Fire safety in spacecraft: past incidents and Deep Space challenges.

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Abstract

Fire safety is listed among the areas of prime concern for inhabited space exploration. The naturally high risk of an accidental fire has to be carefully assessed to avoid damaging consequences to both the crew and the spacecraft while fulfilling the objectives of the mission. Twelve acknowledged incidents from past exploration programs are compiled and contrasted here. The causes and consequences are described within their respective technological contexts, to show how fire safety planning has evolved and learnt from those incidents. In the process, missing information and knowledge gaps are brought forward to avoid any misinterpretation of the facts and evaluate the adequacy of the updated fire strategies. Eventually, the present fire provisions in the International Space Station are analysed to understand how a safe and sustainable situation is achieved in Low Earth Orbit. Yet, with

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long-range long-duration missions planned in the near future, there is a need to rethink existing solutions. New issues specific to Deep Space exploration are detailed, to understand the nature of emerging threats and identify paths of future research.
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1. Introduction

Never in the history of mankind have we been so close to establishing a sustainable presence on the Moon, and stepping on Mars is slowly transitioning from fiction to reality. The Apollo Program demonstrated in 1969 the capability to send a human beyond the Low Earth Orbit (LEO), and the now twenty years of continuous human presence on the International Space Station (ISS) have supported the steady improvement of a sustainable Environmental Control and Life Support System (ECLSS) covering all the elements required to survive in the fundamentally hostile environment of outer space [1].

Yet, the development of a permanent settlement beyond LEO, in what has been coined Deep Space, still carries a lot of challenges and uncertainties. Radiation protection, logistics, crew health, resources management, environmental monitoring, fire safety, communication and autonomy have been identified as the seven main areas where improvements are required [2, 3].

The issues related to these different categories can jeopardize a long-range mission and may even pose a threat to the life of the crew members. However, the associated dangers are not equivalent because their effects vary in magnitude, in characteristics of consequences, and in capacity to recover. In addition, their probabilistic nature can vary in a given situation over a set period of operation: some would happen with a probability of one, and are thus considered deterministic, while others follow a random probability distribution that may not be predicted precisely, and are thus considered stochastic. Assessing both their nature and magnitude, risk management has to be designed accordingly.

To illustrate this situation, the efficiency of the Air Revitalization System (ARS) to recover O_2 from CO_2 provides a straightforward upper limit to the duration of any mission. The danger associated with running a mission longer than what the ARS allows is deterministic and irreversible: once the oxygen content in the spacecraft drops below a certain level, the crew cannot survive. Yet, a close monitoring of the atmosphere can provide confidence in the evolution of oxygen depletion, and danger only arises in case of failure of the monitoring equipment. Consequently, the Air Revitalization System is designed with a certified efficiency and missions are planned accordingly, resulting in minimal risk. Similarly, radiation shielding is needed to prevent deterministic effects of short term exposure to radiations, causing cataracts, dermatitis, sterility and radiation symptoms [4]. But improved radiation shielding is also needed to reduce the odds of sporadic galactic cosmic rays and solar particle events disrupting electronics and affecting the health of the astronauts since, with each additional dose of radiation, the probability of a dramatic outcome such as cancer or leukaemia increases. In the absence of perfect shielding technologies, this issue is treated as a risk and consequently an 'acceptable' level of risk has to be defined.

In the presence of heat sources, oxygen, and fuel, the risk of a fire in spacecraft or on the ground is deterministic in nature, and a fire will develop if prevention is overlooked. Interactions between these three components must be carefully considered and provisions for fire introduced in order to lower the probability of ignition, to control fire growth and spread, and to grant effectiveness to mitigation and clean-up processes. Unfortunately, the odds of a fire in a spacecraft are increased by the presence of multiple electric systems required to power and operate various modules, which face unusual overheating challenges in the absence of natural convection [5, 6]. In addition, the adoption of atmospheres that differ from the nominal mixture of 21% oxygen, 79% nitrogen at a sea-level pressure of 101.3 kPa (14.7 psia) not only modifies the likelihood of ignition, but also affect the severity of a subsequent blaze by altering flame spread rate and smoke production. Exploration atmospheres have repeatedly featured low-pressure oxygen-enriched atmospheres, in order to reduce the amount of inert nitrogen and consequently the overall pressure and payload, but specific investigations are then required to maintain an informed and acceptable level of fire risk in this unusual environment. From a material perspective, compromises regarding functionality must be met because flammable components can be present in a spacecraft either in the form of high-tech equipment, like polyethylene used for radiation shielding [7], but also in off-the-shelf instruments, or daily objects required for the comfort of living during long missions (paper, towels, food, magazines, and souvenirs) [8]. Accidents of other nature, such as leakage, must also be considered in a thorough fire risk assessment, since they can introduce flammable components in the pressurized volume or modify the atmospheric composition [9]. Similarly, the accumulation of waste in long duration missions must also be cautiously monitored to avoid increasing the fuel load in the vicinity of heat sources.

Owing to the stringent measures that have been implemented in the past decades, the probability of generating a significant fire in a spacecraft remains quite low. However, it should be kept in mind that the consequences can still be dramatic. In an environment with restrained resources, any damage caused by a fire is almost irreversible, and the crew will need to make do with the loss of burnt down equipment. If key elements of the spacecraft are impaired, the crew may have to abort the mission, face the potential loss of the module, and address a possible threat to their own lives. In the absence of infallible fire prevention, space design must thus include systems and procedures dedicated to fire detection, fire mitigation, and post-fire clean-up. Mature systems have been developed and tested at normal gravity for that purpose, but modifications in the physics of heat and mass transfer triggered by the reduction or absence of buoyant flow increase the uncertainty regarding their reliability in space, Lunar, and Martian environments. Briefly, the absence of natural convection affects both heat and mass transfer, and increases the response of a burning system to flow perturbations. Combined research efforts by space agencies over the past 50 years to study the implications of low gravity on smouldering [10], flammability [11, 12], flame spread and burning rate [13, 14], flame interactions [15], particulate emission [16], and flame extinction mechanisms [17] have highlighted the unique features of a flame in such an environment. It is not the ambition of the present work to recall past literature on that topic, and reviews are available to the reader [18, 19]. A key learning is that, to this day, considerable efforts are still required to understand the underlying ignition, spread, and extinction mechanisms at reduced gravity before a reasonable fire hazard assessment can be carried out and adapted fire safety systems subsequently developed.

Space exploration requires a tremendous amount of innovations, and compromises must be made when the time required to develop new systems much needed exceeds the timeline of missions dictated by political pressure. This situation was particularly true during the Cold War and the Space Race era, but is relevant to this day as spacecraft still materialize the technological excellence that a nation -or a group of nations- is eager to demonstrate. All aspects of flight safety thus aim at minimizing hazards in a given operational, technological, and financial context [20]. As a consequence, it is important not only to recall past fire incidents but also to understand which strategies concerning fire safety were in place when they occurred, and how these strategies were altered. Identifying the most frequent modes of ignition, the subsequent fire-related issues, and the efficiency of means of mitigation in realistic scenarios is central to avoid repeating past mistakes, while providing ground for the development of a comprehensive fire safety framework for space exploration. If scattered information can be found in various sources, no thorough analysis of past fire events in their technological context exists. The present study aims at filling this gap, compiling all available information in a chronological development. In the process, both the gaps of information and the gaps of knowledge are carefully highlighted to stress the limits of contextualization and question the sustainability of adopted solutions. Then, the state-of-the art fire safety framework implemented aboard the ISS is described and contrasted with listed incidents to understand how past shortcomings are now addressed. Finally, projecting these solutions in the context of Deep Space exploration, limitations are outlined and opportunities of research are identified.

