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A discussion on policies and regulations governing the risks associated with radiation exposure for space tourism flight participants

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ABSTRACT

Within the next decade it is likely that the space tourism industry will grow and the number of humans travelling into space via commercial entities such as Virgin Galactic and Blue Origin, will increase significantly. Current space tourism ventures focus on short duration sub-orbital flights and visits to Low Earth Orbit (LEO). In the next few decades, a journey into space could become as normal as a transatlantic flight. During these new commercial ventures, the effects of cosmic radiation exposure, especially during sudden changes in space weather, such as ground level enhancement (GLE) or solar particle events (SPEs), could have significant health implications for crew and passengers. Such changes in space weather could expose space tourists to radiation doses in excess of the recommended maximum 1 mSv yearly effective dose uptake for a member of the public and 20 mSv yearly effective dose limit for those working with radiation (ICRP Publication 103, 2007 [1]). Domestic legislation and regulation focussing on potential radiation exposure for space tourists is limited and largely untested; there is heavy focus on conventional risk and wider safety, with guidance stemming from regulation of commercial high-level flights, which are significantly different to space tourism enterprises.

In this paper we consider the current domestic legislation and regulations adopted by the USA and the UK, as two examples of launch nations with legislation and regulation relating to space tourism activities. We acknowledge and consider feedback we have received from the UK Civil Aviation Authority (CAA) on current regulations and topics outlined in this paper. We discuss whether current legislation and regulation offers sufficient protection for space flight participants (space tourists), and whether risk is balanced appropriately between the operators who provide space tourism services and those taking part. Finally, we discuss the routes to acceptance of the radiation risks and make recommendations for legislators, regulators and operators to support them in ensuring that the risks are managed appropriately while also supporting the development of the industry.

1. Introduction

Crew and passengers [1] aboard spacecraft travelling at very high altitudes or in orbit are vulnerable to radiation exposure from natural non-terrestrial sources, i.e., galactic cosmic rays (GCRs). These low levels of radiation can be subject to sudden increases due to changes in space weather, i.e., solar particle events (SPEs) and associated ground level enhancements (GLEs).

The law around space flight and its associated risk liability is complex. Space law incorporates a mix of international law (such as international agreements, treaties, conventions), domestic legislation, and guidance which together govern space-activities.

In this paper we consider the current domestic legislation and regulations adopted by the US Federal Aviation Administration (FAA) and the UK Civil Aviation Authority (CAA) to regulate space activities, specifically the associated potential radiation risk. We discuss whether the current regulations offer sufficient protection for space flight passengers and crew and whether they balance the risk appropriately between the operators who provide space tourism services and those taking part.

2. Background

2.1. Radiation risk

Exposure to low levels of background natural radiation is part of everyday life. Most people are not aware of this exposure and the

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Abbreviations

CAA	UK Civil Aviation Authority
CSLA	Commercial Space Launch Act of 1984
GCR	Galactic Cosmic Ray
GLE	Ground Level Enhancement
EPA	Environmental Protection Agency
FAA	US Federal Aviation Administration
HSE	UK Health and Safety Executive
ICAO	International Civil Aviation Organisation
ICRP	International Commission on Radiological Protection
IRRs	Ionising Radiation Regulations
LEO	Low Earth Orbit
NOAA	National Oceanic and Atmospheric Administration
NRC	Nuclear Regulatory Commission
ONR	Office of Nuclear Regulation
OSHA	Occupational Safety and Health Administration
SSC	Surrey Space Centre
SEP	Solar Particle Events
UNOOSA	United Nations Officer for Outer Space Affairs
UNCOPUOS	United Nations Committee on the Peaceful Uses of Outer Space
USA	United States of America
UK	United Kingdom
UKSA	United Kingdom Space Agency

potential risks to our health, for example a ~80 μSv effective dose from a commercial flight from UK to USA (Public Health England, 2010 [2]).

Exposure to elevated levels of ionising radiation (mSv range), such as those possible during GLE or SPE events, has been noted by the UK Health Protection Agency [2], to potentially "cause damage to DNA, lead to mutations, uncontrolled cell division and lead to malignancy". The effects of such rapid changes in space weather and the observed radiation exposure could have long term health implications for future high altitude and space tourism flight crew and passengers [3]. Ranging from a minor increase in the risk of health defects to serious health implications such as cancers and malignancy.

