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A historical overview of experimental solid combustion research in microgravity

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Abstract

Studying solid combustion phenomena in microgravity environments can be complex, and this is furthered by many limitations and constraints in the available microgravity research platforms. Consequently, fire safety in spacecraft is also a complex subject. The main limitations found in the field are related to the microgravity quality, the duration of microgravity conditions, the rig capabilities in volume and size, time scales, length scales and the diagnostic systems, and these are therefore the focus in the current investigation. The laboratory capacity of ground-based platforms has remained somewhat stalled since 1990s, some drop towers have recently been upgraded to extend their performance. New space-based platforms have been or are being established and could extend the windows-of-opportunity to perform research. In addition, a discussion is provided on the implications of the fact that the phenomena studied in the experimental investigations and the type of material employed covers both programmatic and scientific needs. It is found that a handful of materials are most widely studied to quantify and characterise some of the phenomena, while some materials have been employed even in single experimental efforts. The current literature review provides a very comprehensive overview of previous experimental studies and the experimental methodologies utilized. Thus, this study can become an aid to planning for future studies.

Highlights

1. The ground-based laboratory capacity for microgravity research has remained somewhat stalled since the 1990s.
2. New space-based laboratory capacity is extending the windows-of-opportunity for research.
3. The major constraints behind every research platform are experimental duration, sample scale and microgravity quality and levels.
4. Previous studies have investigated a range of diverse materials to comply with programmatic and scientific needs.
5. Diagnostic systems have improved the quantification of the phenomena behind solid combustion in microgravity.

Keywords: microgravity, research platforms, solid combustion, fire safety, Spacecraft

Acronyms

ABS	Acrylonitrile butadiene styrene
BAME	Broadband Modulated Absoption/Emission technique
BASS	Burning and Suppression of Solids experiments in the MSG aboard ISS
CGSB	Canadian General Standards Board
CFM	Candle Flames in Microgravity
CNES	French National Centre of Space Studies
CSA-CP	Compound specific analyser-combustion products
Conex®	meta-aramid fabric
COSMOTORRE	Uematsu Electric´s zero gravity experiment tower
DAS	Diamond Air Services
DARTFire	Diffusive and Radiative Transport in Fire Experiment
DIAMONDS	Detection of Ignition And Mitigation On board for Non-Damaged Spacecrafts
EDS	Energy Dispersion Spectroscopy
ESA	European Space Agency
ETFE	Ethylene tetrafluoroethylene
EVA	Exploration Vehicular activities
FGBU VNIIPO EMERCOM	Federal State Budgetary Establishment " All-Russian Research Institute for Fire Protection of the Ministry of the Russian Federation for Civil Defence, Emergencies and Elimination of Consequences of Natural Disasters
FEP	Fluorinated ethylene propylene
FIAT	Flame Image Analysis Tool
FIRE WIRE	Setup developed by Hokkaido University and JAXA
FIST	Forced-flow ignition and flame spread test
FFFT	Forced Flow Flame Spread Test
FLARE	Flammability limits at Reduced-g Experiments
FPA	Flammability propagation apparatus
GBX	Glovebox Experiment Facility aboard the USML-1 mission
Genitax	Phenolic paper laminate sheet
GEL	Growth and Extinction Limit (project)
GIFFTS	Gravitational Influences on Flammability and Flame-spread Test System
HASTIC	Hokkaido Aerospace Science and Technology Incubation Center
HDPE	High density polyethylene
HNIRI	Hokkaido National Industrial Research Institute
HRR	Heat release rate
JAXA	Japanese Space Agency
JAMIC	Japan Microgravity Centre
Kevlar®	Para-amid fabric
MCA	Major Constituents Analyser
MGLAB	Microgravity Laboratory of Japan
MiniTexus/Texus	European/German sounding rocket programme
MLOC	Minimum limiting oxygen concentration

MSC	Microgravity Smouldering Combustion research programme
MSG	Microgravity Science Glovebox
MOC	Maximum oxygen concentration
MWT	Microgravity Wind Tunnel (project)
Mylar G®	Film made of PET
NASA	National Aeronautics and Space Administration
NMLC	National Microgravity Laboratory China
Nomex® HT90-40	(meta-aramid) nylon fabric
LDPE	Low density polyethylene
LIFT	Lateral Ignition Flammability test
LOI	Limiting oxygen index
PC	Polycarbonates
PE	Polyethylene
PDMS	Polydimethylsiloxane
PEEK	Polyether ether ketone
PI	Polyimide
PMMA	Poly(methyl methacrylate)
POM	Polyoxymethylene
PP	Polypropylene
PP/PG	Polypropyelene glass fibre composite
PPSE	Polyphenylsulfone ethyltetrafluoroethylene
PRIRODA	Shuttle-Mir Science Project
PS	Polystyrene
PTFE	Polytetrafluoroethylene
PVC	Polyvinyl chloride
PUR	Polyurethane
REXUS	Rocket Experiments for University Students
RITSI	Radiative Ignition and Transition to Spread Phenomena
Saffire	Spacecraft Fire Experiments
SCEM	Solid Combustion Experiments Module (project)
SEM	Scanning Electro Microscope
Shinkolite™	MMA resin film
SH144YA	Silicone rubber
SIBAL	75% cotton – 25% glass fibre
SJ	Shi-Jian Satellite Programme
SKOROST	nonmetallic-material flammability evaluations in the combustiontunnel apparatus
SLICE	Structure and Liftoff in Combustion Experiment
SoFIE	Solid Fuel Ignition and Extinction
SR-50	Silicone resine
SSCE	Solid Concurrent Combustion Experiments
SoFIE	Solid Fuel Ignition and Extinction (project)
STEF	Glass-fiber laminate

STS	Space Shuttle Programme
Teflon	Modified ethyltetrafluoroethylene
TEM	Transmission electron microscope
TENGU	Very thin cellulosic paper made of mulberry tree and manufactured by Hidakawashi Co. LTD
TGA	Thermogravimetric analysis
TOPOFLAME	Combustion chamber at ZARM facilities
Ultem® 1000	Polyetherimide film
USMP	United States Microgravity Payload
WIF	Wire Insulation Flammability
ZARM	Center of Applied Space Technology and Microgravity

1. Introduction

The development of the spacecraft industry, which began with the space race between the US and URSS is and now being joined by private industry, has required careful considerations of how to manage fire risks. Spacecraft are not exempt from fire risk, and fire accidents and incidents have been reported [1–5]. The worst fire accidents occurred in mock-up tests on Earth, where the excessive amount of oxidiser in the environment led to speedy fire growth and development [3–5]. From these accidents, the fire safety strategy was then focused on reducing the oxidiser level in the spacecraft environment to reduce the risk of fires. Then, an alternative environmental design for Spacecraft was established to be 21% oxygen concentration and 1 bar ambient pressure that occurred in the Space Shuttle Programme. NASA has developed a fire safety strategy where the main focus relies on the reduction of the fire risk, either by designing the ambient composition or selecting materials based on its flammability behaviour [2,6,7]. The flammability behaviour of materials could be improved by adding inert fillers to their composition [8].

The development of spacecraft technology and the advent of Spacecraft Stations (Mir and ISS) pushed for a better understanding of the combustion behaviour of solid materials in microgravity. Consequently, various experimental studies have taken place since the first work conducted by Kimzey et al. in 1966 [9–11]. As seen in *Figure 1*, several experimental programmes along with experiments conducted in various ground-based and space-based microgravity platforms have taken place. These studies can provide key information to better predict fire scenarios in microgravity and other gravity levels (including Earth's). At the same time, fundamental information can benefit fire safety strategies. Thus, both topics, solid combustion and fire safety on Spacecraft, are essential and complementary. Solid combustion entails smouldering, ignition of solids, flaming combustion, soot, smoke particulates and extinction of flames. Some of these phenomena can occur in a sequence and they are affected by environmental variables.