2. Past Incidents

Since Yuri Gagarin's first orbit in 1961, fire safety protocols have been regularly updated through modifications of atmospheric conditions, introduction of pre-flight material ground testing methods, development of new fire detection and mitigation equipment, and definition of specific crew training prior to any mission. Taking this evolution into account, twelve identified incidents are described in their respective context.

2.1. Apollo 1

On January 27^{th}, 1967 a fire killed three astronauts aboard Apollo 1 during a launch rehearsal test. An unidentified ignition event lead to the rapid spread of fire in the closed cabin, and astronauts trapped inside could not escape in time [21]. The first report of fire by the astronauts was associated with an immediate but limited rise in cabin temperature and pressure, followed by a sharp increase leading to the rupture of the command module 15 seconds after the initial detection. The flames then travelled rapidly, and the whole module was engulfed in flames and firebrands carried by the swirling flow that resulted from the rupture in the pressure vessel, according to external observers. After 10 seconds of this intense burning phase, smoke rapidly filled the cabin possibly because oxygen depletion quenched most of the fire, leaving flames only in the vicinity of the environmental control unit where failed oxygen and water/glycol lines continued to supply oxygen and fuel. It was estimated in the investigation reports that the command module atmosphere was lethal less than 30 seconds after detection, leaving no chance to the astronauts locked inside.

Though the events did not happen in orbit, the magnitude of this fire was related to space exploration atmospheric design choices. In the American space program, a pure oxygen exploration atmosphere was considered to decrease weight and ease control engineering: the extreme savings in structural weight, the decrease in cabin leakage rate, and the simplification associated with a one gas system justified the increased fire hazard [22]. With pure oxygen, the module pressure was lowered to 34.5 kPa (5 psia) once in orbit. However, pressure at take-off was 110.3 kPa (16 psia) to maintain an inner overpressure, which prevented the outside air from entering the cabin and altering its atmospheric composition. Though the engineers had considered the issue of a fire in pure oxygen at low pressure, they had overlooked the enhanced fire hazard on the launching pad [23].

As oxygen content is increased at a set pressure, materials which originally do not sustain combustion are susceptible to allow a flame to spread. To identify the range of conditions under which a given material can be safely used, the limiting oxygen index (LOI) characterizes the minimum volume fraction of oxygen required for a material to sustain combustion in a test configuration. Operating at high oxygen content then increases the odds and consequences of a fire by increasing the amount of available fuel in a spacecraft. Concomitantly, increasing oxygen content beyond the LOI of a given material increases flame spread rate and fire growth, meaning that the consequences of an accidental fire can be dramatically inflated. The situation in Apollo 1 was all the more dangerous as several large patches of combustible adhesive Velcro had been attached at the last minute to the wall panels, leg-rests, and seats. On top of that, the pressure rise associated with a rapid combustion process combined with the aforementioned overpressure trapped the crew inside, since the cabin hatch opened inward.

Given the compactness of the crew cabin volume in the Mercury, Gemini, and Apollo programs (ranging from $2.8m^3$ to $5.9m^3$), early exploration vehicles did not adopt any dedicated fire detection system. It was assumed that astronauts could immediately realize if a fire was developing [24]. In such event, the crew was instructed to squirt water from the food rehydration gun, or manually depressurize the cabin by opening an outflow valve if the rehydration gun turned out to be inefficient. To limit hazards to electronic equipment and flash steam generation associated with water spray extinguishing systems, a small portable hydroxy-methyl cellulose extinguisher which could expel $0.06m^3$ of foam over a period of 30s was also being developed [25]. The prototypes were not ready in time for Apollo 1 [26], and the 1967 fire developed too fast for the astronauts to intervene at its early stage anyway. The precise cause of the fire remains unknown as the investigation board was unable to determine the exact configuration of the spacecraft at the time of the accident [21]. Yet, electric wiring and plumbing carrying a combustible and corrosive coolant were considered the most probable ignition sources. Recognizing that complete elimination of ignition sources was not possible, material and atmospheric choices in the module were revised after the accident to reduce the magnitude of any accidental fire. Flammability tests were conducted to limit fire hazard associated with individual components in an oxygen-enriched atmosphere, and more than 100 full-scale mock-up fire growth tests were carried out on the ground to investigate under which atmospheric conditions a fire may propagate beyond its incipient region of ignition in the redesigned spacecraft interior [27]. These tests highlighted an extensive gap in knowledge, as full-scale testing showed that components promoting self-extinction in individual tests, such as a proven fire-retardant coating called Ladicote, failed to prevent excessive propagation once integrated in the spacecraft configuration. These variations indicated that the results of individual testing could not be taken as conclusive when applied to the entire spacecraft configuration.

With limited time to understand the physics behind this issue, a mixture of 60% oxygen and 40% nitrogen at the same pressure of 110.3 kPa (16 psia) was eventually adopted on the launchpad to reduce potential flame spread rate and fire size, while maintaining both physiological and leakage needs. After launch, the atmosphere would still transition to the initially planned pure oxygen low pressure conditions. It should be pointed out that 4 of the 34 full-scale mock-up flammability tests conducted under the updated set of atmospheric conditions still required active mitigation. The statistics show a clear improvement in terms of overall flame spread rate compared to pure oxygen at the same pressure, where 15 out of 30 tests required active mitigation, but it is still not clear whether astronauts would have survived the 1967 fire had the new atmosphere and configuration been already adopted.

2.2. Apollo 13

The first recorded fire-related accident in the absence of buoyant flow took place in 1970 during the Apollo 13 Lunar mission, which featured a pure oxygen atmosphere at a reduced pressure of 34.5 kPa (5 psia) similar to Apollo 1. On April 14th, two days after take-off, a supercritical oxygen tank failed and its internal pressure rose. The initial incident went unnoticed, because the warning system was already reporting another routine failure and could not signal two issues simultaneously [28], until the tank exploded and blew an exterior aluminium panel of the unmanned Service Module. The shock of the explosion put two extra oxygen tanks out of commission, crippling the Command and Service Module (CSM). The mission was consequently aborted, and the crew retreated into the Lunar Module where they successfully improvised an outstanding rescue operation.

Analysing the telemetry data, the following investigation revealed a peak in current accompanied by a drop in voltage in the wires powering a stirring fan inside the supercritical oxygen tank 13 seconds before the internal pressure started to noticeably rise. This electric signature was associated with a short circuit with arcing that would have provided around 10 joules, which is enough energy to ignite elements of Teflon insulation used on the wires in the tank. Pressure would have then gradually increased in the tank because of the ongoing oxycombustion process, until it eventually exploded.