There has been significant terrestrial risk assessment of radiation exposure as part of the evolution of the nuclear industry and its risk assessment process [4]. This is unlike the space tourism industry, which is still in its infancy [5]. M. Kim [6] and others (e.g., S. McIntosh, 2019 [7]), discussed the potential risk assessment for astronauts from radiation exposure noting that assessments had focused on long duration missions outside LEO and did not consider those on a short trip to space as a tourist. Thus, there is still significant work to be done to assess the unique risk of the exposure environment for space tourist flights and the supporting guidance/regulation.

2.2. Space law

2.2.1. Outer Space Treaty

Space law has its origins in the Cold War era, when the Soviet Union and the USA were engaged in a space race to develop the first satellites, manned missions, and intercontinental ballistic missiles. As space activities increased, there was a growing need for a legal framework to regulate the use of outer space and prevent conflicts. The first major international agreement on space law was the Outer Space Treaty of 1967.

The Outer Space Treaty (UNOOSA, 1967 [8]) provides the basic framework on international space law. Through a series of core principles, such as that states are responsible for national space activities whether carried out by governmental or non-governmental entities. Therefore, for states that have signed the treaty (which include the USA and the UK), commercial space objects and their crews are subject to the jurisdiction of the state from which the space object is launched or the state in which the space object is procured. This means that any domestic safety regulations that apply to individuals in the state from which the space object is launched or the state in which the space object is procured should also apply to individuals above the Karman Line (i.e., an altitude above the Earth which is considered to be the boundary of outer space ~100 km [9], who are aboard a spacecraft launched from or procured in that state.

In the US the Occupational Safety and Health Administration (OSHA) regulates workplace safety and potential radiation exposure. It follows that any workplace in which workers might be exposed to ionising radiation is subject to OSHA regulations, this includes workplaces which are in outer space. In the UK the equivalent would be the Health and Safety Executive (HSE) and the Health and Safety at Work Act 1974 (including the Ionising Radiation Regulations 2017 [10]).

2.2.2. Further international treaties

Further treaties were subsequently agreed and introduced to progress the development of international space law, including the Rescue Agreement of 1968, the Liability Convention of 1972, the Registration Convention of 1976 and the Moon Treaty of 1979. The majority of these treaties have been ratified by those nations who are most active in space. The Liability Convention contains provisions confirming that nations are responsible for all spacecraft and space objects which are launched from their territories, and that any claim made under the Liability Convention must be made by one nation against another.

International treaties are notoriously difficult to agree and, even where a treaty has been agreed and ratified, the enforcement of treaty provisions against and between its signatories is challenging.

2.2.3. Domestic legislation

Various nations have developed their own domestic legislation and regulation to control the space activities of their citizens and corporations, partly to ensure compliance and manage liability under international treaties and partly to ensure that any domestic space activity is carried out safely. It is in domestic legislation where provisions relating to radiation protection for members of the public on space tourism flights may be found, but even where such provisions do exist they are still very much in their infancy.

3. Research scope

To assess and discuss the current policies and regulations associated with radiation risk management for space tourism, as well as the potential future legislation, we proposed the following research questions to be answered within this paper.

- **Research Question (RQ) 1**: Identify the scope and limitations of the current legislation introduced by the USA and the UK, that relate to the safety of members of the public engaged in spaceflight activities with potential radiation risk.
- **Research Question (RQ) 2**: Make recommendations on future guidance and regulations for space tourism flights to mitigate potential radiation exposure and the associated risks.

Note: this paper focuses on potential space tourism flights above the Karman Line and below 408 km (maximum orbit for the ISS) (ESA Publication SP1201 [11]), noting that flights outside of this environment would likely be interplanetary, and thus subject to a significantly different exposure and risk environment. Further, the focus is on the

regulation associated with spacecraft crew or space tourists/passengers, generically referred to within this paper as 'space flight participants'.