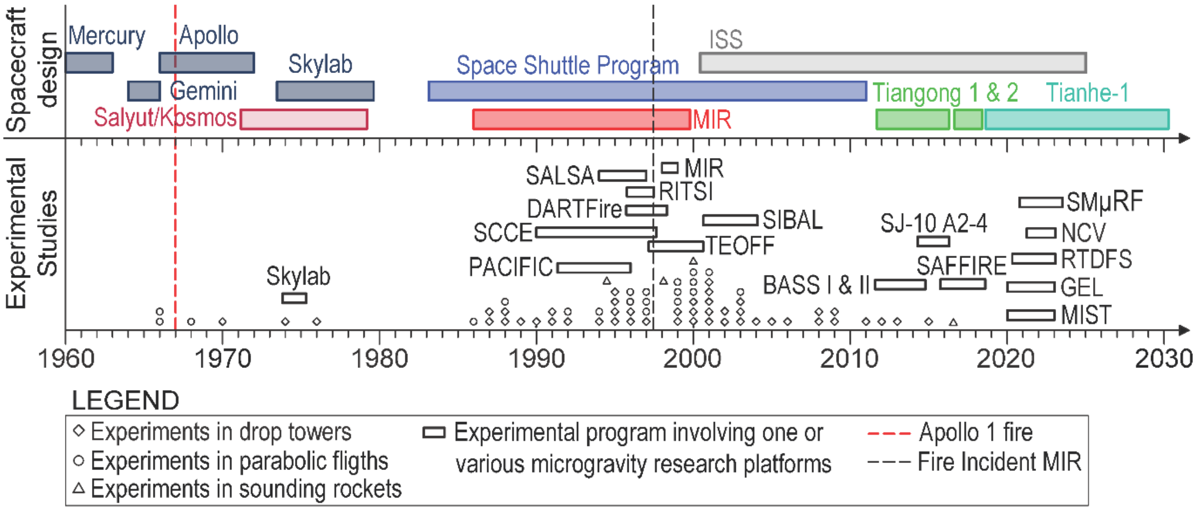

Figure 1 – Historical chart depicting the different projects in solid combustion research in microgravity along with past, current and forthcoming human space stations in orbit.

Conducting experiments in microgravity environments on Spacecraft is severely limited (financial, spatial and logistic constraints), but there are research platforms on Earth where microgravity can be achieved. Each research platform has its limitations and capabilities. Consequently, choosing a platform depends on the type of flammability problem to be studied (ignition, flame spread, smouldering, soot, etc.), as well as on the environmental conditions and the diagnostics used for measurements. In addition, the various research platforms have their own limitations and constraints. In turn, not all phenomena can be studied in all platforms, as the relevant timescales of the phenomena might not fall within the available experimental time.

The current literature review provides an overview of the experimental methodology, coupled with the phenomena and materials that have been used for experimental studies in the last 50 years or so. It is envisioned that future studies can use this information to fully map the many aspects behind solid combustion research in microgravity. All these aspects will be discussed in the following sections. First, the up-to-date available research platforms used for solid combustion research in microgravity are introduced and discussed according to their available experimental time scale, microgravity levels and flexibility. The first Section also contains a discussion of the spatial capacities of the combustion chambers used in various research platforms, and it provides an overview of the flammability phenomena that have been studied according to the microgravity research platform and type of material. In the second Section, an overview of the diagnostic systems is provided.

2. Research platforms, phenomena and materials used

The microgravity levels experienced on spacecraft (˜Ωj˜Ω ρ ћ˜) can be obtained in several ground-based platforms, such as drop towers, parabolic flights, sounding rockets, and microgravity combustion research has taken place in all of these, including on spacecraft in orbit. Various gravity levels can be achieved in the different platforms that have or are being used, see *Figure 2*. However, it must be noted that the gravity levels offered by the research platforms can vary and are not consistently reproducing the same levels as in spacecraft.

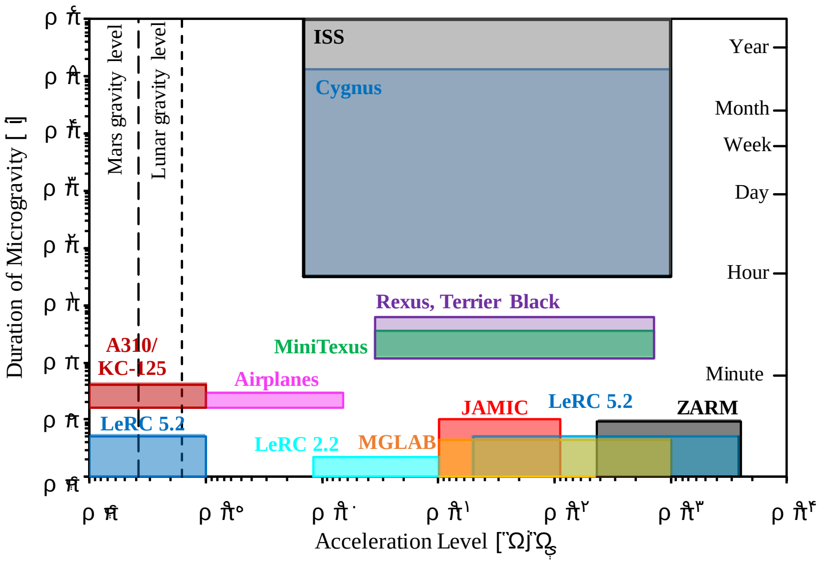

Figure 2 – Characteristic acceleration levels and duration in the microgravity of different platforms and microgravity laboratories. Adapted from Ross and co-workers [12,13]. *Some platforms are not included (HNIRI, HASTIC, the NMLC drop towers and the Chinese Satellites).*

As shown in *Figure 3* the most frequently used platforms for microgravity combustion research are drop towers and parabolic flights. This is primarily due to their relative ease of operation and the relative low-budget associated with operations compared with other platforms. The number of publications with experiments on spacecraft is relatively moderate. Despite the logistic difficulties to carry out research with such platforms, the need for fundamental studies and long-duration, true microgravity has driven experimental work on spacecraft. Sounding rockets and satellites are not as widely used because they entail operational difficulties and do not offer high productivity. Lastly, for centrifuge, there is no strong motivation to conduct experiments with large gravity accelerations. The corresponding references to the platforms employed in solid combustion research in microgravity are listed in the Data-in-Brief.

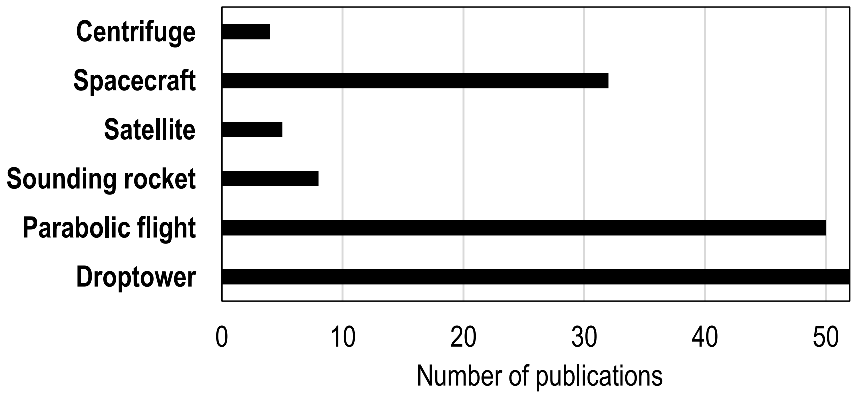

Figure 3 – Number of publications where the various research efforts from ground-based and spacecraft platforms were reported for solid combustion research since the 1960's to present. Experiments or experimental studies in combination with numerical investigations were counted.

2.1. The platforms

2.1.1. Drop towers

In the late 1950s, Kumagai and Isoda [14] used a drop system for the first time to study liquid droplet combustion. As with the spacecraft development technology since the 1970s to the ISS assembly, a range of drop towers was established worldwide in the same period. These research capabilities have been developed further by the Chinese Space programme [14] and by requirements for higher productivity through novel methods designed by ZARM in Bremen and NASA.

