work in accordance to physical laws and functionability rules." [1]

troubleshooting is the process of determining and remedying the causes of these symptoms. Determining the most likely cause is a process of elimination of potential causes of a “trouble”.

Every maintainer is responsible for performing the full range of maintenance tasks. However, not all tasks count equally in determining whether or not a maintainer is doing a good job, from the operational point of view. The basis for judging the “goodness” of a maintainer is the ability to find and fix problems efficiently. Troubleshooting is the very first step in that direction. Hence, in today's competitive business environment, maintenance organisations are judged on their ability to keep functionable system type in Positive Functionability State (PFS) not how good they are in the maintenance facilities.

Maintainers must possess both, the knowledge and skills, to identify undesirable in-service disturbances, also known as troubleshooting ability, efficiently and return the system to PFS. Thus, troubleshooting is the most valued maintenance abilities are also the most difficult to acquire and practice. It requires many years of experience, on-the-job observations, and “common sense”. Troubleshooting is a complex subject as it is driven by both sides of the equation, namely system designers that conceive troubleshooting processes and maintenance managers that manage them during the life of a functionable system. that it is much easier to teach and learn manual skills than troubleshooting skills. [2]

Consequently, in this paper the troubleshooting as a mechanism of the motion of a functionable system type through MIRCE Functionable Field (MFF) is addressed together with some fundamental human factors concepts related to this extremely important element of a maintenance process, as both are driving forces for the in-service reliability, cost and effectiveness[50].

**2. MIRCE Mechanics Overview**

Human needs for transportation, education, ventilation, communication, refrigeration, information, computation and many other functions are continuously satisfied through human created and managed products or constructions, commonly called systems.

In summary, the body of knowledge comprising of axioms, mathematical equations and methods that enable engineering, predicting and managing the functionability performance of functionable systems through time, based on the scientific understanding of the mechanisms that cause occurrences of observable positive and negative functionability events through the life of functionable systems constitutes MIRC Mechanics.[3]

**3. Corrective Maintenance Task as a Negative Functionability Action**

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[50] Mechanics at Naval Air Station Oceana in Virginia had been taking up to 8.5 hours to troubleshoot wiring problems on the military fighter jets F/A-18 Hornet using paper manuals or digital displays on a laptop, and sometimes they had to retrace their steps because they took a wrong step opening panels around the aircraft. Now they are taking about 1.5 hours by opening just the right panels to get at the problem in just the right sequence, according to Avatar Partners [9].

The second axiom of MIRCE Science states: *"the probability of failure of a system to deliver a measurable function at any interval of time is greater than zero"*. Hence, at random points in time when the system is operating, failures are likely to occur and will be detected by the operator through visual, audio, and/or physical means. The operator proceeds to notify the appropriate maintenance organisation that a problem exists.

The maintainer(s) assigned to deal with the problem must analyse the situation and verify that the system is indeed faulty. In some instances, the fault will be obvious, particularly in dealing with mechanical or hydraulic systems when a structural failure has occurred or a fluid leak takes place. On other occasions, the maintainer must operate the system and attempt to repeat the condition leading to failure occurrence. This is often the case for electronic equipment when the failure is not always obvious[51].

Generally speaking, during the life of any functionable system, corrective maintenance commences with the identification of a failure symptom such as the system does not work, the hydraulic system leaks, the engine does not respond in terms of power output, no voltage indication on the front panel meter, and so on. Based on a symptom of this nature, the maintainer proceeds to troubleshoot and accomplish the necessary maintenance tasks.

**4 Troubleshooting Activities**

Troubleshooting may be extremely simple or quite complex. For example, if a hydraulic leak is detected, the source of the leak is often quite easily traced. On the other hand, the failure of many components in computers and other electronics based equipment is not readily identified. In this instance, the maintainer must accomplish a series of steps in a logical manner, which will lead him or her directly to the faulty item. However, in majority of cases, these steps are not adequately defined and the maintainer is forced into a trial-and-error approach to maintenance. A good example is when the maintainer starts replacing parts on a mass basis (without analysing cause-and-effect relationships) hoping that the problem will disappear in the process. This of course, affects the duration of stay in NFS of a system and spare/repair part needs, as the maintainer may replace many parts when only one of them is actually faulty.