4. Regulatory framework

We have selected the USA and the UK as two examples from the small number of nations which have introduced legislative frameworks with commercial space flights in mind.

The following subsections provide a background on the current flight regulators for the USA and UK, as well as identifying the existing regulatory frameworks which are applicable to space tourism operations.

4.1. USA and UK flight regulators

4.1.1. USA Federal Aviation Administration

The Federal Aviation Administration (FAA) is the USA's agency responsible for civil aviation safety. The FAA is involved in regulation of civil aviation, operating air traffic control, and regulating USA commercial space transportation/travel. Specifically, they regulate and encourage the USA commercial space transportation industry, which includes space tourism. The FAA licenses commercial space launch activities and private launches of payloads on space launch vehicles.

4.1.2. UK Civil Aviation Authority

The Civil Aviation Authority (CAA) is the UK's aviation regulator. They ensure that the aviation industry complies with the relevant regulations, safety standards and manages risks accordingly. The CAA is responsible for the licensing and regulation of UK spaceports and spacecraft, this includes potential space tourism.

4.2. Radiation regulation

For potential radiation exposure the International Commission on Radiological Protection (ICRP) specifies an occupational effective dose limit for radiation workers of 20 mSv per year and a 1 mSv limit for members of the public (ICRP Publication 103, 2007 [1]). These ICRP limitations and associated guidance feed directly into worldwide regulation regarding control of radiation exposure, which includes aviation and space travel.

In comparing regulation for potential space tourism activities, we have also looked at terrestrial regulations and guidance, as these have often formed the basis for space & aviation legislation. We have provided a high-level summary of the relevant terrestrial legislation in the following subsections. However, it is noted that there are several limitations to applying terrestrial radiation regulations to space tourists, due to the unique and varying exposure environment of space.

4.2.1. USA radiation regulation and associated legislation

4.2.1.1. USA terrestrial radiation exposure regulation. In the USA, the radiation exposure limits for individuals who are exposed to radiation in terrestrial environments are established by the Environmental Protection Agency (EPA) and the Nuclear Regulatory Commission (NRC).

The EPA regulates radiation exposure in the environment, including exposure from natural and man-made sources such as radon, x-rays, and radioactive materials. The EPA has established radiation exposure limits for the general public and for occupational workers who may be exposed to radiation in the workplace [12].

The NRC regulates radiation exposure from nuclear facilities, such as nuclear power plants and nuclear waste storage facilities. The NRC has established radiation exposure limits for workers at nuclear facilities and for members of the public who may be exposed to radiation from such facilities [13].

4.2.1.2. USA space flight regulation. The primary law that governs commercial spaceflight operations in the United States is the Commercial Space Launch Act of 1984, as amended (CSLA).

In addition to the CSLA, the FAA also enforces regulations that establish requirements for the safe operation of commercial spaceflight vehicles. These regulations include Title 14 of the Code of Federal Regulations (CFR) [14], which sets forth requirements for obtaining a license to conduct commercial spaceflight activities.

The FAA has also issued guidance documents, such as Advisory Circulars [15], that provide additional guidance on specific aspects of commercial spaceflight safety, including radiation exposure. For example, FAA advisory AC 120-61B "In-flight Radiation Exposure", provides guidance on radiation protection requirements for commercial spaceflight crew.

The regulations adopted by the USA establish radiation exposure limits for crewmembers of commercial spaceflight vehicles. These limits are based on recommendations from the National Council on Radiation Protection and Measurements (NCRP) and the ICRP. Fig. 1 summarises the basis of the USA space flight regulation, including the regulatory and legislative documents that are applicable to space flight operations and the associated risks.

Overall, the regulation of radiation exposure for space tourists in the USA is based on a combination of laws, regulations, and guidance documents that are designed to ensure the safety of individuals who participate in commercial spaceflight activities. There is no single overarching document or regulation for specific space tourism activities.

4.2.2. UK radiation regulation and associated legislation

4.2.2.1. UK terrestrial radiation exposure regulation. In the UK, the regulation of radiation exposure for individuals who are exposed to radiation in terrestrial environments is overseen by the Health and Safety Executive (HSE), the Office of Nuclear Regulation (ONR) and Public Health England (PHE). The HSE and PHE provide guidance on radiation protection and establish radiation exposure limits for workers and the general public.

