Fire Safety in Space Flight: Experience and Strategy

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ABSTRACT

An orbital station is a closed system designed to provide and maintain the environment suitable for human living and working in the space flight. Its ultimate isolation implies any potential onboard failure and emergency to be particularly hazardous. In this context, fire is the most threatening of possible accidents. In this paper, we consider the experience and strategy of fire safety onboard the orbital station.

KEYWORDS: Space flight, fire safety, orbital station, ISS.

INTRODUCTION

Being a closed system designed to sustain the environment suitable for human living and working in space flight, an orbital station is ultimately isolated, which implies any potential onboard failure and emergency to be particularly hazardous. An onboard fire is the most threatening possible accident, in which the crew cannot rely on any assistance coming from outside. During a very short time, the fire can utterly contaminate air and destroy the station systems and components; if the shell of the module is damaged then depressurization may occur.

Potential sources of ignition, smoldering, and burning include, among others, the heating elements in the onboard systems and research equipment, a short circuit in electric wires, failure of the oxygen generators. The fire risk is aggravated by the close accumulation of electric equipment, oxygen supply facilities, and hydrogen storages in the same compartment.

HISTORICAL OVERVIEW

The history of orbital stations includes several fire accidents. The first one goes back to 1971 when two cosmonauts, Georgy Dobrovolskiy and Victor Patsaev, suppressed burning of the power supply cables in the pressurized compartment of the Salut-1 orbital station. In 1978, cosmonaut Georgy Gretchko suppressed fire development by switching off the power supply to the ignited piece of equipment.

On February 23, 1997, the most dangerous fire in the history of piloted space flights happened in the pressurized compartment of the Kvant module attached to the Mir space station. The fire was initiated by the ignited solid fuel in a faulty oxygen-generating canister, which is routinely used to maintain the oxygen partial pressure in the pressurized compartments. In this accident, a strong jet flame of 0.5 m length developed, being directed towards the control desk of the habitable compartment and the body of the module. Damaging the body of the module had become possible [1] thereby imposing an extreme hazard on the six crew members: Valery Korzun, Aleksandr Kaleri, Vasily Tsibliyev, Aleksandr Lazutkin, Reinhold Ewald, and Jerry Linenger (see Fig. 1). The entire station was filled by smoke, and all the crew members put gas masks on. After the

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cosmonauts activated three fire extinguishers, burning of the oxygen generator was eventually suppressed. However, it took a very long time to recover normal atmosphere suitable for breathing.

Fig. 1. This crew of the Mir station survived the most dangerous fire in the history of piloted space flights. February 1997.

In 1998, another fire accident in the Mir station (initiated by faulty operation of the air cleaning system followed by smoke generation) was precluded by the crew member who switched the faulty system off.

During 20 years of ISS (the International Space Station) operation, the fire alarm was activated more than one hundred times; in most cases it was a false alarm albeit in five cases it was due to fire events. On September 19th, 2006, after switching the oxygen supply system on, the crew members reported the hydrogen after-burning unit temperature to increase up to 90-100 C followed by the smell of smoke and the leakage of liquid components. To prevent further development of the emergency, the crew members switched the oxygen supply system off. Following subsequent instructions by the Mission control center, the crew members used the individual protection means (glasses, breathing masks, gloves) while deactivating the internal ventilation, monitoring the air composition, activating the air filtering, thereby returning the ISS to the normal state.

The water heater of the service module is known to be the most frequent fire origin onboard ISS. In several cases when the smoke was produced by the heater, further development of the accident was prevented by switching both the power supply and the ventilation system off. These cases are briefly described below.

On October 20th, 2008, the ISS-17 crew members observed vapor release in opening the hot water taps. Several attempts to deactivate the heater by the console button appeared to be unsuccessful, and the indicator control panel showed the heating to proceed. The apparatus temperature increased, and the smoke appeared. The incident was tackled by deactivating the power supply, and the apparatus was then replaced.

Nevertheless, a similar incident occurred on July 10th, 2009, when smoke was observed and smelled by the crew. After deactivating the power supply, the smoke release ceased. The amount of smoke was insufficient to activate the smoke detectors, and no fire alarm was signaled. The gas analyzers had shown 3 to 4 ppm CO which is within tolerable limits. Following the instructions by the Mission control center, the air filter A-2 was located in close proximity to the potential source of ignition and was activated for 1 hour. A similar incident where smoke released from the water heating apparatus was reported and mitigated by the crew on June 10th, 2014.