Pursuing this hypothesis, it was shown that incidents during ground preparation could have rendered this oxygen tank particularly hazardous. Initially installed in Apollo 10, it had been removed and underwent a series of high-voltage operations which may have degraded internal heater thermostatic switches before being installed in Apollo 13, increasing the likelihood of a short circuit. The accident report recognized that NASA had not originally identified the combined presence of heat sources and fuel within the supercritical oxygen tank as a major hazard. After reviewing the numerous pressure vessels of the Apollo spacecraft, it was determined that the fuel cell oxygen supply valve module also contained a similar combination of high-pressure oxygen, electrical wiring, and Teflon. Changes in response to the incident focused on making the oxygen tanks safer by removing the wiring from any contact with the oxygen in the tank, minimizing the use of combustibles in the presence of potential ignition sources, improving ground testing equipment, and designing an optimal CSM emergency evacuation plan. Overall, the recommendations focused on risk reduction and contingency planning, but acknowledged the lack of understanding of the physics of a fire in supercritical oxygen in the absence of buoyant flows.

2.3. Salyut-I

The following year, an accidental fire broke in the Soviet Salyut-I Space Station on June 16^{th}, 1971. A faulty fan which was cooling scientific equipment seized but its motor continued to drive it [29]. Dense smoke was produced as a result of heat generated by the winding stator, and a strong smell of burning electrical insulation was reported by the cosmonauts. In the absence of any visible flame, the precise source of the smoke was not located before June 17^{th} because the fan was behind a panel on the aft wall separating the habitable part of the station from the propulsion section. Eventually, switching off the equipment stopped smoke production and air filters worked for the next 24 hours to clean the atmosphere of the space station, but cosmonaut Vladislav Volkov reported persistent headaches in the following days.
Contrary to the American space program, all Soviet spacecraft and space stations featured the standard sea-level atmosphere with 21% oxygen and 79% nitrogen at a pressure of 101.3 kPa (14.7 psia) [30]. The weight addition associated with the extra nitrogen was not an issue since Soviet rockets had larger launching capacities. Once the spacecraft was in orbit, oxygen

would be mostly produced by non-regenerative potassium superoxide cartridges [31]. Though nominal atmospheric conditions would considerably limit the potential consequences of an accidental fire with reduced flame spread rate and fire growth compared to a pure oxygen atmosphere, this process of oxygen production could result in local peaks of oxygen contents in the cabin up to 40% oxygen, far above the LOI of most materials on board. Having lost cosmonaut Valentin Bondarenko in an accidental fire during an endurance experiment in a 50% oxygen-enriched low pressure atmosphere in 1961, Soviet scientists were well aware of the enhanced flame spread rate and flammability issue associated with such high oxygen content [32].

Given its volume of 100 m^3, the Salyut-I space station could not rely solely on observations by cosmonauts. Instead of designing dedicated sensors, Salyut fire detection system relied on a CO_2 analyser also used to track the toxicity of the air. It was assumed that a rapid increase of CO_2 content would reveal any unnoticed fire [33]. Little is available in the literature about the existence of potential mitigation apparatus at that stage of the Soviet Space program. Water mitigation was considered, and it seems that between 1969 and 1971, fire safety was improved by including a Freon fire extinguisher system though the efficiency of the devices in case of a spacecraft fire is undocumented [32]. Contrary to the Apollo fires, the events in Salyut unfolded at a pace slow enough to allow intervention. Yet, the lack of visibility and the impossibility to perform continuous communications with ground control caused the cosmonauts to panic, deviating from the established protocol and almost terminating the mission as the crew rapidly sought shelter in the Soyuz reentry module [29]. Such a divergence in smoke emission between normal and reduced gravity environment was not expected, and as such training was inadequate. In addition, this incident illustrates the challenges of detection in the absence of buoyant flows. As forced convection and diffusion become the dominating transport mechanisms, combustion products flow away from the fire source slowly. With increased transport time, the fire can develop to a much larger size before detection occurs, to the point that the crew would notice smoke or flames even before an alarm goes off. Lowering detection threshold, on top of increasing the rate of false alarms, can hardly circumvent this issue as combustion products either display steep gradients near the fire source, or diffuse to indiscernible levels in the volume of the spacecraft in the case of CO_2 after a while [34].

2.4. Salyut-VI

Two major smoke incidents were reported in Salyut-VI a few years later. This space station, with a pressurized volume of $90m^3$, featured the same atmospheric conditions as Salyut-I, and presumably the same fire detection and mitigation devices of still unproven capabilities.

In 1977, a scientific device caught fire when its power switch was turned on by ground control operators and dense smoke filled the module. Georgy Grechko, holding his breath and feeling his way through the smoke, switched off the faulty device and extinguished the flames with his hands, suspecting that using a fire extinguisher might damage the electronics [35]. Though instructed to shut any flow by the fire safety protocol, he instead activated the ventilator of the filter to clear the air, with no further issue.

The next year, a control panel caught fire on October 4^{th} 1978, producing dense white-blue smoke which quickly spread through the station [36]. The control panel was disconnected and this time fans were switched off to stop the air supply to the fire. Though no visible flame was reported, the cosmonauts discharged a fire extinguisher to mitigate the smoke production. In the process, three surrounding control panels were short-circuited, proving Georgy Grechko right. Emergency evacuation of the space station was considered for a short amount of time but the situation returned to normal after a day of air filtering [37]. In the meantime, the cosmonauts had donned air filtering masks to avoid breathing toxic fumes.

In both cases the exact cause of the fire is not clearly established, and the possible activation of the fire alarm is not reported. Moreover, the initiative by Georgy Grechko to act against protocol illustrates that the capabilities of the mitigation devices were not assessed, that the cosmonauts were aware of this gap of knowledge, and that the mitigation process had not been clearly defined in the absence of any form of tracking regarding atmosphere contamination. This becomes problematic as donning masks is a temporary solutions, which requires knowledge of when the situation is back to normal. NASA engineer James Oberg, NASA historian David Portree, and French spationaut Jean-Loup Chrétien have mentioned several other fires occurrences aboard Soviet spacecraft in the 1970s and 1980s, however they are not reported here since few factual or detailed crossed information from official sources can be found [37, 38].

2.5. Space Shuttles

Five incidents identified as electrical failures were reported in the NASA Orbiter fleet from 1983 to 1992. None of them actuated the detection system, nor did they develop into a full-scale fire since the astronauts noticed the smoke and could shut down the corresponding equipment before atmospheric contamination levels able to trigger the alarm system were attained [39]. In April 1983, wires fused and the crew noticed an odour; in August 1989 a short circuit on a teleprinter released smoke detected by crew members and instruments, but the circuit breaker failed to open; in December 1990, a resistor overheated in a digital display unit, producing a noticeable odour; in June 1991, the fan of a freezer failed and post-flight analysis deemed the atmosphere contaminated; and in June 1992, an electronic capacitor failed and the crew noticed an odour, but no atmospheric contamination was recorded. The Shuttles were the first American space vehicles to feature a standard 21% oxygen, 79% nitrogen mixture at a pressure of 101.3 kPa (14.7 psia), but were able to switch to a 26.5% oxygen, 73.5% nitrogen mixture at a pressure of 70.3 kPa (8.2 psia) to reduce prebreathing time before extra-vehicular activity [40]. Relying on the technology implemented in the aviation sector, the fire detection system was built around ionization smoke sensors [41, 42]. Sensors were located along strategic avionics lines to optimize the response time in the absence of natural convection, with nine of them placed in the Orbiter and an additional six in the Spacelab. In case of fire, a complex halon-based extinguisher system was integrated to the vessel structure. Halon 1301 was used in spite of the known long-term toxicity and corrosiveness of its decomposition products [43], because of its positive track record in the aviation sector and because of the ability in the Shuttle program to conduct extensive clean-up and restoration operations on the ground between flights. Utilization of halon was however stopped shortly after, in the context of longer duration spaceflights [44]. In the Orbiter Shuttle, a central tank of halon was equipped with distribution lines in each avionic bay, complemented with four additional portable extinguishers in the Orbiter, and two in the Spacelab. Manual cabin depressurization was also available in case of a fire, and the immediate electrical power shut-down of the affected zone was also prescribed, to cut external heat source.