NASA was the first to build drop towers, and these two have been widely used since the early 1960s. In the 2.3 seconds drop tower (NASA Glenn Research Centre), the hardware and the rig are protected by a shield due to the aerodynamic drag. Initially, the experiment encountered a problem related to shock load (100 g) when the hardware approached the bottom of the drop [7]. This issue was solved by an air-bag decelerator installed in the facility at the beginning of the 1990s when the drop tower suffered significant renovation [15]. In the 5.2 seconds drop tower, the undesired drag forces were removed by evacuating the drop in low pressure or vacuum (13 Pa). It has recently been proposed to undergo an upgrading renovation that will extend the microgravity duration owing to a catapult system. Moreover, the maximum load of the hardware will also be increased along with a higher number of tests that will be performed daily.

In 1992 the drop tower in JAMIC (Japan Microgravity Centre) started operations [16], and further microgravity combustion research was implemented in Japan. The JAMIC drop tower offers 10 seconds of microgravity, the longest drop worldwide. Other drop towers in Japan are the drop shaft or MGLAB (Microgravity Laboratory of Japan) in Gifu [17], a drop tower located at HNIRI (Hokkaido National Industrial Research Institute), the COSMOTORRE drop tower located at the University of Hokkaido, and finally the drop tower at HASTIC (Hokkaido Aerospace Science and Technology Incubation Center).

In Western Europe, the only drop tower used for combustion research is located in Bremen. It is commonly referred as the ZARM (Center of Applied Space Technology and Microgravity) drop tower and was constructed between 1988 and 1990. The 110 m of free fall within a vacuum shaft (10 Pa) initially provided 4.65 seconds of microgravity. A catapult system was added later and allowed the drop tower to extend its microgravity duration to 9.3 s [18]. A second and smaller drop tower is being built at ZARM, which will offer a shorter microgravity time (2 s) but with a high yield of tests per day. In the Russian Federation, the FGBU VNIIPO EMERCOM (Research Institute for Fire Protection) uses a drop system that can provide 0.72 s of microgravity [19, 20].

The drop tower at NMLC (National Microgravity Laboratory China) is also used in microgravity combustion research [21]. It can obtain 3.5 seconds of microgravity during 83 m of free fall. An additional drop system provides 2.3 seconds of microgravity [22].

Drop towers offer stable microgravity acceleration levels that are very close to those characteristic in Spacecraft. Besides, the maximum hardware load in the various drop towers ranges from 100 to 2100 kg, allowing the installation of significant diagnostic systems. The number of experiments that can be executed per month is 40 to 160, or potentially even higher; hence, allowing considerable parametric studies. In *Table 1*, the most important technical specifications for all drop towers are listed. The only drawback of this platform is the short microgravity duration that is in most cases insufficient to attain steady problem (e.g. a steady flame). Thus the researcher is restricted to certain material and flammability phenomena.

Table 1 – Characteristic times and specification for different drop towers used for microgravity combustion research.

Drop Tower	**Duration [s]**	**Max hardware load [kg]**	**Tests per day**
NASA Glenn Research Centre	2.2	125	8-12

Zero Gravity Research Facility*	5.2 (9.9)*	450 (2100)*	1-2
JAMIC	10	1000	3
MGLAB	4.5	400	6
HNIRI	1.2	100	-
HASTIC-COSMOTORRE	2.5	400	-
ZARM	4.74	260	3
ZARM (Catapult)	9.3	100	3
ZARM 2nd tower§	2	-	50-60
NMLC	3.5	630	2-4
Drop system (NMLC)	2.3	-	-
Drop system (FGBU VNIIPO)	0.72	-	-

**The 5.2 s drop tower is undergoing an upgrade and the microgravity duration will be extended.*

§ A new drop tower will be built

2.1.2. Parabolic flights

Another widely used platform for microgravity combustion research is aeroplanes flying in parabolic (Keplerian) trajectories. This method can achieve longer microgravity times (15 to 40 seconds) than those in drop towers, though with higher gravity levels ($5x10^{-2}$ to $75x10^{-2}$ g). Lunar (0.16 g) and Martian (0.38 g) gravity levels can also be achieved. Further reduced gravity levels can be achieved if the rig floats freely during the parabolic trajectories, and the duration of microgravity is reduced for such experiments. One major challenge associated with parabolic flights is that g-jitter effects, which arise due to vibrations of the aircraft during the parabolic flights, might influence the results in a negative manner [23].

NASA initially used a Lewis AJ2 aircraft that could provide up to 30 trajectories per flight [24]. This aircraft was later replaced by a DC-9 model in 1995 [15], providing up to 40 trajectories per flight. The KC-135 turbojet (Lyndon B. Johnson Space Center) can supply the same amount of trajectories. In Europe, CNES (Centre National d'Etudes Spatiales) began using a Caravelle aircraft for microgravity research. It was replaced by an Airbus 300, which was replaced by an Airbus 310 model in 2015. This is the airplane Novespace currently operates. The A310 flights typically provide 31 trajectories per day for 3 days during research campaigns. In Japan, DAS (Diamond Air Service) operates the Mitsubishi MU-300 and Grumman Gulf Stream II aircraft for microgravity combustion research at the Parabolic Flight Center; both can provide 8 to 15 parabolic trajectories per flight. In Russia, a private company, Atlas Aerospace, offers parabolic flights aboard an Ilyushin Il-76 airlifter at the Gagarin Research and Test Cosmonaut Training Center has a dedicated Ilyushin IL-76-MDK for microgravity research [6]. From the last two aircraft, no research in solid combustion has been reported.

2.1.3. Sounding rockets

A sounding rocket can provide much longer microgravity times than the platforms presented previously, and microgravity can be for as long as 300 seconds. The experimental payload, 150-400 kg, must, however, withstand quite critical gravitational forces (10-40 g) during take-off and landing [7]. The first sounding rocket used for microgravity combustion research was the MiniTexus 3 at the beginning of the 1990s [25,26]. Later on, MiniTexus 6 [27,28] and the larger sounding rocket version, Texus 38 [29], were also used. Both are part of the sounding rocket program run by the European Space Agency (ESA) and the German Space Agency (DLR). For the DARTFire testing programme (Diffusive and Radiative Transport in Fire Experiments), NASA used four Terrier-Black Brant sounding rockets [30–34]. More recently, a sounding rocket as part of REXUS European program was utilised for flame spread investigations of PMMA rods [35].

2.1.4. Satellites

Free flyers such as the non-crew Satellite can be used to conduct combustion research. This platform also offers an extended period of microgravity and adequate gravity levels. The Chinese Academy of Science has used a recoverable satellite "Shi-Jian" (SJ) to conduct various scientific experiments across a range of fundamental topics. The SJ-8 and SJ-10 were launched in 2006 and 2016 and hosted tests looking at ignition, smouldering and flame behaviour [36–38].

2.1.5. Spacecraft and space stations

Spacecraft can provide the most extended duration in microgravity conditions. However, experimentation in this type of platform is more challenging, primarily due to the substantial financial, technological and logistic constraints. Some of the missions of the space shuttle program (STS-USML) also hosted dedicated test programs and innovative hardware, such as SSCE (Solid Surface Combustion Experiments), RITSI (Radiative Ignition and Transition to Spread Phenomena), WIF (Wire Insulation Flammability), FFFT (Forced Flow Flame Spread Test), candle experiments and smouldering tests [39–43].

Skylab was the first space station to host a laboratory for fire experiments [11]. In more extended permanent inhabited space stations, such as Mir, a few experiments also took place using the hardware developed by Piroda [44]. The ISS currently has the Microgravity Science Glovebox (MSG), where various experimental programmes have taken place (BASS & GEL) [45–47].

In the near future, the ISS will offer many more opportunities, since it will host new facilities for microgravity combustion research, such as the Microgravity Wind Tunnel (MWT), SoFIE (Solid Fuel Ignition and Extinction) and SCEM (Solid Combustion Experiments Module).

Furthermore, the ongoing Saffire (Spacecraft Fire Experiments) experimental series takes place in the ISS supply vehicle Cygnus after delivery of the payload, and five flights have been completed [48–56].