Note: within the UK domestic health and safety laws (such as the Health & Safety at Work Act 1974) could be applicable to space flight activities (analogous to the nuclear and aviation industries).

4.2.2.2. UK space flight regulation. In the UK, the regulation of radiation exposure for crewmembers of commercial spaceflight vehicles is undertaken by the CAA.

The CAA regulates commercial spaceflight activities in and from the UK, predominantly through the Space Industry Act (SIA) 2018 and the Space Industry Regulations (SIR) 2021, which requires operators to obtain a license to conduct spaceflight activities and specifies key requirements (including safety and environmental). The CAA also provides guidance to assist potential licensees with launch activities, i.e., CAP 2213 [16].

Part 9 of the SIR impose restrictions on the maximum effective dose

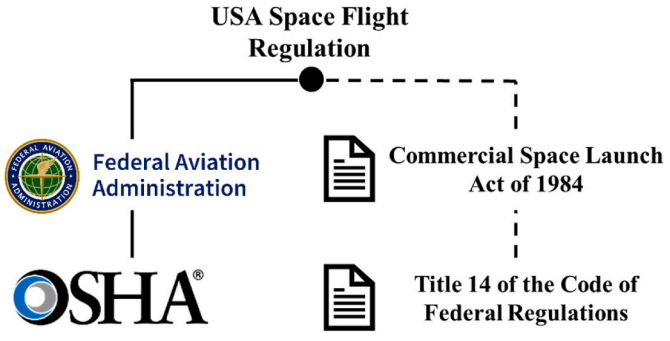

Fig. 1. USA Space Flight Regulation, showing relevant government agencies and legislation for flight operations.

of cosmic radiation to which spaceflight operators may expose their crews in a calendar year, namely, 6 mSv for crew members and 20 mSv for classified crew members; however, these restrictions do not apply to non-crew (such as space tourists).

In addition to the SIA and SIR, the UK Air Navigation (Cosmic Radiation: Protection of Air Crew and Space Crew) Order (ANO, 2019) imposes restrictions on the amount of cosmic radiation to which operators may expose their crews. Specifically, it sets out the effective dose limits per calendar year for a crew[1] member. The ANO forms the basis of regulation in the UK for very high altitude flights and could potentially be applied to future space tourism. The ANO sets out effective dose limits 1 mSv for a CAA non-authorised operator crew member (i.e., no SIA Licence, (or equivalent), approved training or declaration to the CAA), members of the public would be treated as non-authorised crew, and 6 mSv for a CAA authorised operator crew member. It should be noted the ANO covers a relatively small number of commercial aviation operations, as the vast majority of commercial (and some non-commercial operations) are still governed by the retained EU regulations that are in force following the UK leaving the European Union. The ANO is mainly used by the CAA for low-altitude rocket launches (i.e., ones that don't qualify under the Space Industry Act and Regulations); these rocket permissions are granted under Article 96 of the ANO.

In addition to the regulation and guidance provided by the CAA, the UK Space Agency (UKSA) also provides guidance on radiation exposure limits for crewmembers of commercial spaceflight vehicles. Note: this guidance is based on recommendations from the ICRP for space activities.

Fig. 2 summarises the basis of the UK space flight regulation, including the regulatory and legislative documents that are applicable to space flight operations and the associated risks.

4.3. Informed consent

As a key part of the regulation of space flight operations, specifically those activities involving crew and space flight participants in both the USA and the UK, is to use a process known as "informed consent". Informed consent is used to provide prospective participants with comprehensive information about the potential risks involved with space travel.

Informed consent is designed to ensure that individuals are fully aware of the potential risks and have sufficient necessary information to make a decision on whether to participate on flights, and a willingness to accept said risks. The process requires a transparent communication from the commercial space flight entity, potentially detailed disclosures of technical information and an accurate/complete risk assessment of all the potential hazards associated with a flight. The use of informed consent continues to be the norm for current space tourism activities.

5. Space policy and regulation discussion

We have considered the regulatory frameworks adopted by the USA and UK, and noted that the scope of the frameworks provides very limited regulatory protection to potential space flight participants from the risks associated with cosmic radiation.