A new and major shift in the fire safety strategy was the definition of a flammability criterion for space material testing, formalized in 1974 in the NASA Handbook (NHB) 8060.1 A [45]. Derived again from aircraft regulations requirements, this NHB provided a framework to control various risks associated with each payload and their combination [46]. To ad-dress fire risk, the NHB pointed to the *Flammability, odor, and off-gassing requirements and test procedures for materials in environments that support combustion.* This procedure was further updated in 1998, as the *Flammabil-ity, odor, offgassing, and compatibility requirements and test procedures for materials in environment support combustion* that specifies to this day how materials employed in habitable and non-inhabitable parts of a spacecraft have to be tested at normal gravity regarding flammability, offgassing, reactivity in aggressive environments, and arc tracking in the case of elec-tric wires [47].Test 1, illustrated in Fig. 1, evaluates the primary criterion of flame propagation over a material exposed to an ignition source in its worst-case atmospheric environment. The test is passed only if none of the five standard-sized specimen materials burns over more than 15cm, and if no test specimen propagates a flame to a paper placed below by the transfer of burning debris. Such drastic pass/fail evaluation deviated from aircraft standards which cap the admissible flame spread rate and fire growth rate (see for instance Federal Aviation Regulations 25.853), but do not require the absence of flame spread nor self-extinction. These stricter rules were devised as a consequence of existing concerns regarding the ability to correlate test results obtained at normal gravity to the actual reduced gravity conditions of the spacecraft. Such concerns have been reinforced by the experimental observation of lower LOI in reduced buoyancy, occurring at flow velocities below what can ever be achieved in the presence of natural convection [17]. The outcome of the test then supports a high-level system hazard evalua-tion, in which the overall fire prevention tolerates the inclusion of elements deemed unsafe by the test as long as proper spacing, storage, and elimination of fire-propagation paths are implemented following NASA's guidelines [48]. To that end, components are given different flight ratings associated with the tests's outcome, and never dismissed since vital spacecraft operations can require their presence on board.

In the absence of dramatic outcomes, this series of events still under-

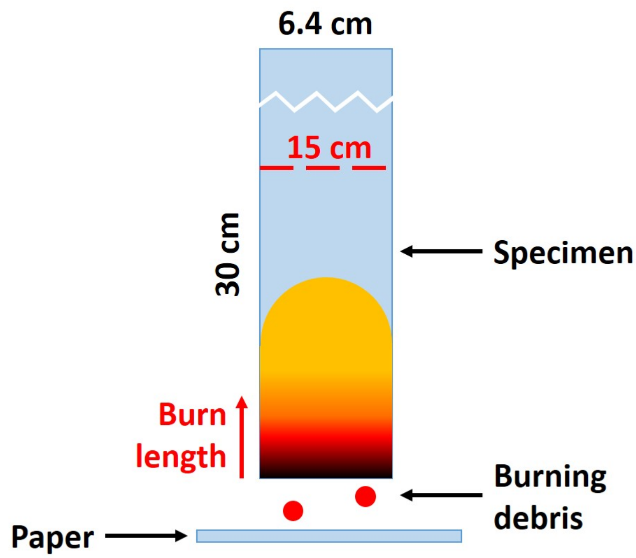

Figure 1: Schematics of NASA Standard Test 1 for material flammability. The test is failed if burning debris ignite the paper placed under the sample, and/or if the burn length exceeds 15cm.

lines the existing gap of knowledge at that time, from prevention to mitigation. First, Shuttle missions spent a relatively small amount of time in space and, up to 1992, electrical failures resulting in thermal degradation of polymeric material roughly occurred once every two months of mission time. This frequency of failure is far above any aircraft statistics in the same years [49], despite the hyper-controlled envi-ronment. The electrical nature of the failures also highlights the lack of understanding of overheating mechanisms in this context. Later investigations revealed that high humidity had led to either shorts [50], or hydrolytic degradation of wire insulation allowing electric arcs to propagate along wiring bundles and degrade the insulating material in the process [51]. It is supposed that degradation never led to ignition of Kapton polyimide (MIL-W-81381), which had been picked as wiring insulation in the Shuttle for, among other properties, its non-flammability at normal gravity [52]. However, the rationale for extrapolating normal gravity data to spacecraft configuration had still not been systematically investigated, meaning Test 1 might generate an inadequate database. Eventually, the absence of rigorous scientific basis for the system hazard evaluation limits its scope to common sense decision-making or to a rigid adherence to regulations, which is particularly vulnerable to any disruption in spacecraft material or configuration that modifies the fire risk in a different way with buoyant flows (test scenario) and without (real case scenario).

The detection system also pointed out a risky lack of knowledge: the fire alarm was never actuated as wires over-heated, meanwhile 14 false alarms or built-in-test failures were reported in the Shuttle over a period twice as long [53]. This system was a new addi-tion that deviated from the previous American space station, Skylab, which was equipped with ultraviolet sensors meant to track specific chemilumines-cence. In spite of an extensive preflight qualification [54], ultraviolet sensors had generated numerous false alarms [55] attributed to a lack of knowledge regarding the radiant signatures for low-g fires. Because of the engineering challenge of providing ultraviolet detectors with a line-of-sight to the area to be monitored, fire detection based on smoke was preferred in the Shut-tle program, regardless of unresolved challenges related to the appropriate alarm level, dust discrimination, sampling in the absence of buoyant flows, and, again, the lack of a knowledge base of fire signatures in the absence

of buoyant flows [56]. The sensors relied on coarse assumptions regarding particle size to discriminate smoke from regular dust particles, in the absence of precise knowledge of the size distribution of the particles released in a fire event. An additional pump was added to control the air stream through the apparatus, though the associated mechanical failures drastically reduced the operational life of the whole system on test benches. Overall, the new ionization sensors did not show any improvement compared to the previous UV sensors, due to the sustained absence of information regarding a low-g fire signature. Eventually, electrical shut-down proved to be enough to mitigate these situations but, should a fire of a larger magnitude develop, the performance of the halon extinguisher in the absence of buoyant flows had not been assessed, and only one discharge test had been performed on board to train the astronauts. Similarly, the supposed safety net provided by manual depressurization was known to be hazardous, since 1974 flammability observation in Skylab revealed that the associated venting initially intensifies the flame [57] and the lack of existing data forced the definition of a gradual venting from a limited set of experimental results.
In spite of the gaps of knowledge, no additional incident was reported after 1992 until retirement in 2011 thanks to technical wiring improvements.

2.6. Mir

Two fire incidents took place aboard Mir. This space station of Soviet design featured the same nominal atmospheric conditions as the Salyuts in a pressurized volume of 350m^3. Oxygen production relied on two water electrolysis units [58], supplemented by lithium perchlorate candles [59] to support the presence of six astronauts and cosmonauts on board. Fire detection was based on optical smoke detectors [60], and mitigation relied first on portable extinguishers releasing a water-based foamy solution expanded by halon 1301 [43, 61]. In order to suppress fires in inaccessible areas, the astronauts and cosmonauts could also open valves connected to the outside vacuum [62].