To preclude the possibility of wasting time and resources when the system is deployed in the field, the system design must provide the necessary characteristics to enable the maintainer to proceed in an accurate and timely manner in identifying the cause of failure. Such characteristics may constitute a combination of go/no-go lights, test points, meters, and other readout devices that are providing the necessary information, which allows the maintainer to go from step to step with a high degree of confidence that's/ he is progressing in the right direction. This objective is one of the goals of the maintainability engineers during the design process. This facet of the analysis is best accomplished through the development of logic troubleshooting

[51] According to Jack Hessburg "Zeros and ones do not leak from the computers and their connecting cables", Doctoral Diploma Graduation Ceremony at the MIRCE Akademy, Woodbury Park, Exeter, UK, 2003

flow diagrams, including go/no-go solutions on a step-by-step basis, and supported by diagnostic software where applicable. [3]

The maintainability engineers as a part of integrated design team, should review failure mode and effect analysis data to determine cause and affect relationships, and then to produce a list of all of the major symptoms which the system is likely to experience. For each identified cause, various troubleshooting approaches should be analysed in terms of maintenance time and logistics resources, and the best approach selected. The analysis process is accomplished through the generation of logic troubleshooting flow diagrams in conjunction with the completion of maintenance task analysis sheets and for the troubleshooting requirement.

Since its establishment in 1999, staff, students and fellows of the MIRCE Akademy has analysed tens of thousands of maintenance task, including the troubleshooting activities. Some of the most common practises are presented below.

- **Consistent Fault Set (**CFS), *is* one of the names given to the group of all possible failures that can reasonably explain a given set of trouble symptoms. The name comes from the fact that the group contains faults "consistent" with the symptoms. For example, when a car engine does not start, the **CFS** could contain an ignition failure, or fuel problem, but would not contain a failed windscreen wiper motor, for example.

- **Decision Tree, o**ne type of maintenance job performance aid is called a "decision tree". A decision tree is a printed or computerised chart that directs the maintainer along a logical testing and diagnosis path for a particular system or product. After each test or observation, the decision tree branches to another test, or conclusion, based on the test results. An easy characterisation of a decision tree is a series of "if-then" statements, like “If the voltage is below 'x,' then do this."

- **Easter Egging,** a method **o**f troubleshooting is to replace various modules and components until the symptoms of trouble disappear. This method is known as "Easter Egging" because a maintainer never really knows where he or she will find the failed part. Easter Egging is an extremely inefficient, expensive way to find a problem.

- **Substitution Method** is troubleshooting by substituting a known good component for a suspected bad component. For modularised systems or those with easily replaceable components, substitution may reveal the component that is the cause of the problem. One potential problem with modular substitution, though, is that a higher-level cause can damage the replacement component as soon as it is installed. This may complicate the issue if the failure is immediate as the will be the same symptoms after the replacement. If the failure is not immediate, this will give you a clue that the real cause of the problem is external to the module.

- **Einstellung, also** known as Psychic Blindness, describes a phenomenon discovered in the early 1940's and since shown to exist in different domains.

It has been found that when people have spent time solving one particular type of troubleshooting problem, it is virtually impossible for them immediately to diagnose a different type of problem. Interestingly, this phenomenon holds even when people are told that they will see a new and different type of malfunction.

- **Test-Induced Failure,** When a maintainer performs a functional test on a system or component, there is some probability that the test will cause a failure. Thus, a maintainer must balance the need for functional testing against the likelihood of a test-induced failure. Even further, test-induced failures are safety risks only when they remain undetected. That is, a maintainer can test a subsystem, find it functioning properly and turn it off. If there is a test-induced failure, the component will be left in a failed state and will not work the next time it is needed.

- **Tunnel Vision** describes viewing a situation as though through a tunnel, which means seeing in only one direction and being blocked from seeing information coming from other directions. In the maintenance domain, tunnel vision is a well-known occupational hazard. Once a trouble-shooter thinks s/he knows what is causing a problem, information that might disprove the hypothesis tends to be given less weight than information confirming it. “*You cannot teach a person who knows that he knows.”* One of the most common causes of tunnel vision in maintenance is maintainers' use of problem reporting information that goes beyond describing symptoms to suggest a cause.

- **Expert System,** are diagnostic decision-making aids used in a number of different domains, including medicine, geological exploration and maintenance. Expert systems are usually computer-based. They are generally developed by embedding a set of rules acquired from human experts. For example, if an expert system for diagnosing problems in aircraft braking systems is to be developed, the first step would be to determine how human experts do such diagnosis and then put these "rules" into our expert system. Expert systems in aviation maintenance are commonly embedded in computer-based training systems or diagnostic equipment.