2.1.6. Centrifuge

A centrifuge can be used to achieve higher gravity levels than Earth's, and NASA used one for flammability studies [57]. The Japanese Space Agency (JAXA) has a centrifuge rotating arm which has also been used for flammability experiments [58]. It has been demonstrated that buoyancy effects at higher gravity levels than Earth's can provide useful data in order to correlate flame spread from microgravity to several gravity levels [59]. In the Russian Federation, at the FGBU VNIIPO laboratory, a centrifuge system in a drop system can attain several gravity accelerations [19, 20]. NASA has recently expanded its capabilities to produce Martian and Lunar gravity levels in their drop tower. A centrifuge (drop bus system) can be allocated inside the 5.2 seconds drop tower [60, 61]. As a result, Lunar and Martian gravity levels can also be achieved in the drop tower and parabolic flights. However, the Lunar and Martian gravity time provided is short, and only specific phenomena with very short characteristic times can be studied.

2.2. Volumetric capacity

Different apparatus and combustion chambers have been utilised to carry out microgravity combustion experiments on solid fuels. The capabilities of the platforms can severely restrict the volumetric design of the combustion chambers (of tunnel rigs). Thus, the scientific objectives for any combustion project can also be limited by these constraints.

Figure 4 depicts the characteristic times, the sample size and volumetric capacity in the rigs that have been used for research projects on solid combustion in microgravity. As seen, in some of the drop towers, the volumetric capacity is large (NASA), but the specimen size still cannot be larger than 110 cm^2 due to the microgravity time restriction. In parabolic flights, rigs are restricted in size, and the sample size is also small, most often for safety reasons. On other platforms (satellites, sounding rockets and other Spacecraft), the volumetric capacity of the rigs is not improved, and the hosted samples are comparatively small, e.g. BASS (1 dm^3). On the contrary, the Saffire rig tunnel has a much larger volumetric capacity. Given the longer microgravity times and the large volumetric capacity of the oxidiser, larger samples can be burned. Similarly, the planned MWT can host mid-size specimens.

Another aspect to take into account is the productivity of each platform. Drop towers offer a high yield of experiments for parametric studies. Parabolic flights can also provide enhanced productivity. However, other platforms, especially Spacecraft, do not provide such flexibility. The future rigs, such as MWT, SoFIE and FLARE, will offer much higher flexibility than previous rigs used on Spacecraft.

In summary, selecting a microgravity platform depends on the type of problem to be studied, the sample dimensions and the required environmental conditions. For example, flame spread over an infinitely thick slab, spontaneous ignition or smouldering through porous media should be studied using spacecraft platforms.

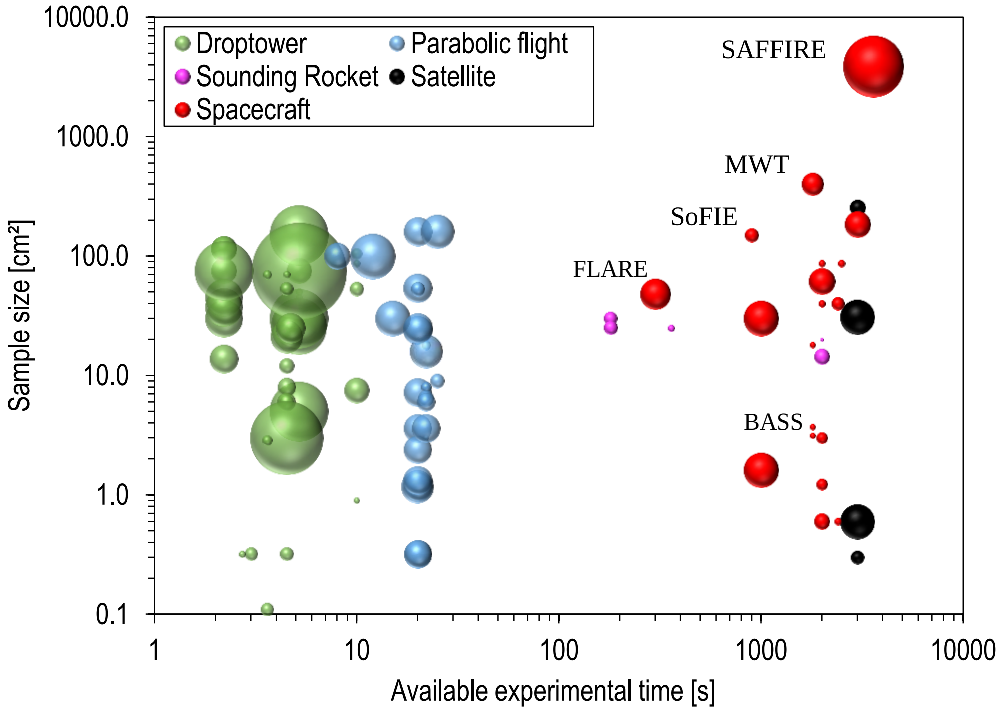

Figure 4 – Available experimental times and sample size in various experimental rigs and microgravity research platforms. The size of the data point shows the relative volume of the experimental environments. The corresponding references can be found in the Data-in-Brief.

2.3. Phenomena and fuel types

This section discusses which flammability phenomena have been studied in each microgravity research platform and which materials have been used for this purpose. The goal is to identify which flammability phenomena can be studied in each platform. The flammability behaviour of solid materials on Spacecraft are defined by ignition, flame spread, near-limit and smouldering. For observation of those phenomena, it is often essential to quantify the soot production, burning rate and heat release rate.

Ignition can be either piloted or spontaneous. For the piloted ignition, a small flame or ignition wires can act as the pilot; using ignition wires is the predominant technique used in microgravity experiments. In the case of spontaneous ignition, it can be due to conduction through the solid-phase from overheated wires (for wire jackets), or in a hot environment. Ignition due to intense radiative heating is also considered spontaneous ignition. For flame spread, three main scenarios studied in solid combustion are flame spread in quiescent conditions (no forced flow) and under forced flow – opposed or concurrent.

Figure 5 depicts the number of publications per flammability phenomena studied in microgravity. In some publications, more than one phenomenon was reported for experiments using various platforms. Therefore, the total number of publications per platform does not coincide with *Figure 3*. Across all microgravity research platforms, the most studied flammability aspect is flame spread. In drop towers, most studies have been reported for flame spread under quiescent or opposed forced flows. The characteristic time to establish a steady flame in such conditions can be achieved by employing thermally-thin fuels. It is difficult to attain a steady-state for concurrent flame spread experiments in drop towers [12] unless an extremely thin fuel is used or one with very low density. A similar trend is observed in parabolic flights and satellites where most flame spread studies focus on the opposed case or quiescent conditions. On Spacecraft, steady concurrent flame spread can be achieved, as longer microgravity times can be provided.

Near-limit phenomena have mostly been studied in parabolic flights and primarily for opposed forced flows. Studying near-limit requires longer microgravity times and also a large number of experiments. The flammability limits or extinction limits, more than being a physical parameter, map the regions where flame spread cannot be sustained.

As seen in *Figure 5*, the extinction boundary limits of various materials have been reported in several publications. These extinction limits can be a function of the oxygen concentration, the forced flow, the pressure level, the gravity level and other parameters. They are essential since the drawing of both branches of the limits (quenching and blow off) can help to determine the critical conditions at which flame is viable, where both curves collide, and hence the flammability of the material associated with the environmental conditions can be ranked [62].

It is somewhat surprising that ignition has received relatively less attention than some of the other phenomena given that NASA's prevention strategy relies on reducing the likelihood of ignition [6]. Most ignition studies have taken place in drop towers and parabolic flights, with only a very few on spacecraft platforms. This is probably due to the fact that ignition studies often require a rather substantial experimental matrix. It is also to be noted that spontaneous ignition has received little attention, and smouldering has only been briefly studied on Spacecraft. The characteristic times for the latter are notoriously long (>1000 s) and can thus only be achieved on Spacecraft. Spontaneous ignition leading to smouldering has not been reported.