On October 15^{th}, 1994 cosmonaut Valeri Polyakov reports a first fire related to the malfunction of an oxygen canister, setting its cover cloth in flame [63]. The fire was rapidly put out using a jumpsuit to cover the flames while turning off the unit's power. The jumpsuit kept burning unperceived afterwards, and flamelets had drilled a hole in the chest area of the suit when the crew noticed it.

Quickly resolved and with no consequences, this incident still highlighted the lack of understanding of fire spread as the flames propagated in the jumpsuit. It is not known exactly what protocol Valeri Polyakov should have followed in this situation, but the absence of immediate verification of the jumpsuit illustrates that common sense solutions fail to integrate aspects specific to combustion in the absence of buoyant flows.

The failure of a similar oxygen generator was reported three years later on February 23^{rd}, 1997, when the tank of a canister burst into flame during a routine ignition operation. Unlike in 1994, this fire involved the extremely reactive generator's core chemical compounds [64], resulting in a flame extending about one meter in length, hot enough to expel melting bits of metal that rapidly spread around the module. Since the burning canister was standing in the way between the crew and one of the two three-seat Soyuz escape vehicles, evacuation of the six crew-members was not an option. After the fire alarm was activated, intervention was delayed first by distraction, given that the master alarm was used indiscriminately for real emergencies or routine operations such as wake-up calls, and, once the crew noticed the smoke, by a lack of preparation as the fire extinguisher had to be freed from their launch and transport straps and unfastened using pliers and screwdrivers. In the meantime, large amounts of black smoke increased confusion as visibility decreased to the point the men on board could not even see their own hands [65]. Donning oxygen masks, they realised a number were faulty, putting further stress on a quick and successful intervention. Unfortunately, the sprayed foam did not stick to the surface of the canister where heat, fuel, and oxygen all originated, because of the inertia of the fast flame jet. To make matter worse, hot steam was produced as the water-based foam crossed the flame, adding to the smoke. Changing strategy, the crew then sprayed three extinguishers on the surrounding walls instead of targeting the base of the flame, hoping to provide an insulating layer to avoid the melting of the aluminium hull. Eventually, the fire burned without spreading until all the solid fuel was consumed. The duration of the incident is subject to debate, ranging from 90s in officials reports [65, 66] to 5-15min according to astronaut Jerry Linenger who was present on board [67]. In the aftermath of the fire, the dense smoke was filtered by the ECLSS. Because there was no capability to assess if the air was actually safe to breathe at that time [66], the crew donned surgical masks to limit the effects of smoke inhalation, and repetitive exams to check lungs and blood of all crew members were carried out in the following 48 hours. Urgently needed oxygen cartridges and three new fire extinguishers of the same nature as the depleted ones were supplied two months later [68]. Apart from the burnt oxygen canister, the material damages turned out to be very limited: a plastic switch cover was burnt down but the switch itself was not, while four cables on the carbon-dioxide removal unit were damaged. One of them had to be removed, disabling automated operations and forcing astronauts to manually control carbon-dioxide removal [37].

Investigations carried out over the following couple of years concluded that either an accidental hydrocarbon contamination of the canister or a mistake in the preparation of its ignition system could cause a similar thermal runaway [69]. Lacking further evidence, the former hypothesis was deemed more realistic because the ignition manoeuvre had previously been executed without incident 2500 times on Mir, and 1500 times on the ground. It was suggested that a piece of the latex gloves worn in the making process could have accidentally ended up in the canister. In the absence of a viable alternative to the lithium perchlorate oxygen generators, manufacturing and operating procedures were improved to increase vigilance towards contamination, the location of the canisters was restricted to the base block of Mir to avoid creating dead ends, and a new protective ceramic casing was designed.

This fire demonstrated the continued existence of loopholes in the fire strategy, which forced the astronauts and cosmonauts to improvise under paramount pressure [70]. In spite of the 1994 incident three years before, no fire drill had been performed to properly train the crew and familiarize them with the equipment, as demonstrated by the still-locked extinguishers. Combined with the desensitizing to the master alarm, the overall delay leads to a sub-optimal response time. In that situation, it means more smoke could build up in the module, cancelling out any benefits from an early detection. In the absence of regular training, astronauts and cosmonauts also faced for the first time practical issues they were not prepared to: only one person could spray foam on the fire in the narrow paths of the station; the reactive propulsion associated with the foam jet of the fire extinguisher was a surprise; crisis communication with ground control was not well defined to provide adequate support; atmospheric contamination was not monitored at all through the incident; and it was later realised that had the crew been forced (and able) to escape with the two Soyuz vehicles, both capsules were programmed with the same set of re-entry coordinates, which could have resulted in a catastrophic collision. As far as mitigation is concerned, the extinguishers showed their limitation in the presence of a jet flame where the high momentum of the gases overpowers the spray of the extinguisher, preventing access to the material reacting inside the oxygen generator cartridge. The efficiency of the thermal blanketing of the hull can also be questioned: halon extinguishers primarily rely on chemical effects to inhibit combustion, and the initial intervention showed that the flame would vaporize water from the foam. In the absence of further knowledge of the nature of the fire extinguisher, the exact contribution of this improvised strategy to the outcome cannot be evaluated.

3. Shortcomings of past fire safety strategies

Although informal reports also suggest that several other minor fires have occurred in the over ten years of Mir operations, documentation of these incidents is again sketchy [46]. The twelve incidents described previously have been summarized in Table 1, and are included in the chronology of international space exploration displayed in Figure 2. These situations can be contrasted against five different aspects of a fire safety strategy, namely prevention, early detection, training, suppression, and recovery, to summarize the associated shortcomings. By definition, prevention failed in each of the twelve cases because the unsupervised combination of fuel, oxidizer and heat sources is in essence inevitable until material flammability in the absence of buoyant flows has been fully understood. The introduction of a standard test aimed at bypassing this knowledge gap, but the later Space Shuttle and Mir incidents highlight the shortcomings of this approach. In addition, in the three situations where a fire developed to a life-threatening size (Apollo 1, Apollo 13, Mir 1997), it did so before the crew members could effectively intervene, illustrating the potentially disastrous effects of inadequate prevention even in the presence of early detection. Early detection was effective in the nine remaining cases (Salyut I, Mir 1994, all instances of Salyut VI and the Space Shuttles). However, it should be pointed out that none of these detections actually relied on instrumentation, even though dedicated fire sensors were systematically present on board. Again, a lack of knowledge (this time regarding the low-g fire signature) drastically limits the efficiency of any automated detection system. Training, as a key component in the resolution of emergency situations, is designed to provide the crew with an automatic and effective response in a potentially stressful context. In the enclosed volume of a spacecraft, the level of stress when facing a fire can be increased by the possible dense amount of smoke produced (Salyut I, Mir 1997). However, the level of improvisation to tackle the fire identified in four instances (Salyut-I, Salyut-VI 1977, Mir 1994 and 1997) shows the lack of confidence in the established protocols. Given that training can hardly be assessed in the very brief Apollo 1 and Apollo 13 situations, the recommended course of action was only pursued with a positive outcome in the five minor Space Shuttle incidents (power shut-down). In contrast, the prescribed use of fire extinguisher discharge in Salyut-VI in 1978 potentially caused more damages than the incipient fire itself. As such, the evaluation of the different suppression techniques is subject to caution: because of the complex layout of a spacecraft, any mean to suppress a flame should do so with as little impact as possible on the surrounding environment. In that sense, power shut down has proved to be an effective technique, but the impact of a water-based fire extinguishers on the different elements of the spacecraft needs to be better understood. Last, though an early available fire mitigation technique, depressurization has never been used in a fire context but the observations in Skylab question its efficiency in most fire situations [57].