- **Heuristics Algorithms**, commonly known as rules-of-thumb, troubleshooting algorithms are another method that could improve the efficiency of troubleshooting. Rules-of-thumb represent the distilled wisdom of maintainers who over a long period of time became experts in the troubleshooting process for specific type of systems, modules or components.

Rules-of-thumb vary, depending on the specific component or system. An example of them is a “wisdom” confined in the following statement: *"If the symptoms include a low pressure indication, then always check the pressure sender unit first."* Embedded expert systems depend on a rule base developed by consulting expert trouble-shooters.
Algorithms are usually unwritten procedures telling trouble-shooters generally how to proceed.

Some research studies show that troubleshooting performance improves when maintainers are reminded, in generic terms, what they should do first, second, etc. For example, an generic algorithm might require a maintainer to gather information related to failure symptoms, to generate as many hypotheses consistent with the symptoms as possible, to prioritise the hypothesis set, etc. Such generic algorithms seem to have the effect of dissuading maintainers from deciding on a specific failure being the cause of the symptom before they have enough information.

**5. Troubleshooting constraints**

Like all other processes, which convert inputs into output, by using certain resources, troubleshooting process is also impacted by certain constrains, some of which are briefly presented below.

- **Environment,** most troubleshooting tasks are conducted in work settings that include noise, heat or cold (or both), limiting lighting, cramped physical spaces, work during night-time hours and so forth. These environmental factors have all been found to affect troubleshooting performance, albeit sometimes unpredictably. Also, it is worth pointing out to "the obvious" impact factors, like:

    - The work in very hot or very cold environments causes maintainers to lose their ability to concentrate and to perform logical operations such as inductive reasoning.
    - The impact of noise affects novice and expert trouble shooters differently. A study of the effects of noise on troubleshooting performance found that high noise levels degraded experts' performance, but "enhanced novices'. Possibly, the high noise levels caused novices to stay alert and pay more attention to problems, whereas the noise simply distracted experts.

- **Time Pressure,** an obvious examples are departure gates at airports, maintenance boxes in pit lane during car races, military operational theatres, and similar. Research performed has shown that the time pressure degrades both novices' and experts' troubleshooting performance. This degrading effect is present even for troubleshooting tasks performed in laboratory settings with abstract "systems." According to Hessburg part of chief mechanic job, at Boeing Company, is education. It is his task to make people aware of the environment in which mechanics operate. "It's not that designers are stupid, but they're inexperienced on this side of business. For example, they have to learn that there are different types of maintenance. Anyone can maintain an airplane component or system on the bench. However, the gate environment is very much result and schedule driven. That's different type of maintenance" Knezevic (1998).

- **Experience,** is an area of individual difference research where findings support the common-sense view that more experience leads to better troubleshooting performance. As with other skills acquired over time, experience enhances one's ability to learn from new troubleshooting experiences. Much research in this area has been conducted in the aviation maintenance domain; this fact alone should make the research results directly applicable to the guidance we provide. However, it is necessary to point out that while experience enhances troubleshooting performance, its advantages do not hold under all conditions. When certain job aids or specific troubleshooting procedures are employed, performance differences between experienced and novice trouble-shooters tend to disappear.

- **Individual Differences,** people differ both physically and psychologically. In the troubleshooting domain, a number of individual differences have been studied. These include cognitive style, general ability, aptitude and similar.Cognitive style is a general term used to classify people into categories related to a particular psychological variable. For example, common "scales" used in cognitive style research include "reflective-impulsive," "field dependent-field independent," "passive-aggressive," etc. If it could be shown that people with particular cognitive styles make better troubleshooters, this could be applied profitably to the personnel selection process. While cognitive style has been shown to affect troubleshooting performance, the link between troubleshooting performance and general ability and aptitude is rather tenuous. Levels of ability and aptitude are generally inferred from scores on qualification tests design to measure specific characteristics of individuals. These measures have a fairly strong relationship with the time required to complete instructional modules and to the ability to use certain job aids. However, troubleshooting skills tend to be acquired over long periods. As individuals have an opportunity to work on actual systems, small performance differences related to initial abilities and aptitudes tend to disappear.

## 6. Reducing Troubleshooting Errors

> “*As it is true of all skills, troubleshooting proficiency cannot be attained simply by reading books or by listening to someone explain what to do or watching a video*.” Jack Hessburg[52]

Troubleshooting errors are the challenge for most maintenance organisations. In fact, troubleshooting is notoriously error-prone. The fundamental complexity of many technologically modern systems contributes to the number and type of errors observed in actual troubleshooting tasks. There are also human traits that contribute to relatively poor troubleshooting performance.