Another phenomenon that has not received much attention is soot measurements, even though it is an essential aspect of the radiative transport phenomena for flame spread. Only very recently, studies on soot formation over insulated wires have been conducted [63–67], and this will be discussed in more detail later.

Burning rates are very challenging to measure using traditional gravimetric techniques in microgravity environments. Only visual diagnostic can be used to measure the mass loss of solid-materials. Thus, only a few studies have been reported on burning rates.

Lastly, heat release rates have not been studied parametrically and only in a few studies have been reported. Parameters associated with gas concentrations, combustion and burning of the solid material have only been reported in a few publications, as seen in *Figure 5*.

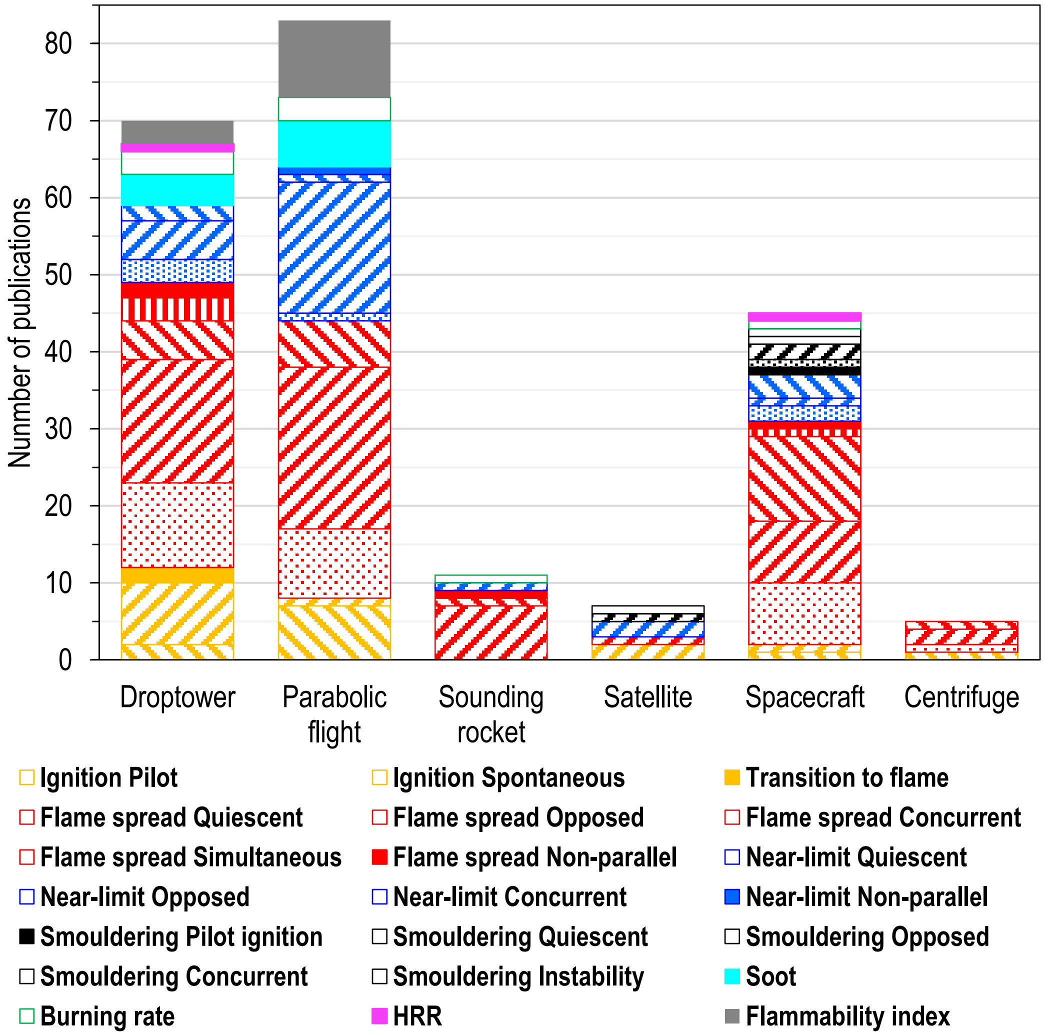

Figure 5 – Flammability phenomena studied in each microgravity research platform per number of publications. The studies selected to create this figure are pure experimental work, or experiments accompanied by numerical studies. The corresponding references can be found in the Data-in-Brief.

As seen in *Figure 6*, a range of materials has been tested in microgravity combustion experiments. Among these materials, there are thermoplastics (PE, PP, PS, PVC, Nylon, etc.), some thermosetting plastic (polyester, PUR, silicone, neoprene and rubbers), organic polymers such as cellulosic materials (wipes and paper), cotton fabrics, flame-resistant fabrics made of synthetic polymers (Nomex®, Kevlar® and Conex®), a few composites and other polymers. Many of the materials depicted in *Figure 6* are found in various applications on Spacecraft [8]. While testing them in microgravity provides direct information on their flammability behaviour, many materials have been investigated for fundamental studies. One example is a candle tested aboard Mir and STS [1,68], while another is the wax tested on Skylab [69]. The most widely used solid fuels for fundamental studies are cellulosic fuels and thermoplastics (Polymethyl-methacrylate and polyethylenes (PMMA).

Cellulosic charring fuels are mostly used in drop towers, where steady phenomena can be achieved (opposed flame spread) or where characteristic ignition times are easily achieved. Using an extremely thin cellulosic fuel for concurrent flame spread would allow achieving steady conditions [69]. Alternatively, if one wants to evaluate the flame spread over an infinitely thick fuel, then polyphenolic or a PUR foam slab would be ideal [70,71]. PMMA in the form of thin or thick flat samples (Biot number definition in thermal behaviour) and as rods and spheres is by far the most tested material. PMMA is an amorphous, non-crosslinked thermoplastic polymer, and it is very suitable for experimental studies due to its purity and homogeneity. It can be presented as extruded or cast; the former has a dripping behaviour, whereas the latter tends to drip much less and thus can be used to study steady flame spread [72]. Also, PMMA has very stable properties and does not char. As seen in *Figure 6*, researchers preferably use PMMA to study flame spread and near-limit across several platforms, but especially in parabolic flights and other platforms with longer microgravity times (more ideal for thermally-thick samples).

Notably, spheres of PMMA, and other thermoplastics (PE and PS) have been used to study the burning rate [73,74]. A few studies also report that the burning rate and heat release rates have been measured or empirically determined. Another type of material tested for ignition and flame spread, mainly in parabolic flights, is electrical wire insulation. The wire jackets tested are normally made of polyethylene, thermoplastic compounds with ethylene and other polymers. Only a few studies focusing on soot have only been reported with PMMA and LDPE wire jackets as solid materials [63–65,75]. For smouldering studies, foams (PUR) fuels have been selected given their porous properties [76].

As seen, the database of materials tested in microgravity is extensive, and new materials have been added recently. However, not all materials used on Spacecraft have been tested in microgravity [77]. Therefore, it is imperative to continue to investigate other materials (composites and new) and extend the pool of knowledge as pointed out in NASA's decadal review recommendations [6].