Year	Spacecraft	Ignition source (* presumed)	Smoke / flames	Detection	Mitigation	Significant consequences
1967	Apollo 1	*wiring, *flammable coolant	flames	visual	no	Destruction of the CSM, death of three astronauts
1970	Apollo 13	*short circuit	flames	visual, instruments	no	Destruction of the CSM
1971	Salyut-I	fan mechanical failure	smoke	odour	power off	none
1977	Salyut-VI	*electrical	smoke	visual	power off	loss of scientific equipment
1978	Salyut-VI	*electrical	smoke	visual	water extinguisher	4 control panels lost: 1 to the fire, 3 to water
1983	Space Shuttle	wire fuse	smoke	odour	power off	none
1989	Space Shuttle	short circuit	smoke	visual, instruments	power off	none
1990	Space Shuttle	resistor overeating	smoke	odour	power off	none
1991	Space Shuttle	fan mechanical failure	smoke	odour	power off	contaminated atmosphere
1992	Space Shuttle	electronic failure	smoke	odour	power off	none
1994	Mir	failed cooling of the cloth filter	flames	visual	power off, quenched with jumpsuit	damaged canister
1997	Mir	*oxygen canister contamination	heavy smoke, flames	instruments	complete burn out	canister destroyed, one cable removed

Table 1: Summary of documented fire and smoke incidents in spacecraft.

4. Present fire safety strategy in the ISS

None of the 5 presently active manned space programs has reported any significant fire issue, as illustrated in Fig.2. Among them, the ISS features the largest pressurized volume (915.6 m^3) and has been continuously operated for more than 20 years. To understand the sustainability of the present situation, its fire safety strategy is evaluated in light of past fire incidents. Capitalizing on the past experience from joint American and Russian space programs, the ISS was built after the plans of the cancelled Mir-2 space station. Its atmosphere is a 21% oxygen, 79% nitrogen mixture at a pressure of 101.3 kPa (14.7 psia) [71]. In addition to providing standard conditions for medical observations regarding the impact of weightlessness on the human metabolism, it enhances fire safety by limiting flammability and fire growth rate compared to oxygen-enriched spacecraft. Oxygen generation relies mostly on water electrolysis, with the Oxygen Generation System in the American segment and Elektron in the Russian segment, but also CO_2 reduction into water and oxygen in the Advanced Closed Loop System in the European segment since 2018. However, frequent failures of these systems require the use of oxygen bottles supplied from Earth as well as lithium perchlorate candles derived from those used in Mir, meaning that high oxygen leakage or buildup above material flammability specification is still possible. This material specification is derived from material standard testing procedures, which have capitalized on the database compiled since the Shuttle program. The various space agencies involved in the ISS project have developed slightly different material testing protocols, but the overall philosophy is the same with single-element tests used as a basis for high-level fire prevention designs [46]. In order to rationalize the approach and share it with ISS visiting vehicles for consistency, the flowchart which specifies the needs in terms of fire detection and/or mitigation is specified in the SSP 50808 [72]. This strategy has shown its limitation in the Space Shuttle and Mir fires, since the gap of knowledge regarding flammability and fire spread in reduced gravity has not been fully addressed. To this day, academic experiments are still in planning to devise and validate methods to extrapolate fire safety in the absence of buoyant flow from data obtained at normal gravity [73]. In the meantime, since material that has been specifically designed to withstand thermal degradation at normal gravity can fail in the absence of buoyant flows, minor wire degradation events similar to those experienced in the Space Shuttles were still observed in the ISS [74].

In terms of fire detection, the Russian Orbital Segment is equipped with 10 optical sensors and 13 ionization detectors. This high density is meant to curb false alarms from dust through redundancy by triggering the master alarm only when multiple detectors are actuated, and to facilitate source location via a modelling of the airflows in the segment [1]. Similarly, the American, Japanese, and European modules rely on 17 optical sensors coupling light obscuration with forward light scattering measurements, and post-assessment of dust discrimination based on frequency analysis is provided by a software overlay which integrates the most recent state of knowledge regarding low gravity fire signatures [41]. These sensors are located next to ventilation inlet grids to force air through them, and additional ones are mounted in the different systems and payload racks to help the crew locate smoke origin [75]. The redundancy also allows a reduction in the each sensor alarm threshold without multiplying false alarms from electronic noise or benign atmospheric pollutants [39]. In locations where a smoke detector cannot be fitted, additional data monitoring is carried out to track unusual temperature spikes in the gas phase [61]. If there is suspicion of air contamination, the ISS is equipped with six handheld Compound Specific Analyzers for Combustion Products. The crew can then monitor the level of carbon monoxide, hydrogen chloride, and hydrogen cyanide in the atmosphere [76], and regular checks are conducted in the powered racks to detect any slow-burning fire. If threshold levels are exceeded, the crew is instructed to don either emergency masks that supply pure oxygen in case of smoke build-up, or masks that filter the ambient air if there is a visible flame to avoid supplying extra oxygen to the flames. This upgraded monitoring of the atmosphere, which had been lacking in Salyut-I and in Mir, supports a constant tracking of post-fire contamination, assisting the crew with crucial data in the recovery phase. However, from a detection perspective, the far from complete understanding of fire signature in reduced gravity hampers any tentative to build an efficient system, as the sensors at the very core of the complex detection strategy can provide inadequate information.

Russian OKP-1 sprays 0.8l of a foam agent pressurized by gaseous nitrogen at 10.0MPa. The foam can be delivered in less than 30s, to ef-fectively tackle fire on module appliances s [75]. This type of extinguisher would prove to be inefficient if the case of fire-burning clothing on a human, so it is complemented by a 2.5l water-based ОСП-4 that can switch between foam and jet, providing the adapted level of moisture to different fire situations [77]. The American, Japanese and European modules feature CO_2 portable fire extinguishers that contain 2.7kg of gas compressed at 58 atm which can be discharged over forty-five seconds. An additional water-based extinguisher can generate deionized water mist for about fifty seconds, producing droplets of under 100μm to avoid shock hazard to crew if discharged on electrical equipment. During training, crew members are instructed that the presence of the primary CO_2 removal system Vozdukh [78] forbids the use of CO_2-based fire extinguishers in the Russian module to prevent overloading. However, CO_2 fire extinguisher would be preferred in the event of a rack fire to avert damages to electrical equipment. As in previous spacecraft, flow and electrical shut down are available to mitigate both oxygen and heat supply. Depressurization is also possible, once the affected module is isolated. This variety of mitigation equipment prevents further damages caused by the extinguishers, and would have certainly been welcomed in the 1978 Salyut-VI fire. Yet, the primary concern should be about the efficiency of these different methods to actually quench the flames. If past experience on the ground suggest all types of fire can be addressed with this full spectrum of solutions, there is again a critical lack of knowledge regarding the transposition of these performances in orbit. The Mir 1997 fire, where power and flow shut-downs were inefficient, is a clear reminder that uncertainties related to mitigation performances should not be tolerated when only limited evacuation options are available.