Various strategies can be used to reduce troubleshooting errors. From both organisational and human factors perspectives, each technique has its advantages

[52] Jack Hessburg (1934-2013), the “king” of troubleshooting, on both sides of the equation. As an in-service engineer with a degree in Aircraft Maintenance Engineering he learned his troubleshooting skill in day-to-day operations of airlines, worldwide. As Chief Mechanic on the development of the Boeing 777, with a degree in Mechanical Engineering, he was responsible for the design of troubleshooting process that is “friendly” to the gate mechanics, whose responsibility is to enable “airplanes go on time and never crash.” [2]

and disadvantages. The following techniques appear to hold the most promise for error-reduction:

- Teaching the theory of operation for systems and components, without also teaching how to use that knowledge to troubleshoot.
- Observing examples of specific troubleshooting experiences.
- Teaching non-specific troubleshooting techniques.
- Classroom instruction, in general.
- Non-interactive computer-based instruction.
- Teaching from technical manuals.

Although many issues and problems are associated with troubleshooting the following three troubleshooting issues that seem to pervade majority of maintenance organisations.

**6. 1 Proceduralisation of Troubleshooting**

Proceduralisation can improve troubleshooting performance. When troubleshooting is properly proceduralised, performance differences between expert and novice trouble-shooters can be virtually eliminated. However, as with any other endeavour, there are good and bad procedures. More accurately, there are procedures improving performance and procedures with either little effect or that actually degrade performance.

Proceduralisation must be preceded by a thorough analysis of relevant troubleshooting tasks to determine what each troubleshooting step tries to accomplish, what information is required and produced, and what tests or tools should be used. As with certain aspects of automation, it is possible to proceduralise to the extent that human maintainers are left with an essentially mechanical role. It is necessary to stress that:

- Troubleshooting procedures exist in an overall organisational and work environment.
- Good procedures are worthless if they are used improperly or ignored.

Although maintenance procedures serve various purposes, reduction of errors is certainly an implicit goal of all such procedures and as such they should be:

- **Specific,** for a specific component, system, or piece of test equipment.
- **Clear,** The terminology should be consistent with the language commonly used by the people who will complete the procedure.
- **Explicit,** in order to tell maintainers what they are supposed to do, as they do not have time to "to read between the lines".
- **Detailed,** Include all required steps in the procedure, as it is unrealistic to assume that maintainers will know the entire sub steps required to achieve a specific system state.
- **Accessible,** procedures must be stored in a place and manner so they are easy to obtain, otherwise they will improvise.

- **Usable, p**rocedures must exist in a format and on media that make them easy to use while maintainers perform the tasks they describe.

**6.2 Training**

Maintainability engineers, as well as, maintenance practitioners have long recognised that one of the most difficult aspects of troubleshooting is teaching and learning it. The most challenging questions that training materials and training courses should incorporate are:

- What content should be taught?
- How should it be taught?
- What part should on-the-job experience play in training?
- How appropriate are simulators for troubleshooting training?
- Should troubleshooting training be equipment-specific or general?
- Do troubleshooting skills deteriorate with time?
- Is refresher training required?

**6.2 Incorrectly Identified Failures**

Large proportion of failures causing Line Replaceable Units (LRUs) to be pulled during line maintenance turn out to be Can Not Duplicate (CND) or sometimes called non-reproducible. However, it would be wrong to conclude that all CNDs are caused by line maintainers' improper troubleshooting. Built-in test algorithms in LRUs often leave line maintainers with no choice but to replace the module. In other instances, incorrect troubleshooting is caused by a number of conditions that have nothing to do with maintainers' ability to test and diagnose. For example, failures are sometimes reported by flight crew members or other third parties. The initial reports often incorrectly attribute cause.

Regardless of the cause, incorrect troubleshooting is a common and repeating problem across majority maintenance organisations, which is manifested in increasing repair time and making the maintenance process inefficient.

**6.3 Simulation-Oriented Computer-Based Instruction**

Simulation-Oriented Computer-Based Instruction (**SOCBI)**, is one of the most diligently studied training methods that combine many elements for success in troubleshooting training. Work in SOCBI began in the aviation maintenance domain in the late 1970's. SOCBI provides students with a two-dimensional, interactive depiction of the particular system or component that they are learning to troubleshoot.
If the component is small enough, an SOCBI module can actually show a picture of its controls and displays,

Students use the working controls and displays to practice diagnosing a number of faults built into the simulation, which are usually randomly occurring. **SOCBI** modules also contain diagrammatic, i.e., logical, representations of the system being taught. These functional/logical diagrams teach students how a system is functionally connected and allow them to use logical troubleshooting algorithms such as half-splits.