On August 30, 2014, the crew reported occurrence of smoke and smell in the Mini-Research Module 2 (MRM 2), also known as Poisk. It was found to be caused by a short circuit in the onboard thermostatic equipment. The crew then switched the power supply off and regenerated the ambient atmosphere [2].

FIRE RESEARCH IN MICROGRAVITY

The importance of fire safety in space inspired the research program focused on the studies of combustion and fire suppression in an orbital flight. Burning of solid combustibles and the efficiency of the fire suppression systems were addressed by the Rocket and Space Corporation Energia and the Keldysh Research Center, who developed the experimental setup Skorost' [3] and conducted orbital experiments onboard the Mir station in 1992-1998.

The specific objective of these experiments was to determine the critical airflow velocity that causes the extinction of the flame produced by solid combustibles in microgravity. The experimental equipment for the ground-based experiments was developed in the Keldysh Research Center to replicate the microgravity conditions of the orbital flight, and the Skorost' setup was developed by the Energia Corporation. Non-charring (PMMA), charring (fabric-reinforced laminate), and smoldering (cotton cord) samples were used both on Earth and in orbital flight.

In the ground-based experiments replicating the onboard conditions, the extinction of flame produced by the solid combustibles was observed at the cross-flow velocity of 2 cm/s and below. However, three series of the experiments performed in the orbital flight revealed a very distinct flame behavior. First, at the airflow velocities of 5–20 cm/s (note, that this is the range characteristic of air circulation inside the ISS pressurized compartments) sustained combustion was observed to be possible. Furthermore, sample burning intensity was found to be even greater in microgravity than that in the ground-based experiments. Second, decrease of the airflow velocity below 1–2 cm/s in microgravity results in a dull flame which is extinguished at the critical velocities of 0.2–0.5 cm/s in the flaming mode and below 0.2 m/s in the smoldering mode [3]. More details can be found in [4].

These experiments confirmed the possibility of burning suppression by reducing the airflow rate which can be achieved by switching the ventilation system off. In the absence of buoyancy, flame extinction occurs as a result of the oxygen depletion in the reaction zone. This observation was then implemented in the passive fire suppression strategy in the microgravity conditions. This strategy requires the air circulation to be stopped.

THE FIRE SAFETY CONCEPT

Fire detection

The design of the modern orbital space station utilizes the above-mentioned research findings and the long-term previous experience, particularly that of the fire accidents in the orbital flights. The use of the flammable materials and the heating elements is reduced to a minimum. The fire detection system is continuously improved to ensure that the fire source is detected as early as possible thereby enabling emergency actions by the crew to prevent flaming combustion and fire growth. The fire detectors are made sensitive to the aerosols produced in combustion and smoldering of the electric wire insulation, the major fire load onboard. The fire detectors are uniformly distributed over the internal volume of the pressurized compartments with the directions of the ventilation flows taken into account.

Two types of the smoke detectors, optical and ionizing, are used in the Russian ISS segment. The optical smoke detectors are used in the service module, and the ionizing ones are installed in the inhabited modules. The optical sensors respond to the occurrence of smoke aerosols causing a decrease of the air and smoke optical density; the fire alarm activates if the visible smoke appears, and its optical density falls by 4% or lower (compared to that of the fresh air). In the ionizing sensors (also called the induction sensors), the tested gas is ionized by the electric charge, and the recorded current depends on the admixture concentration. The sensor activates when the admixture concentration exceeds a critical threshold. The ionizing sensors have two activation thresholds, 3-4 and 5-8 times above the ambient value. The ionizing sensors are more sensitive than the optical ones, and they may activate before visible smoke appears.

Microgravity implies the absence of buoyancy and natural convection air flows. Therefore, the air flow must be deliberately arranged for the air to pass by the smoke detectors. The absence of natural convection also results in accumulation of dust (particularly in the closed space behind the panels) thereby causing false alarms when the panels are opened.

In the US Segment of the ISS, optical smoke sensors are used. To reduce the probability of false alarm, the scattered optical signal is required to exceed a critical value in several consecutive tests.

Activation of the smoke detectors is processed by the onboard computer system; it is shown by the displays and control panels and is accompanied by an audible alarm. The air circulation and some other onboard systems are switched off automatically to obey the requirements of the passive fire suppression. This must also be done manually, if the crew members discover flame, visible smoke, or smell of smoke before the fire alarm activates automatically.