We understand that the rationale for this, in part, is that the perceived risk to space tourists is considered to be very low, especially as there have been no large space weather events for decades. With no recent events complacency starts to set in with regards potential risks, a similar example were the effects of Eyjafjallajökull volcanic eruption and subsequent ash cloud on aviation in 2010. Further, as space tourism is an emerging industry, with a limited number of space flight participants the perceived risk is considered to be low. However, as space tourist flights increase in volume and duration the risks will increase.

The current limitations around lack of radiation exposure data, standards, research and legislation will need to be addressed to ensure appropriate and efficient regulations are in place for commercial operations.

The following subsections discuss the scope and limitations in the current legislations (identified in Section 4), which, relate to safety of members of the public and crew from potential radiation exposure risk (RQ1). We make recommendations for future guidance and regulations relating to space tourism flights and potential radiation exposure (RQ2) based on the perceived limitations of existing legislation.

5.1. Regulatory framework

The regulatory frameworks established by the USA and the UK have been designed primarily to cater for commercial space transportation activities, such as launching and re-entering spacecraft. They consider potential hazards to crew but set minimal or no specific requirements to ensure the protection of space tourists.

Space tourism is a relatively new industry, and the regulatory frameworks established by these agencies are still evolving. There are many technical challenges associated with spaceflight that are not present in the aviation industry, which includes exposure to elevated radiation levels (i.e., space weather). As the industry evolves the regulations will need to continue to evolve to meet the requirements of the industry and ensure the safety of space flight participants. The FAA and CAA, which have little or no experience of regulating space tourism activity, will need to work with industry to develop their understanding of the risks and adopt effective means of regulating the sector.

5.2. Space policy and legislation analysis

5.2.1. USA space flight participant analysis

The FAA regulates space flight under the CSLA by issuing licenses to commercial companies for launches and re-entries. Any licensed launch or re-entry may then be subject to requirements protecting space flight participants (i.e., those persons who are not crew members and not federal employees, meaning that they are not protected under the OHSA).

The Commercial Space Launch Amendments Act 2004 (CSLAA), which amended the Commercial Space Launch Act (CSLA) to authorise the FAA to license commercial suborbital space tourism, imposed minimal obligations on space flight operators to protect space flight participants.

The CSLA went so far as to prohibit the FAA from regulating the design or operation of launch vehicles to protect the health and safety of crews and space flights participants initially until the October 1, 2015, however this has continued to be renewed until at least October 2023. The CSLA does require that all space flight participants provide written informed consent to the technical risks of human space flight.

Legislation passed in Florida on 1 July 2023 (CS/SB 1318 [17]) goes further by exempting spaceflight operators from liability for injury to or death of a participant (meaning an individual who is not crew or a government astronaut) or crew resulting from spaceflight activities, as long as they do not act (or fail to act) with gross negligence or wilful or wanton disregard to participant or crew safety, do not intentionally injure the participant, and do not have actual knowledge of an extraordinarily dangerous condition not inherent in spaceflight activity.

The spaceflight operator would only liable if it had actual knowledge of an extraordinarily dangerous condition that is not inherent in spaceflight activities. Radiation is an inherent dangerous condition (and an operator would not have advance knowledge of GLEs or SPEs)

[1] Note: "crew" is denoted in the ANO as "those persons carried in an aircraft for the purpose of performing duties in the interests of the safety of the passengers" or "members of the flight crew". There is no direct mention of the protection of passengers, the ANO only refers to crew. Further, exceptional events, such as rapid changes from space weather, are excluded from the defined dose limits.