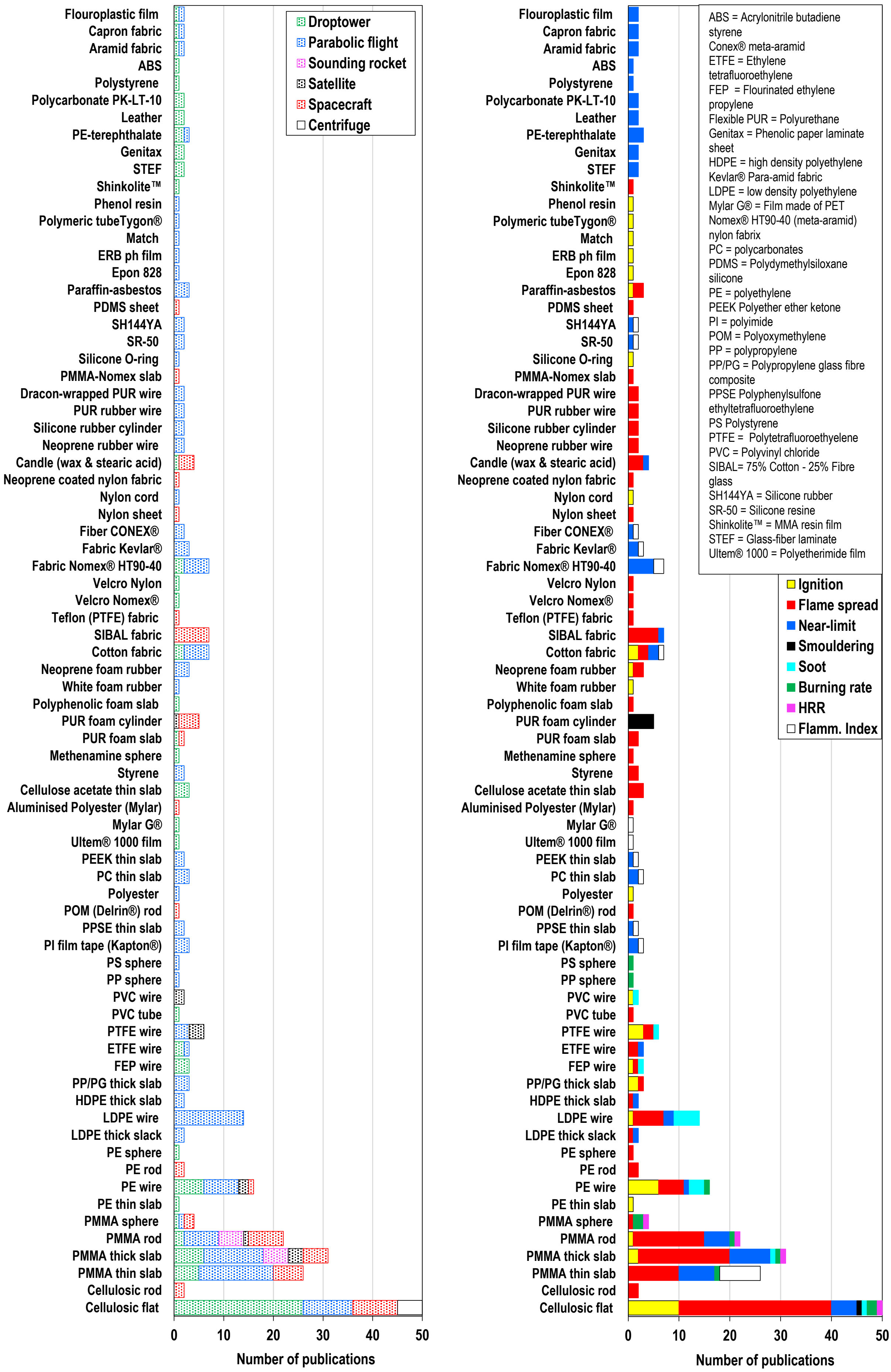
Flouroplastic film
Capron fabric
Aramid fabric
ABS
Polystyrene
Polycarbonate PK-LT-10
Leather
PE-terephthalate
Genitax
STEF
Shinkolite™
Phenol resin
Polymeric tubeTygon®
Match
ERB ph film
Epon 828
Paraffin-asbestos
PDMS sheet
SH144YA
SR-50
Silicone O-ring
PMMA-Nomex slab
Dracon-wrapped PUR wire
PUR rubber wire
Silicone rubber cylinder
Neoprene rubber wire
Candle (wax & stearic acid)
Neoprene coated nylon fabric
Nylon cord
Nylon sheet
Fiber CONEX®
Fabric Kevlar®
Fabric Nomex® HT90-40
Velcro Nylon
Velcro Nomex®
Teflon (PTFE) fabric
SIBAL fabric
Cotton fabric
Neoprene foam rubber
White foam rubber
Polyphenolic foam slab
PUR foam cylinder
PUR foam slab
Methenamine sphere
Styrene
Cellulose acetate thin slab
Aluminised Polyester (Mylar)
Mylar G®
Ultem® 1000 film
PEEK thin slab
PC thin slab
Polyester
POM (Delrin®) rod
PPSE thin slab
PI film tape (Kapton®)
PS sphere
PP sphere
PVC wire
PVC tube
PTFE wire
ETFE wire
FEP wire
PP/PG thick slab
HDPE thick slab
LDPE wire
LDPE thick slack
PE sphere
PE rod
PE wire
PE thin slab
PMMA sphere
PMMA rod
PMMA thick slab
PMMA thin slab
Cellulosic rod
Cellulosic flat
Droptower
Parabolic flight
Sounding rocket
Satellite
Spacecraft
Centrifuge
0 10 20 30 40 50
Number of publications
ABS = Acrylonitrile butadiene styrene
Conex® meta-aramid
ETFE = Ethylene tetrafluoroethylene
FEP = Flourinated ethylene propylene
Flexible PUR = Polyurethane
Genitax = Phenolic paper laminate sheet
HDPE = high density polyethylene
Kevlar® Para-amid fabric
LDPE = low density polyethylene
Mylar G® = Film made of PET
Nomex® HT90-40 (meta-aramid) nylon fabrix
PC = polycarbonates
PDMS = Polydymethylsiloxane silicone
PE = polyethylene
PEEK Polyether ether ketone
PI = polyimide
POM = Polyoxymethylene
PP = polypropylene
PP/PG = Polypropylene glass fibre composite
PPSE Polyphenylsulfone ethyltetrafluoroethylene
PS Polystyrene
PTFE = Polytetrafluoroethyelene
PVC = Polyvinyl chloride
SIBAL= 75% Cotton - 25% Fibre glass
SH144YA = Silicone rubber
SR-50 = Silicone resine
Shinkolite™ = MMA resin film
STEF = Glass-fiber laminate
Ultem® 1000 = Polyetherimide film
Ignition
Flame spread
Near-limit
Smouldering
Soot
Burning rate
HRR
Flamm. Index
0 10 20 30 40 50
Number of publications

Figure 6 – Materials studied in previous solid combustion investigations in microgravity per number of publications. On the left, the number of publication per materials is segregated further into the research platform where the material type was tested. On the right, the segregation is done according to the flammability phenomena studied. The corresponding references can be found in the Data-in-Brief.

3. Diagnostic systems

Conducting experimental research often requires dedicated diagnostic systems to measure the parameters of interests. Using a specific diagnostic system or measuring tool depends on the objective for each fundamental study, as outlined in *Table 2.* In microgravity combustion research, each research platform has limitations that can affect the choice of diagnostic procedures. For ignition, flame behaviour and smouldering, the interest relies on obtaining the gas-phase and solid-phase temperatures and visual recordings of the phenomena. Notably, for flame behaviour studies, it is crucial to quantify and characterise the flame geometry, the velocity profile around the flame and the soot distribution (for sooty flames). In the case of soot, sophisticated diagnostics are employed to provide the soot distribution and morphology. For measurements of the mass loss rate, as it is impossible to perform gravimetric measurements in microgravity, other methods (visual) to track the regression rate have to be used.

Table 2 – Summary of the diagnostic systems used to quantify various parameters in experimental studies conducted in microgravity.