With training on the ground prior to any mission and regular fire drills in the ISS, both the crew and Mission Control centres are frequently tested to ensure optimal response and communication [79]. The definition of a clear and, crucially, simple sequential protocol in which each member has a predefined role allows a lean management of any critical situation, reducing the stress and clarifying the decision-making process [75, 80]. In case of a fire, while a Response Team intervenes, PC Operators in the ISS would incorporate information produced by all the sensors and inform the actions from a safe haven by tracking the smoke detectors messages, locating eventual failed equipment, performing powerdowns, and keeping track of the use of resources in constant communication with the Response Team and Ground Control. Incorporating lessons from the Mir 1997 fire, this rigorous and thorough definition of protocols relies once again on the assumption that both sensors and mitigation devices perform adequately in this new environment.

It is worth noting that, since 2003, China is the third country to have independently operated space stations in LEO in the scope of the 921 Project Shenzhou [81] and as such may develop a spacecraft fire safety strategy of its own. Information on that topic is scarce, but it can be assumed that Chinese Shenzhou spacecraft and Tiangong space stations feature an atmosphere with a pressure of 91 kPa (13.2 psia) and an oxygen content of 21% [82]. They are equipped with fire alert and mitigation devices [83], however, to the authors' knowledge, there is no literature available describing the adopted technologies and protocols. Only the existence of public reports of a false fire alarm underlines the importance given to potential fire scenarios [84].

5. Looming challenges of Deep Space exploration

Transitioning from LEO to Deep Space will challenge the existing tools and concepts of spacecraft fire safety. The technical solutions presently implemented in the ISS are not designed for long range missions, and, more importantly, surface operations on the Moon or on Mars will introduce intermediate buoyancy conditions which have barely been investigated, in spite of the known non-linear influence of gravity on solid combustion.

Partial gravity levels of 0.16g on the Moon and 0.38g on Mars affect the whole chain of the fire safety strategy, with expected consequences on flammability, flame spread rate, smoke production, detection, mitigation and clean-up. Concomitant to the fortunate absence of fire incidents in partial gravity, there is a regrettable lack of experimental data, and early experiments have reached ambiguous conclusions [85, 86]. Measurements conducted in parabolic flight indicated that downward spreading flames could propagate at lower oxygen contents in Lunar and Martian conditions than at both 0g and 1g. Yet, the minimum oxygen content for upward spreading flames was shown to be a decreasing function of the gravity level, which was confirmed by another set of experiments in centrifuges [93]. Investigating a range of combustible material, centrifuge experiments highlighted that material fire risk ranking could change at partial gravity, for instance paper-based laminate which is less flammable than natural leather at normal and Martian gravity levels has a lower limiting oxygen index at Lunar grabity [94]. These studies also showed that downward flame spread peaks close to Martian conditions, while upward flame spread would linearly increase with gravity. These observations have been complemented by numerical modelling which evidenced that the heat release in spreading flames rate would also peak at an intermediate gravity level [91]. Additional experiments are required to understand whether flammability, flame spread rate, smoke production, and other fire-related hazards are positively or negatively modified in low gravity fields. Until measurements are performed and a deeper understanding of gravity-related mechanisms is gained, this lack of knowledge exposes space exploration to unforeseen dangers, leading to a risk-adverse approach without effectively guaranteeing a safe environment. Additional safety factors in material screening may hamper the use of high-tech polymer equipment, while the efficiency of detection is once again hardly predictable in the absence of a comprehensive understanding of a fire signature at intermediate gravity levels. Similarly, the effect of mitigation techniques needs to be characterized in the desired environment, to avoid new surprises in operation. As an example, stopping the ventilation in the presence of a residual buoyant flow which will naturally drive oxygen to the flame at an unprecedented low flow rate needs to be assessed to qualify the relevance of this strategy, as it was done in Mir and the ISS [92].

These underlying scientific aspects are all the more important as the range of any Lunar or Martian Deep Space project envisioned these days exceeds any mission executed so far and calls for improved self-reliance. With present propulsion technologies, a one-way trip to Mars roughly lasts 6 months, and up to 500 extra days could be spent on the surface to wait for the ideal planetary alignment before flying back. Similarly, even though a journey to the Moon is only a matter of days a permanent Lunar settlement is inherently built to last for years. Yet, the fire safety protocols in the ISS previously described rely heavily on contingency emergency resupply, and the ability for the crew to escape the station in emergency Soyuz vehicles. Discharge of fire extinguishers, depressurization, and atmosphere clean-up are open-ended protocols which mean they can only be performed a finite number of times in an autonomous spacecraft. If a fire event depletes these resources, the crew is left defenseless in case of a second accident. The development of lightweight closed-loop systems, or of equipment which can harvest lo-cal resources such as ice on the Moon or low-pressure atmospheric CO_2 on Mars will curb the risk of operating without a safety protocol.

Indirect consequences of this increased exploration range will also affect fire safety. In order to reduce the unavoidable leakage rate [87] and at the same time lower the structural load on the hull (and consequently its weight), exploration vehicles will likely feature low-pressure atmospheres. This will also reduce pre-breathing time, which is extremely valuable for frequent surface extra-vehicle activities (EVAs). The currently considered atmosphere for the Gateway vehicle which operates in microgravity is a 26.5% oxygen, 73.5% nitrogen mixture at 70 kPa (10.2 psia), while the Lunar Lander is expected to feature a higher 34% oxygen content at $P = 56.5$ kPa (8.2 psia) [13]. This increase in oxygen content puts an additional strain on fire safety. A much wider range of material will sustain combustion to an unacceptable level at oxygen content higher than 30%. In addition, even though low pressure usually results in reduced flame spread rate, it also translates into reduced air cooling, increasing the risk of thermal runaway from electrical equipment. It should be mentioned that human lungs can actually perform well under a pressure of 70 kPa (10.2 psia) without increasing the oxygen content [88], a situation which corresponds to Earth-like conditions at an altitude of around 3000m. Unlike the other space agencies which are reluctant to move away from normoxic conditions, i.e. conditions with an oxygen partial pressure of 21 kPa (3.0 psia) similar to sea-level conditions, the Chinese lunar exploration program is considering a 58 kPa (8.4 psia) atmosphere with 21% oxygen [82]. Such hypoxic conditions usually met at an altitude of 5000m, if favourable to fire safety, put however an extreme strain on breathing in cases of efforts.

Long term exposure to radiations will also generate indirect fire safety issues. So far, LEO space stations have orbited within the Earth's geomagnetic field, which protected them from solar radiations and cosmic rays. And while the Apollo missions ventured far outside the Earth's protective shield, radiometer measurements showed that the small doses received were totally acceptable because, in addition to being fairly short, all Apollo missions thankfully happened in the absence of any major solar event which would have put the crew in serious danger [89]. Though individual eruptions from the solar surface have proved impossible to forecast, it is certain that future long duration Deep Space missions will experience solar events given their frequencies, making radiation shielding the top priority. This means fire safety will be subject to radiation requirements, and the nature and configuration of large shielding and cover elements will have to be assessed with great care to avoid creating a major fire hazard. In addition, there is a lack of knowledge regarding the impact of long-duration radiation exposure on material flammability and coatings efficiency [90]. In time, this could downgrade an initially fire safe configuration, which is especially dangerous in a long duration mission context where attention from the crew members decays, the odds of an electrical failure increase, and trash accumulates after a long flight period.