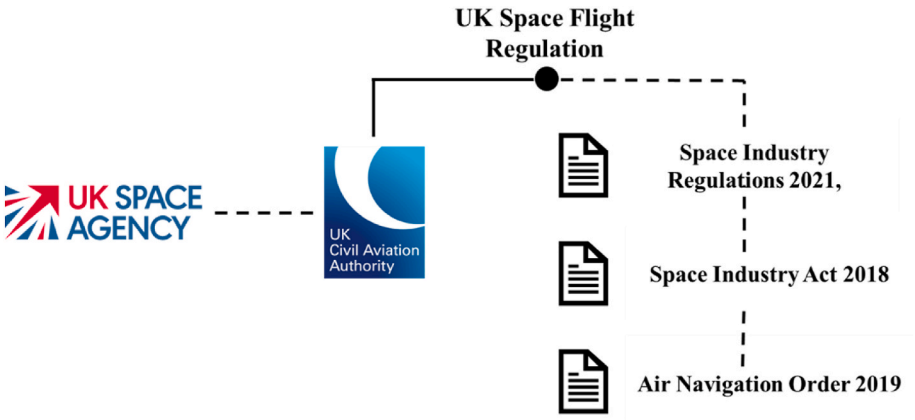

Fig. 2. UK Space Flight Regulation, showing relevant government agencies and legislation for flight operations.

therefore this example of exclusion of liability would leave participants negatively affected by radiation with no recourse.

To be exempted a spaceflight operator needs to distribute a warning to the participant or crew, who must sign it. The warning (copied below) is a very short statement: it clearly does not provide full and complete disclosure of the risks involved.

> "WARNING: Under Florida law, there is no liability for an injury to or death of a participant or crew in a spaceflight activity provided by a spaceflight entity if such injury or death results from the spaceflight activity. Injuries caused by spaceflight activities may include, among others, injury to land, equipment, persons, and animals, as well as the potential for you to act in a negligent manner that may contribute to your injury or death. You are assuming the risk of participating in this spaceflight activity".

Florida has only very recently introduced this legislation and it will be interesting to see how this sits with the informed consent concept and whether this impacts prospective space tourists seeking to take flights from Florida. It will certainly be attractive to operators by reducing their liability and, no doubt, insurance costs and this may result in other states or nations following the same path.

Legislators and regulators across the globe often face difficulties in regulating innovative and fast moving industries, as the technology and market often evolve faster than the legislation. There is a balance to be struck: on the one hand using effective regulation to ensure that activities are undertaken safely and on the other hand considering whether overly prescriptive or onerous regulation may restrict industry and associated innovation, potentially impacting the competitiveness of the sector. In the US the legislators and regulators have come down on the side of a lighter touch regulation when it comes to the safety of space flight participants.

5.2.2. UK space flight participant analysis

Under the ANO there is no current requirement for real-time radiation monitoring on commercial aircraft or spacecraft. Further, space weather is considered an exceptional circumstance, which is not considered as part of yearly dose uptake to crew or passengers, with all exposure calculations completed using appropriate software to estimate potential dose uptake. This method of dose assessment has the potential for under recording exposure if conditions during flight are not well understood or there is a change in radiation conditions, i.e., space weather, causing an increase in exposure.

The cosmic radiation risk mitigation requirements set out in SIR Part 9 only apply to crew on a launch vehicle or carrier aircraft, not to non-crew members (such as space tourists) who are just passengers taking part in spaceflight activities.

Section 9 of SIA requires an applicant for an operator licence to carry out a health and safety risk assessment for individuals taking part in a prescribed role (crew) or capacity (spaceflight participant not involved in the operation of the spacecraft – e.g., space tourist). This is the element of risk assessment that could provide potential protection to the prospective space tourists.

Chapter 3 of SIR sets out the prescribed requirements for that risk assessment, namely:

- Identify hazards, when and how they occur.
- Assess the likelihood and consequences of scenarios.
- Evaluate risk to health & safety of human occupants.
- Define measures to prevent hazards and mitigate consequences (and set performance standards/mechanisms for review).
- Comply with Schedule 2.

Schedule 2 sets out matters which an applicant must take into account for the risk assessment and lists 10 dangers that a human occupant may experience or undergo and requires the applicant to consider all hazards that may cause them. This list does not include cosmic radiation exposure.

The safety requirements for crew under SIR Part 9 are more prescriptive than those for non-crew under SIA s. 9. We understand from our discussions with the CAA that this is because when drafting the legislation and regulations it was considered that the risk to non-crew space flight participants (such as space tourists) from cosmic radiation exposure was so low (due to the limited periods of time that they would be in space) that more prescriptive requirements were not required. In addition, the SIR regulations currently intentionally preclude the licensing of UK commercial human spaceflight to brief sub-orbital flights, which is consistent with the Blue Origin and Virgin Galactic current flight operations. This seems to be a reasonable stance considering the extent and nature of the space tourism industry today and in the near future.