Effective **SOCBI** allows students to acquire diagnostic information from the same sources available in the work environment. Students must be able to observe indications, such as lights and gauges; to perform specific tests on the system; to receive verbal reports from flight crew members, etc.

A number of **SOCBI** systems have been compared with more traditional training methods such as classroom instruction and demonstrations of actual equipment. In these studies, SOCBI produces troubleshooting performance as good as, or better than, that produced by less-efficient techniques

**6.4 Practice**

That "*practice makes perfect*" has been proven for troubleshooting tasks. The major factor distinguishing expert trouble-shooters from novices is experience, i.e., practice.

Troubleshooting is a complex skill with cognitive and manual elements. As is true of all such skills, troubleshooting proficiency cannot be attained simply by reading books or by listening to someone explain what to do. Providing opportunities for meaningful practice is a valid, relatively inexpensive method to reduce troubleshooting errors.

Regardless of which training method, or combination of methods, one uses to teach troubleshooting skills, students must be given an opportunity for practice. To be meaningful, troubleshooting practice should:

- Pertain to the equipment that will actually be maintained on the job
- Be done using mock-ups that provide the same types of information as the real system
- Allow students to gather information from the same sources as in the actual work environment
- Provide feedback regarding the outcome of various tests and other actions
- Allow students to know how long their actions would take in the actual work environment

However, troubleshooting practice does not have to be on real equipment; in fact, real equipment is often an inefficient practice medium with the following drawbacks:

- It is difficult to know the precise nature of failures embedded in real equipment
- Experts often disagree as to the appropriate troubleshooting path(s) for failures in real equipment
- Using real equipment as practice aids prevents the equipment from being used to support operations
- Errors made while troubleshooting real equipment can have safety implications

- For failures to be intentionally embedded in real equipment, someone has to embed the failures, check the equipment when practice troubleshooting is complete, and ensure that only controlled failures are present.

### 6.5 Context-specific knowledge

Many maintenance skills are generalisable from one domain to another. For example, skill in the use of tools for repairing automobile engines is directly applicable to using tools to repair turbine engines. However, troubleshooting skills tend to be context-specific. The ability to identify problems with a television set does not directly transfer to troubleshooting avionics modules. When teaching troubleshooting knowledge, it is important to provide specific information, which should be:

- **Simple** - Students will not be able to remember long, involved troubleshooting procedures. Break these procedures into simple, serial steps. If there is no easy way to decompose a troubleshooting process, then supply a written procedure.
- **Specific** - Relate troubleshooting steps to the component(s) on which students will be working. For example, don't tell students how to perform a general half-split test. Tell them how to do a half-split on the antiskid controller.
- **Explicit** - Tell students how you expect them to use the information you are providing. Don't rely on them to guess how it should be used.
- **Heuristic** - There are almost always rules-of-thumb for troubleshooting specific components or subsystems. Describe them for the students.

## 7. Conclusions

The purpose of a paper is to address the troubleshooting, an activity performed by maintainers to identify a failed component or module, as a mechanism of the motion of a functionable system through the MIRCE Functionability Field. For effective maintenance troubleshooting, as one of the main drivers of the “speed” of moving through negative functionability state, is essential element of any corrective maintenance task. To successfully perform troubleshooting tasks maintainers must possess both the knowledge and skills to find and fix problems efficiently

Troubleshooting is a form of problem solving, applied to the motion of functionable systems through MIRCE Functionability Field. It is a logical, systematic search for the source of a problem in order to solve it, and return a system to PFS again. Troubleshooting is needed to the symptoms. Determining the most likely cause is a process of elimination – eliminating potential causes of a problem. Finally, troubleshooting requires confirmation that the solution applied has return a system into positive functionability state.

In general, troubleshooting is the identification of “trouble" in the functionable system type caused by any NFA whatsoever. The problem is initially described as symptoms of malfunction, and troubleshooting is the process of determining and remedying the causes of these symptoms.

Numerous years of research have demonstrated that it is much easier to teach and learn manual skills than troubleshooting skills. The paper clearly demonstrates that troubleshooting is a complex undertaking as it is driven by both sides of the equation, namely the design office that conceive troubleshooting processes and maintenance departments that deals with them during the life of a functionable system.

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