Individual fire protection

Generation of toxic volatiles in the thermal decomposition of polymers is extremely hazardous for the crew members. Indeed, in the enclosed space of the ISS the concentrations of toxic species can rapidly build up to a level greatly exceeding the tolerable threshold. Safety of the crew members can be provided by either using individual gas masks or by creating a safety zone. In view of the spatial restrictions, creation of a safety zone may be rather difficult.

(a) (b) (c)

Fig. 2. The breathing protective mask ИПК:
(a) – used before 2004; (b) – used before 2014; (c) – currently used.

For individual fire protection, Russian crew members use the bespoke oxygen breathing protective mask (ИПК-1М, see Fig. 2) which protects the human eyes and respiratory system from any kind of harmful and toxic substances. Its operating principle is to generate oxygen in the regenerating cartridge in which the carbon dioxide and water vapor are consumed. However, the mask can be efficient for a limited time period only (from 20 to 140 min depending on the human activity).

The design evolution of the breathing protective mask over time is demonstrated in Fig. 2. Originally, the mask did not have the isolating cap, and the half mask was connected to the cartridge by a corrugated hose. It is this type of mask that was used in the Mir station. In the second version, Fig. 2b, the isolating cap was introduced. The heat exchanger was then included in the third version, Fig. 2c, for cooling the inhaled air. Some other improvements were also introduced in the design of the hose and the cap.

For US crew members, the primary individual mean of protection is the Portable Breathing Apparatus (PBA) shown in Fig. 3. It consists of the mask and the gas bottle that provides oxygen for 7-15 min of work depending on its intensity. The PBAs can be connected to the oxygen ports in the US segment. For the PBAs, the safety distance of 1 m away from an open flame must be provided. In case of fire, all the crew members can use both Russian breathing masks and US Segment breathing apparatuses.

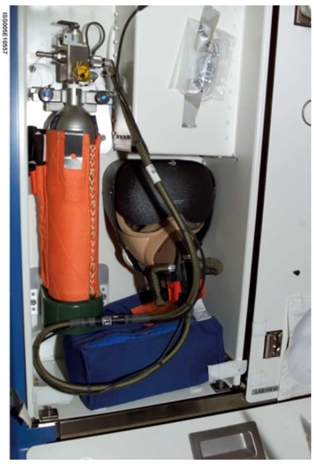

Fig. 3. The Portable Breathing Apparatus (PBA).

Both the Russian breathing masks and the US Segment breathing apparatuses operate for a limited period of time and considerably restrict visibility, mobility, and communication.

Fire suppression

To suppress the fire, two types of portable fire extinguishers, ОКР-1 and ОСП-4, are available in the Russian ISS segment. Both fire extinguishers use the foam produced by the extinguishing agent and nitrogen, which acts as an inert diluent. The foam is chemically neutral, it easily adheres to a solid surface, and it can also be easily washed out. The design of the fire extinguishers enables its operation in microgravity, as well as in any orientation in normal gravity [2]. According to the safety instructions, fire suppression must be performed by a group of at least two crew members.

No fire extinguishers are provided in the Soyuz transport vehicle. A possible fire is to be extinguished by depressurizing the orbital module and the re-entry capsule.

In the US Segment ISS, two types of fire extinguishers operating with carbon dioxide and water vapor are provided. The carbon dioxide fire extinguishers contain CO_2 gas, that can be ejected through one of two detachable nozzles designed for use either in the cabinets and behind the boards and desks (which have special fire ports for connection) or in an unconfined space in the module. The water fire extinguishers have no detachable nozzles and it can only be used in an unconfined space. It generate a water mist, which has the important advantage that neither air breathing mask nor CO_2 removal from the air is required.

(a) (б)

Fig. 4. Fire extinguishers used in the Russian Segment ISS: (a) – ОКР-1; (b) – ОСП-4.

(a) (б)

Fig. 5. Fire extinguishers used in the US Segment ISS: (a) – carbon dioxide; (b) – water.

Thus, the fire extinguishers of the US Segment are particularly efficient for fire suppression in the cabinets and behind the boards and desks. It is anticipated that fire in the Russian and US Segments ISS should be extinguished, respectively, by the Russian and US Segment fire extinguishers. However, in a catastrophic accident, the crew commander may order use of the US Segment fire extinguishers in the Russian Segment ISS. The voltage of the electric network in the US Segment ISS segment (120 V) is higher than that in the Russian one, which prohibits use of the Russian fire extinguishers in the US Segment.

Use of the US Segment fire extinguishers in microgravity is special, since the spray or gas jet generates a momentum that may result in uncontrolled movement of the human body or the items impacted by the jet.