However, as the space tourism industry develops and as new industries and services grow (such as point to point transport), it will result in a greater number of non-crew space flight participants spending more time in space. Thus, the SIA and SIR regulations may need to be developed to ensure the safety of non-crew space flight participants.

The SIA and SIR also have requirements around informed consent for space flight participants and the health and training requirements for space flight participants. These are important factors as part of the overall safety of space flight missions: a detailed analysis of this is beyond the scope of this paper and is an area for further research.

6. Space policy limitations and recommendations

6.1. Crew vs non-crew regulation

There are limitations around regulation of non-crew space flight

participants (identified in Section 5). This is likely to be an intentional policy decision, as the space tourism industry is seen as in its infancy and has not yet conducted mass commercial flight operations. However, within the next decade this is likely to change with the number of space tourists flying with commercial companies likely to increase into the thousands.

Recommendation 1, for UK space flight regulation, we make a recommendation to the regulator that SIR Schedule 2 be amended to include "(h) cosmic radiation exposure". For example, the consideration of stochastic or deterministic effects, e.g., minor increase in the risk of health defects to serious health implications such as cancers and malignancy.

Recommendation 2: For all spaceflight regulators we recommend that more prescriptive guidance be provided in terms of the type of risk assessment to be carried out by operators to ensure consistency in assessments and the potential radiation risks from space weather. For example, those used by terrestrial nuclear industries when considering potential radiation exposure for workers and/or members of the public.

With regards to informed consent the regulators will want to make sure that not only does the space flight participant see the risk assessment but that the risk assessment is in a form that can be understood by a space flight participant who may not have technical knowledge or expertise so that they can make an informed decision to proceed.

Recommendation 3: Risk assessments and the associated safety case be produced such that a non-technical summary can be provided to potential space tourists and that it is in a form that is easily understandable[2] by a non-space weather/radiation expert. Hence, the risks associated with any potential flight can be reviewed by flight participants and they can then give true informed consent should they still wish to fly.

In summary the key focus from regulation is currently on crew, as the perceived risk to paying non-crew participants is deemed to be low due to current space tourism flight cadence and the potential exposure window. However, the space tourism industry is fast evolving and the risks to participants will also need to be assessed, including the dose limits and liability for injuries etc.

6.2. Risk assessment regulation limitations

Applying terrestrial regulations and guidance to the space radiation exposure environment is a useful starting point for this unique and new industry. However, there are several limitations to applying terrestrial radiation regulations to space tourists:

- Lack of data: The space radiation environment is significantly different from the terrestrial radiation environment, and the radiation exposure levels experienced by space tourists are not well monitored and solar events are unpredictable. This makes it difficult to establish radiation exposure limits for space tourists based on terrestrial regulations alone. ***Recommendation 4***: Regulators should encourage operators (either voluntarily as a responsible operator or imposed through licence conditions) to accurately monitor cosmic radiation encountered by their spaceflight missions (by means of onboard radiation detectors or otherwise) and for that data to be shared with industry, researchers and other regulators, with the aim of increasing the available data set for the exposure environment, detecting rapid changes in space weather and possible elevated radiation levels. These activities would support a better understanding of the risks and informing the evolution of the regulations.
- Duration and intensity of exposure: Space tourists are exposed to radiation for a much shorter period of time than occupational workers in the nuclear industry or astronauts, who spend extended periods of time in space. However, during the brief period of a space tourism flight, the radiation exposure can be much more intense and concentrated than what is typically experienced on Earth. ***Recommendation 5***: Regulators to consider the frequency of space weather events, the duration of future flights, and the probabilistic risk limits that are acceptable for associated risk assessments. This further review should take place alongside any changes to the regulations to permit an orbital launch vehicle with human occupants, hypersonic or other point to point transport.
- Variability of space radiation: The space radiation environment can vary significantly depending on a number of factors, including solar activity and the position of the spacecraft. This makes it difficult to establish consistent exposure limits for space tourists that will be appropriate for all types of spaceflights. ***Recommendation 6***: In addition to Recommendation 4, we recommend that available radiation detector data should be shared and applied to updated models to accurately represent the space tourism flight envelope exposure environment to sufficiently model the radiation risk.
- Lack of established standards: There are currently no established standards for radiation exposure limits for space tourists, and the regulations that do exist are largely based on recommendations from international bodies like the ICRP. It is unclear whether these recommendations will be appropriate for the unique circumstances of space tourism. ***Recommendation 7***: With sufficient radiation/risk data each country can set its own standards for space tourism flights. These standards can then be agreed between nations through treaty or best practice/guidance.
- Space data vs ground data: Standards will need to direct companies against using inappropriate radiation exposure data. For example, current National Oceanic and Atmospheric Administration (NOAA) alerts for space weather events are tailored for commercial aircraft altitudes and would be irrelevant to space tourism flights. ***Recommendation 8:*** Companies shall consider the effects of high energy particles, e.g., 500 MeV energies in exposure data/calculations.