Parameter/phenomenon	Diagnostic system
Temperature (gas-phase & solid-phase) and temperature gradient	Thermocouples, IR camera, Rainbow Schlieren, Holographic Interferometry, colour pyrometry, RGB pyrometry
Visual measurements for characterisation of ignition and diffusion flames	Motion cameras, Video camera with CCD sensors
Soot quantification	Video camera with CCD camera, light extinction (Beer-Lambert law), 2D extinction (Bouguer's law), tri-CCD + light attenuation, Intensified UV cameras, Laser-induced incandescence + ICCD cameras, Modulated Absortion/Emission (S-MAE), Broadband Absorption/Emission (B-MAE), colour pyrometry, RGB pyrometry
Soot temperature	Modulated Absortion/Emission (S-MAE)
Soot morphology	Thermophoretic soot sampling and transmission electron microscopy (TEM), Scanning Electron Microscope (SEM), Laser-induced incandescence (LII)
Mass loss rate	Visual diagnostics (CCD camera + backlighting technique),
HRR	Oxygen consumption calorimetry (ISS)
Smouldering	Thermocouples, Ultrasound imaging
Gas measurements	Multispectral intensified UV camera with various filters for each gas

3.1. Temperature measurements

For temperature measurements, the most straightforward technique is using thermocouples. Gas-phase and solid-phase temperature are needed to estimate the heat balance and assess the flame's behaviour over the solid fuel in different environmental and thermal conditions. The discrete use of thermocouples is an easy way to obtain accurate gas-phase temperature. These have been used in several experimental programs across all research platforms, as shown in detail in the Data-in-Brief. Nonetheless, solid-phase temperature measurements can be affected by the gas-phase because the solid surface retracts [78]. Moreover, there is a lack of accuracy to precisely determine the temperature gradient, which adds inaccuracies to estimating the heat back from the flame at the fuel surface [79]. Consequently, other diagnostic systems to measure or qualitatively analyse the temperature and temperature changes in the gas-phase and solid-phase have been used. These methods are holographic interferometry [17,80–84], rainbow Schlieren [23] and infrared cameras (IR) [27,29,35,80,85–88]. For IR cameras, a bandwidth from 3.8 to 4.28 μm to filter the radiation from the gas-phase is required to provide the solid-phase temperatures. These techniques allow quantifying the characteristic solid-phase lengths (pre-heat length and pyrolysis length) and the gas-phase lengths. Other diagnostic techniques can provide accurate temperature fields within the diffusion flame based on the soot characterisation and quantification, and these methods will be discussed later.

3.2. Visual measurements

Characterising ignition occurrence, flame geometry (e.g. flame length, standoff distance), and how it evolves to determine the flame spread rate can also be obtained through the most common visual diagnostic, video and photographic cameras and more sophisticated cameras. Compared to the first photographic cameras used in the first microgravity experiment 70 years ago, the current cameras offer a substantially better characterisation. The 16 mm motion camera used in the first microgravity research in the Skylab could not detect the dim-blue flame characteristic microgravity environments (diffusion-radiative regime), so that had to be directly observed by the operators [11]. Research conducted from the 1970s to the 1990s in drop towers and parabolic flights used colour cameras with 100 to 400 fps, which was considered high-speed at the time [10,89–95]. From the 1990s onwards, the introduction of cameras with CCD (Charged Couple Device) sensors has become dominant in the research conducted until nowadays across all microgravity research platforms, see *Figure 7*. This technology has enabled the video cameras to obtain sharper images for each frame obtained to the detriment of the more considerable amount of frames obtained.

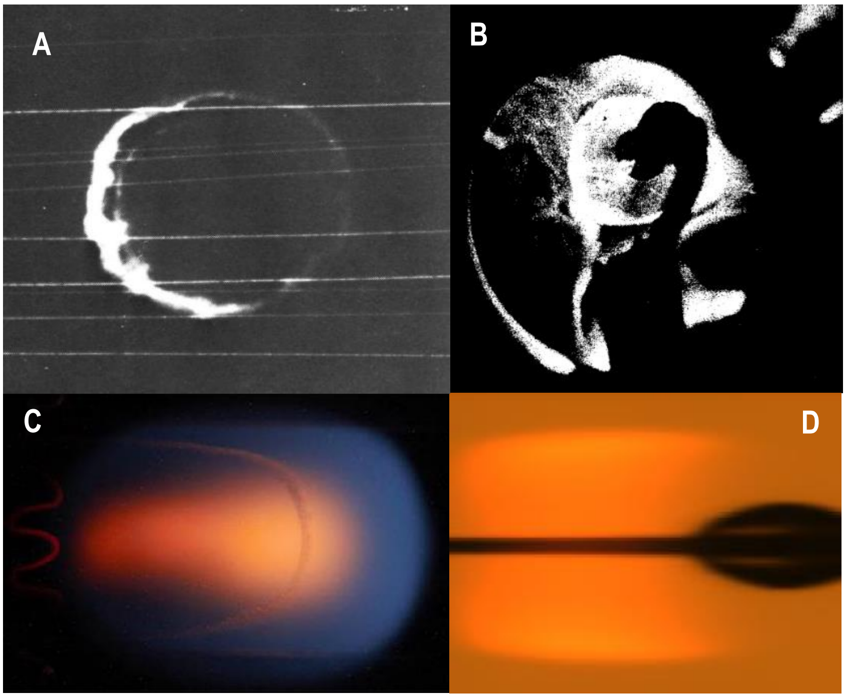

Figure 7 – Images of diffusion from various experimental s D). Image A is the burning of cellulose in a drop tower experiment [89]. *Image B is the burning of polyurethane foam during the Skylab tests* [11]. *Image C is opposed flame spread over a thin and flat PMMA sample* [96], *while image D is an opposed flame over a polyethylene coated wire* [63].

3.3. Soot quantification

The quantification of soot can be done by providing global properties (characteristic residence time, luminous flame length, smoke point) of a jet diffusion flame. Detailed spatial quantification of soot can be used to extrapolate soot temperatures and temperature gradients within the flame. Most of the diagnostics for soot studies, whether complex or modest, have focused on gaseous-jet diffusion flames, as will be discussed in the following, as it can be very useful for diffusion flame problems arising from condensed-matter, as well.

Sunderland, Urban and co-workers [97,98] employed simple video cameras or CCD cameras to reveal the global properties of diffusion flames in microgravity experiments. Fujita [99] used a conventional video camera to qualitatively discuss the soot formation on microgravity diffusion flames established over a paper sheet and butane gas jet diffusion flame. However, other complex techniques are needed to provide spatial quantification of soot formation.

Light extinction (or laser attenuation) is a widely used technique to quantify aerosol particles by using the Beer-Lambert law [100]. The principle behind the method relies on the scattering of light through saturated media; the beam light is absorbed, reflected and transmitted through the body of particles (in this case soot in diffusion flames). The ratio of absorbed light to incident light defines the extinction factor (If transmitting is the dominant phenomenon). This non-intrusive technique can be used to determine soot volume fraction within the flame, and it allows researchers to evaluate soot formation. The volume fraction is a useful property in sooty flames because it affects the amount of radiative heat transfer [101]. The first techniques were based on point-by-point analysis of the soot field (highly time-consuming), while an improved method based on optical tomographic reconstruction from a video image was developed by Greenberg and Ku [101] to describe a spatial (two-dimensions) soot volume fraction. This full-field laser-light extinction technique was used to quantify the soot volume fraction of axisymmetric laminar gas-jet diffusion flames [102–105]. Recently, the technique was used to study the soot generated during the transition from ignition to flaming over wire jackets in microgravity [106,107].

These methods did not account for the luminosity changes under the effect of forced flows, which can affect soot oxidation, and they were thus not ideal for describing such a flame type [75]. Fuentes et al. [75] used a two-dimensional extinction method based on Bouguer's law [108] for estimating the extinction factor in a boundary-layer established diffusion (non-axisymmetric) flame over a solid fuel. In their method, the light beam emitters are green LEDs. This scattered light passes through the flame and then it is received by a monochrome CCD camera with a filter for soot bandwidth. To estimate soot concentration from their method is not straightforward as flames are three-dimensional; corrections are required [75]. Later, Legros et al. [109] corrected the diffusion flame's three-dimensional effect by using chemiluminescence with a tri-CCD camera and a line-of-sight light attenuation technique. In their work, they tracked the soot and chemiluminescence with three cameras with the corresponding bandwidth filters (one for soot and the other for chemiluminescence). This method allows measurements from multiple directions (opposite to extinction measurements). Thus, corrected local soot concentrations are obtained, and soot volume fractions can be estimated. Fuentes et al. used the same method to study the soot trajectory [110]. With the appropriate filter, intensified UV cameras can also be used to track the chemiluminescence and soot, as it was used in the past for flames over solid fuels [34].