The fire is considered to be extinguished if there are no visual signs of the fire, and the CO_2 concentration in the atmosphere is below a specified threshold. After the fire is extinguished, the compartment of fire origin is isolated by closing the hatches.

Dissimilar to compartment fires in on-Earth conditions, the vitiated air cannot be simply replaced by the fresh one after the fire is extinguished. Instead, the air is cleaned by filtering, which is performed by either fixed or portable filters of several different types. The air composition and pollutant availability are measured by gas analyzers.

SAFETY INSTRUCTIONS FOR THE CREW

Safety instructions are an important part of the pre-flight crew training. In case of emergency, the following priorities are set in the decision making:

1. Safety and rescue of the crew.
2. Saving the station.

3. Saving the pieces of equipment, research results, selected modules and compartments.

The crew actions must take into account the availability of individual fire protection, fire suppression tools, facilities for removal of toxic combustion products from the atmosphere and the equipment to control its composition. Prior to the orbital flight, the crew members undergo the extensive training on acting in accidents, see Fig. 6. The first actions to be undertaken after the automatic fire detection system activates are of key importance and must be remembered exactly. If for any reason, the automatic detection system does not activate in case of fire, the system must be activated manually. It will inform all the crew members of the fire, and it also will deactivate certain onboard systems and initiate passive fire suppression.

Fig. 6. Fire training in the Gagarin Training Center.

Other crew instructions include:

- To wear the gas masks in case of visible smoke or flame or in case of super-critical concentrations of toxic gases indicated by the gas analyzers.
- In case of fire inside the Russian Segment ISS, the fire source must be identified by visual inspection and using the detectors indicated by the onboard computer system. The power supply of the equipment located within the fire source is then switched off, and the fire extinguisher is applied.
- In case of fire inside the US Segment ISS, the crew members must escape from the module of fire origin and move together to a safe place. Once the fire source is identified, either visually or by the signal generated by the fire alarm system, the designated group of crew members wears the individual means of protection, takes the fire extinguishers, and moves towards the fire source. The electric supply is switched off locally and, if this is not sufficient to stop fire, the fire extinguisher is applied. In case of fire behind the panels, the gas is sampled through the fire ports. The fire source is considered identified if the carbon dioxide concentration exceeds the ambient value by at least 10%.

During the fire, the escape route to the spacecraft must be kept free. If the fire cannot be extinguished, all the available fire extinguishers are exhausted, and there is instant danger to life, the crew is instructed to isolate the module on fire by closing the hatches, to move to the spacecraft, and to make it ready to undock the station.

The decision to abandon the station is made when the following conditions are met:

– The fire cannot be extinguished or localized by closing the hatches which do not block the escape route to the spacecraft.

– Concentrations of the hazardous pollutants in the atmosphere cannot be reduced to safe levels by the available equipment and means of protection.

In-depth knowledge of the operating principles of the fire detection and fire suppression systems, and practice in the use of fire extinguishers and individual means of fire protection is a crucial requirement to ensure crew safety. Such a practice is undertaken not only in the pre-flight training program, but also during the orbital flight. The existing equipment for fire detection and fire suppression complemented by the comprehensive crew training are the key components to ensure the safety of the piloted orbital flights.

Future developments are required in design and manufacturing of new non-flammable structural materials, sophisticated fire detectors, individual means of protection for the crew members, fire extinguishers, and the equipment for filtering and cleaning the contaminated air after the fire.

REFERENCES

[1] A.S. Melikhov, A.V. Mordvinova, I.V. Istomin, Fire suppression technology in inhabited pressurized compartments of the spacecraft in an orbital flight, In: Fire safety: problems and prospective, 2017, Vol. 1, No 8, pp. 233-236 (In Russian).

[2] S.Yu. Romanov, A.V. Semenov, T.V. Andreeva, Systems and tools of fire safety in the Russian segment of the ISS. Directory “Fire Safety” (In Russian), 2004.

[3] A. Skvortsov. ISS crew mitigated two fires. In: Russian News Agency, 10 October 2014, https://ria.ru/20141010/1027750509.html (accessed 28 February 2019).

[4] I.A. Bolodyan, A.S. Melikhov, L.T. Tanklevskiy, Combustion and Extinguishing of Structural Polymeric Materials in Microgravity, In: Proceedings of the Ninth International Seminar on Fire and Explosion Hazards, St. Petersburg, Russia, 21-26 April 2019, pp. 203-213.