7. Conclusions

The space tourism industry is currently not fully aware of the radiation risks and is instead relying on incomplete "informed" consent basis for non-crew space flight participants. Further, the current regulation for the industry places the risk burden firmly on the space tourist.

Any existing regulation that is applicable to potential space flights focuses on crew, rather than paying passengers. For the potential space tourist, regulation is still catching up with this new industry. Further input into potential future regulation will be required going forward, noting that current fit for purpose legislation for radiation protection, and associated risk assessment, for space tourism does not exist.

The recommendations presented in this paper are advisory in nature, intended for the industry and regulators to consider as the space tourism sector continues to develop. Noting this, and to address the new challenges and activities associated with space tourism flights, the CAA and FAA (and the regulators of other current and future launch nations) may need to consider several key factors when developing new regulations:

- Collaborating with industry stakeholders: The CAA and FAA will need to work closely with industry stakeholders, including space tourism companies, spacecraft manufacturers, and space research organizations, to understand the technical challenges and risks associated with new spaceflight activities. Collaboration will help ensure that regulations are practical, effective, and reflective of the latest technological advances.
- Incorporating international standards: As the commercial space industry becomes more global, it will be important for the CAA and FAA to collaborate with international regulatory bodies, such as the International Civil Aviation Organization (ICAO) and the United Nations Committee on the Peaceful Uses of Outer Space

[2] Note: CAP 2213 provides some limited guidance on presenting a risk assessment in an "easily understandable form" for potential flight participants.

(UNCOPUOS), to develop consistent and harmonized regulations that apply across multiple jurisdictions.

- Emphasizing safety: Safety will be a critical consideration for any new regulations related to spaceflight. The CAA and FAA will need to ensure that new regulations adequately address risks associated with spaceflight, including exposure to radiation, pressure differentials, and the potential for accidents or system failures.
- Encouraging innovation: The commercial space industry is characterized by rapid innovation and technological advancement, and any new regulations must not stifle this innovation. The CAA and FAA will need to develop regulations that strike a balance between promoting safety, encouraging the development of new technologies and approaches, and enabling growth of the industry.

Overall, the development of new regulations for spaceflight will require a collaborative and multi-disciplinary approach, involving input from industry stakeholders, international bodies, and technical experts. As the industry continues to evolve, the CAA and FAA will need to be flexible and adaptive in their approach, continuously reviewing and updating regulations to ensure they remain relevant and effective.

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Author agreement statement

We the undersigned declare that this manuscript is original, has not been published before and is not currently being considered for publication elsewhere.

We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us.

We understand that the Corresponding Author is the sole contact for the Editorial process. He is responsible for communicating with the other authors about progress, submissions of revisions and final approval of proofs.

CRediT authorship contribution statement

C.T. Rees: Conceptualization, Methodology, Investigation, Visualization, Writing – original draft. **J.R. Catchpole:** Conceptualization, Investigation, Methodology, Writing – original draft. **K.A. Ryden:** Writing – review & editing, Supervision, Validation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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