The operations associated with surface activities must also be embedded in the fire safety framework. Regular EVAs will bring large amounts of thin Lunar dust into the base, which may lead to explosion and detection issues. Characterization of the lunar dust was performed in the wake of the Apollo missions [95, 96]. Looking at the composition [97], the low amount of nanometric iron particles found in the overall mixture of inert minerals makes any explosion risk very unlikely [98]. However, from a detection perspective, the size distribution with particles as small as 0.1-1μm means dust sedimentation is limited and such particles of soot-like dimensions may trigger optical and ionization smoke detectors, increasing the likelihood of false alarms. To lower health hazards associated with the dust, vertical forced convection directed towards the ground is considered to increase sedimentation. Yet, this solution would need to be cautiously assessed in the context of smoke detection, since the weak buoyant plume flow of a partial gravity flame would develop against the forced convective flow. As a consequence, the choice of smoke detector location to minimize detection time will need to consider the complex flow fields in the module in the absence of a fire, and the perturbations induced by a flame.

Similarly, the production of local resources to limit supplies must be carefully considered. Growing crops will spontaneously increase oxygen content, but also consume nitrogen [99]. The resulting rise in oxygen content will have to be balanced by the ECLSS, to avoid long-term rise of oxygen content in greenhouses where combustible organic material also naturally develops. More risk will be associated with the need to generate fuel on site, producing highly reactive substances, but also by regular housekeeping activities which may build up pockets of combustible fuel in some areas [100]. Depending on the planned number of crew members in the station and the possibility of a standby mode when the station operates without anyone present will drive the level of automation of the detection and mitigation protocols.

The collaboration of different national and international agencies asks for consistency in the decisions to avoid creating safety loopholes. If this has been successfully resolved in the context of the ISS, the situation can become even more confusing with the growing presence of private actors. This trend will likely raise liability issues [101], and a cautious interaction between the legal and technical frameworks is necessary to avoid creating a dangerous situation where legal requirements overcome safety concerns.

6. Conclusions

Twelve past incidents justify the emphasis on fire safety in spacecraft design. Only three developed to a life-threatening size (Apollo 1, Apollo 13, Mir 1997), but the existence of critical gaps of knowledge regarding one or many aspects of prevention, detection, training, mitigation, and cleanup is systematic. Improvements through the years have relied on sound decisions, which were however based on scarce data to fully understand their consequences. With a fire prevention strategy based on a conservative ranking of material flammability and the possibility to rapidly resupply, the ISS has not suffered any major incident in the past 20 years, increasing confidence in the ability to sustain inhabited presence in LEO over a long period. Yet, Deep Space expeditions featuring no emergency resupply, increased oxygen content in a low-pressure atmosphere, intermediate gravity levels, radiation exposure, and changes in the nature of the missions call for a cautious upgrade of present protocols to ensure a safe development of space exploration. As illustrated by repetitive past failures, the required sustainable upgrades will only be accessible if a solid understanding of the mechanisms related to ignition, spread and growth, smoke production, and extinction is developed.

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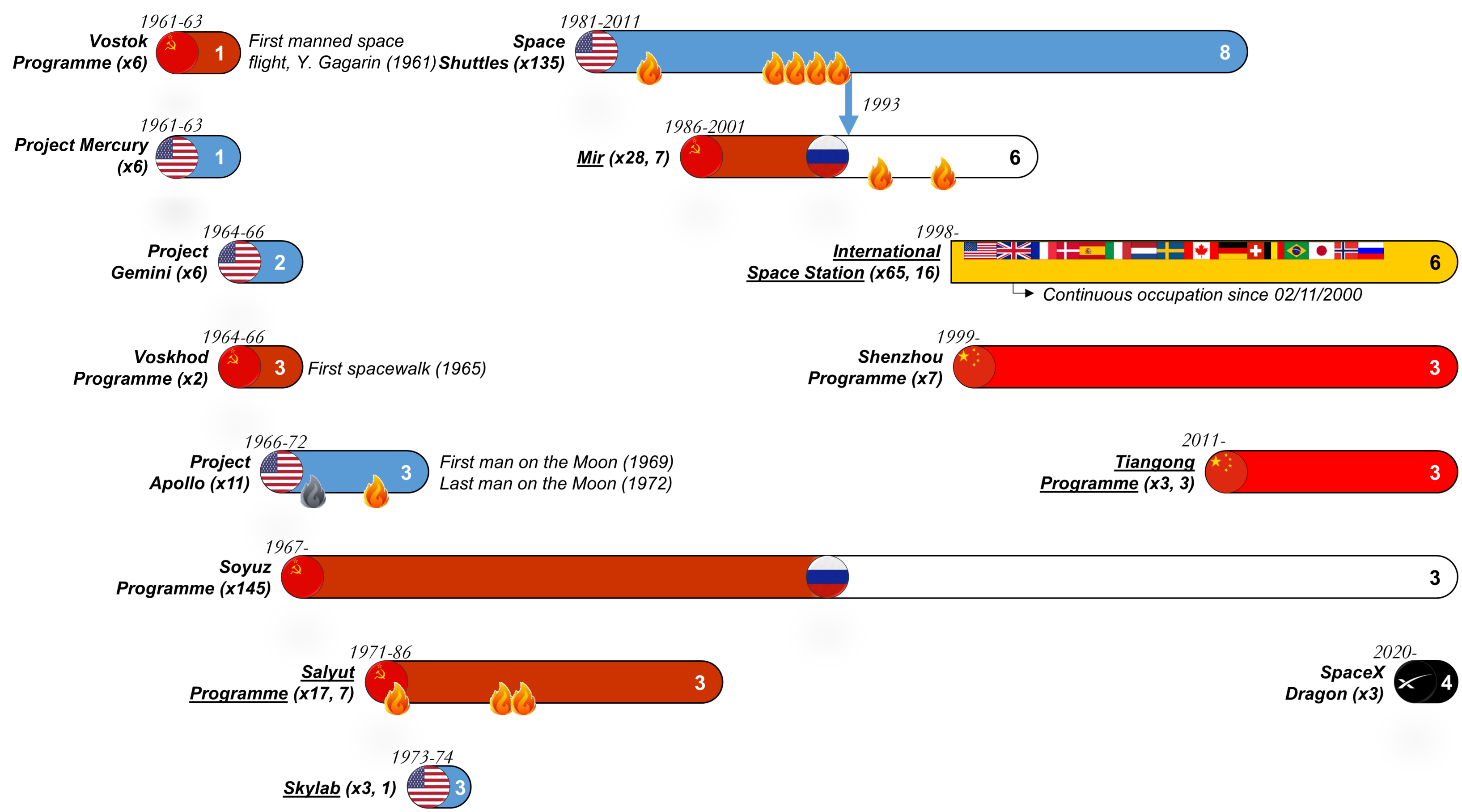

Figure 2: Manned Space Exploration as of 2021. Underlined names indicate space stations; the number into bracket, preceded by a '×' symbol is the number of missions executed; the number of space stations, or modules assembled in space in the case of Mir and the ISS, is then specified; fire symbols mark the events listed in Table 1. The blue arrow shows the beginning of the Shuttle-Mir Program.

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