Fuentes et al. [111] used chemiluminescence measurement along with laser-induced incandescence to provide the soot volume fractions. In the laser-induced incandescence (LII) method, a laser sheet is emitted and passes through the flame; this laser energy excites the soot particles (intrusive). Then, an intensified charge couple device (ICCD) camera with a filter collects the images. For chemiluminescence measurements, another ICCD camera with its corresponding filter is needed. This method has some complications associated with the laser affecting the soot particle's radiative heat for soot temperature extrapolations [112]. Another technique with non-intrusive laser levels is the Modulated Absorption/Emission (S-MAE) technique, which can provide soot volume fraction and soot temperature measurements [113]. Guibaud and co-workers [112] extended the S-MAE technique with an improved optics settings (LEDs with broadband tools) to create the broadband absorption/emission (B-MAE) technique, which requires less space than S-MAE and can fit the spatial constraints of parabolic flights [112]. The B-MAE technique implements Tomographic Three Colour Spectrometry, where a tri-digital CCD camera collects the red, green and blue intensities emitted by the soot (has three spectral bands to discriminate those colours). Thus, spatial (2D) measurements volume soot fraction and soot temperature can be estimated with the corresponding numerical post-processing tools, as they did on opposed flame spread over PE insulated wires in microgravity [63,65–67].

Another simpler and more affordable technique is the Colour-ratio pyrometry, which can track soot formation and temperature changes within the flame. Ma et al. [114] used that technique on gaseous co-flow flames in the Microgravity Science Glovebox (MSG) on the ISS. Similarly, RGB pyrometry technique with affordable digital cameras has been used to obtain the flame's spatial temperature measurements [22,115]. Such a technique is less complex and can fit in very restrictive platforms, though the accuracy of the measurements can be compromised.

3.4. Soot morphology

Soot morphology provides qualitative information on the soot formation, which can be used to compare normal and microgravity environments. For soot morphology (particle diameter) and soot distribution (size distribution), thermophoretic soot sampling and transmission electron microscopy are commonly used techniques. Soot samples are collected and processed in a transmission electron microscopy (TEM) or Scanning Electron Microscope (SEM) and image analysis post-processing. This technique has been used on gaseous diffusion flames in microgravity [105,109,116] and on diffusion flames established on solid fuels [99,106]. The laser-induced incandescence (LII) method can also be used for soot morphology studies [112].

3.5. Mass loss rate and heat release rates

During burning in microgravity, mass loss rate measurements are difficult to accomplish with gravimetric techniques that are commonly used in normal gravity. Visual diagnostics can be used to track the condensed-phase regression during experimental work in microgravity with easy geometries. Droplet combustion of solid spheres benefits from the D^2-law to provide the condensed fuel's burning rates, as it was done in microgravity tests [22,73,74]. A few studies have tried to provide the mass loss with visual diagnostics in other studies with more complex geometries, flat plates or wire jackets. Citerne and co-workers [117] retrieved the burning wire jacket's mass burning rate with CCD camera and a backlighting technique. Such method requires the sample to be thin and uniform throughout the process. If the instantaneous flame spread rates are known, a simple mass balance can then be used to estimate the mass burning rates [96]. By using the same principle, average burning rates can be estimated for the problem's total duration [69,118].

If the HRR's burning rates from solid droplet combustion experiments and the material properties are known, then the HRR can be estimated [74]. For oxygen calorimeter analysis to be used, it is required to measure the concentration of O_2, CO and CO_2 during burning. Two diagnostic systems are installed aboard the International Space Station within the MSG (Microgravity Science Glovebox), the Compound Specific Analyser-Combustion Products (CSA-CP) and the Carbon

Dioxide Monitor (CDM). The first can monitor the O_2 and CO concentrations and the second can track the CO_2 concentrations. Thanks to these diagnostics, combustions parameters can be estimated such as oxygen depletion, gas concentration changes, CO/CO_2 ratio, heat release rate and the global equivalence ratio [46,119].

3.6. Smouldering

In smouldering, various and distinctive processes occur, such as smouldering propagation and self-sustained smouldering [120]. Also, ignition of porous media can lead to smouldering, which could also lead to flaming combustions. Thus, it is essential to measure in-depth reaction changes over time to track the smoulder propagation front and derive the smoulder propagation rates or to look at self-sustaining smouldering. It is possible to monitor the propagation front with a discrete thermocouple embedded in the sample [121–123]. Another technique used during smouldering tests aboard the Space Shuttle [124,125] was ultrasound imaging. Permeability histories were obtained with an ultrasound imaging system. This technology benefits from the change of structure on open-cell foam undergoing smouldering. Both the unburnt foam and the char layer left behind the smoulder propagation front have different permeability, thus contrasting attenuation to ultrasound. For smouldering instabilities over a thermally-thin fuel, a visual diagnostic would suffice, such as the one used to study finger-like smouldering [126].

3.7. Gas measurements

A multispectral intensified UV video camera with a six-filter internal wheel hosting bandwidths in the spectrum that corresponds to each combustion gas, (CO_2, CO, MMA vapour and H_2O) was used by Olson et al. [30,127] during the DARTFire testing programme. There were also other filters for soot and chemiluminescence. This ad-hoc technology allowed the researchers to use only one camera to measure gases species distribution over a sample during combustion in such a contained space (sounding rocket). In the recent Saffire tests, several sensors on the Cygnus spacecraft cargo measured oxygen concentration, carbon dioxide levels, and smoke concentration [52].

4. Conclusive remarks

All the previous peer-reviewed articles, relevant conference articles, and technical reports addressing experimental studies of solid combustion in microgravity have been used and synthesised to produce the current literature review. This paper has presented a detailed overview of the technical aspects and methods behind previous experimental studies reported in the past in two chapters. The goal was to synthesise and provide a precise classification of the technical aspects of solid combustion in microgravity.

The available research platforms on Earth were established during the period ranging from the 1970s to the 1990s (drop towers, parabolic flights and sounding rockets), but the worldwide capacity has not been extended substantially since then. Currently, existing drop towers are being upgraded (Bremen and NASA). The research platforms located or planned on Spacecraft (International Space Station or Cygnus), sounding rockets and satellites (Chinese Space Programme) offer an extended experimental matrix to perform fundamental and experimental studies. However, there are several constraints and difficulties associated with each research platform. Thus, the choice of using a research platform to conduct research will depend on the characteristic time scales and the length scales of the particular phenomena to be studied.

Many materials, mainly plastic and cellulosic, in various shapes (sheets, slabs, rods, wire protectors and spheres) have been employed in experimental studies of solid materials in microgravity environments. Most of these experimental studies have been carried out to address either programmatic or scientific needs, or sometimes both. The most studied materials are cellulosic and poly(methyl methacrylate) in various forms, while the most common phenomena studied are ignition, flame spread and flame extinction. There is also a demand from Spacecraft Industry (Decadal review) [6] to study new and more complex materials.

The quantification of various phenomena in solid combustion requires several specific diagnostic systems and apparatus. The volumetric capacity, weight and technology constraints within each research platform can hinder the quantification of the phenomena. The diagnostic systems have improved substantially since the still camera used by Kimzey et al. [9] in their experiments. Another visual diagnostic system can also help quantify spatial temperatures in the solid-phase and gas-phase, which is advantageous compared to the discrete allocation of thermocouples. Also, the quantification of soot is relevant to correctly predict the radiative heat balance in flame spread phenomena. Thereby, the advance diagnostic systems can extend the window of opportunity for solid combustion research in microgravity.

Studying the various phenomena arising in solid combustion during microgravity can be a complex matter as many constraints hinder the objective of any investigation. Thus, to investigate any particular phenomenon in a specific platform, the relevant aspects to take into account are the characteristic time-scale and length-scale of the problem, the diagnostic system needed to quantify/characterise the phenomena, and the level of flexibility required in the investigation. Thus, for any researchers involved in the aforementioned topic, it would be very beneficial to have detailed information of previous relevant studies. The current manuscript offers a broad detailed picture for researchers, including an extensive list of references classified according to various categories. The compendium of studies and literature used and tabulated (see Data-in-Brief) in the current investigation can also help to design new experimental studies.

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