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Investigating and defining radiation dose risk factors, derived from terrestrial risk assessments, for probabilistic risk assessments for radiation exposure during very high altitude ‘near space’ flights for varying space weather conditions

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ABSTRACT

Current space tourism ventures focus on three specific areas: long duration very high-altitude flights; also referred to as ‘near space’ flights, sub-orbital flights and visits to Low Earth Orbit (LEO). In the forthcoming decades, space travel is expected to become as commonplace as transatlantic flights. Consequently, it becomes crucial to consider the potential health implications of cosmic radiation exposure during these commercial ventures, particularly in light of sudden changes in space weather, such as ground-level enhancements (GLEs) or solar particle events (SPEs), which can have profound effects on the well-being of crew members and passengers.

This paper focuses on the exposure environment and associated risk assessment for very high altitude ‘near space’ flights to the stratosphere. The current probabilistic risk assessment of the hazards for such flights is severely constrained, as the necessary dose risk factor for potential radiation exposure remains undefined for prospective space tourists. Here we examine the existing terrestrial approach to deterministic and probabilistic risk assessment for radiation exposure, specifically within the civil nuclear industry, and its applicability to ‘near space’ very high-altitude flights.

We propose a revised probabilistic risk assessment methodology, including a bespoke dose risk factor, for ‘near space’ flights. Furthermore, we delve into the distinctive exposure events associated with ‘near space’ flights, explore the impact of potential variations in space weather on radiation exposure, and evaluate potential dose risk factors for utilization in probabilistic risk calculations for flight participants.

Plain Language Summary: An investigation into the acceptability and probability of risks associated with potential radiation exposure from flying to ‘near space’ within newly designed craft at very high altitude in the upper atmosphere above the Earth. Comparing and assessing the applicability of terrestrial nuclear industry risk assessment methodology to space tourism and the associated radiation risks.

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1. Introduction

Crew and passengers aboard craft 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 current probabilistic risk assessment of these space weather hazards is limited. The necessary Dose Risk Factor for potential radiation exposure from space weather is undefined for prospective space tourists. In order to define a potential Dose Risk Factor this paper focuses on examining the existing terrestrial approach to probabilistic risk assessment, specifically within the civil nuclear industry. We delve into the distinctive space weather events that could affect exposure on ‘near space’ tourism flights, and the potential implications on risk acceptability for such flights. These initial works at the University of Surrey have focused on the

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potential radiation risks associated with very high altitude or ‘near space’ long duration flights [1].

2. Background

Exposure to low levels of background natural radiation is part of everyday life. Most people are not aware of this exposure and the potential risks to our health, for example a ~80μSv effective dose from a commercial flight from UK to USA [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”. Thus, the effects of such rapid changes in space weather and the observed radiation exposure could have long term health implications for future very high altitude and space tourism flight crew and passengers. Ranging from a minor increase in the risk of health defects to serious health implications such as cancers and malignancy [3].

There has been significant terrestrial work on radiation exposure risk assessment 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 [1]. M. Kim [5], and others [6], 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, and that they nominally accepted some risk as professional astronauts rather than space tourists. Thus, there is still significant work to be done to assess the unique risk of the exposure environment for space tourist / ‘near space’ flights and the supporting guidance/regulation.

The terrestrial nuclear industry uses ‘Tolerability of Risk’ to justify any exposure from normal operations and potential scenarios where radiation exposure deviates from the planned work, e.g., accident scenarios, unplanned incidents, etc. [7].

‘Tolerability’ of risk acknowledges that the hazard exists and that suitable safeguards or measures are in place to attempt to control the level of risk associated with it [7]. For radiation workers (those who have occupations in an environment with work related radiation exposures) this tolerability of risk and the potential radiation exposure is defined ‘As Low As Reasonably Achievable’ (ALARA) or ‘As Low As Reasonably Possible’ (ALARP).

Probabilistic risk assessment (PRA) is designed to demonstrate that the risk associated with a selected activity, operation or facility are tolerable. For terrestrial radiological risk assessments, probabilistic safety assessment is only used where the deterministic requirements cannot be fully met, nominally where the dose to a member of the public dose exceeds 100mSv or worker dose exceeds 1000mSv. Noting that for near space flights participants are equally exposed, i.e., crew and passengers, from a space weather event, the lower limit of 100mSv is deemed more appropriate for the purposes of the boundary between deterministic and probabilistic assessments for such flights.

3. Research scope

Very high altitude ‘near space’ flights (VHAFs) are denoted as those which have a minimum height of 18 km (60,000 ft) and a maximum height of 60 km (197,000 ft). VHAFs have a potential duration of 6 to 12 h (e.g. World View in 2022) depending on the commercial entity, selected craft type, e.g., aircraft, balloon, etc. and proposed flight route.

To assess the potential radiation dose risk factors for hazards associated with changes in space weather, during near space flights, we propose the following research questions to be answered within this paper.

- **Research Question (RQ) 1**: How useful are the terrestrial nuclear dose risk factors for near space flights radiation exposure risk estimation during space weather events?
- **Research Question (RQ) 2**: Is it possible to define a bespoke dose risk factor and associated probabilistic risk equation for initial space tourism flights?
- **Research Question (RQ3)**: Considering the potential frequency of space weather events, what recommendations can be made for the acceptable levels of risk for potential radiation exposure per year for space tourism flight participants?

This paper focuses on potential ‘near space’ tourism flights only and the non-nominal potential radiation exposure environment, i.e., space weather events. Flights outside of this environment would likely be longer in duration, i.e., stays in LEO, visits to the moon, and interplanetary trips, and thus subject to a significantly different exposure and risk environment.

4. Space weather

Space weather is a natural consequence of the behaviour of the Sun, GCRs and their interaction with the Earth’s magnetic field and atmosphere. Space weather is comprised of electromagnetic energy and particles that interact with the Earth’s magnetic field [8]. The most obvious sign of this interaction is the Aurora. The Earth’s atmosphere and magnetic field largely protect us on the ground from potential exposure to these energetic particles; however, there are some space weather events, i.e., GLEs that can result in dramatic changes in potential radiation exposure at aircraft altitudes [1].

4.1. Ground level enhancements

When energetic particles from SEP events (driven by shocks from Coronal Mass Ejection (CMEs)) hit the atmosphere, a large influx of protons can result in showers of secondary particles, especially neutrons, which can potentially reach ground level (if high enough energy to penetrate the atmosphere), these events are called ground level enhancements [9].

GLE events involve the interaction of energetic particles over ~350MeV in energy with the Earth’s atmosphere. These energies are high enough to interact with the atmosphere and generate nuclear interactions that cascade secondary particles to ground level. This air shower of secondary particles can consist of neutrons, protons, electrons, pions, muons and others which can be measured by ground based detectors. GLE events are characterised by the “hardness” of the particle spectrum, i.e., protons at higher energies within the incident SEP event. The nature of the magnetic field lines and the amount a particle is deflected by this field is determined by its rigidity (momentum per unit charge). Lower energy particles are deflected downwards towards the polar regions, hence the field provides little protection here and thus there is potential for higher radiation doses at higher latitudes. With this said, higher energy particles observed during a GLE event have sufficient energy to penetrate the magnetosphere at non-polar regions and result in a cascade of secondary particles at lower latitudes.

GLEs can result in significant rapid increases in radiation at both ground level and at higher altitudes, (e.g., aircraft cruising altitudes) with the potential for current commercial aircraft crew to be exposed to doses in excess of 1mSv during a single flight [10].

To date there have been 73 GLEs recorded since measurements began in the 1940s. Therefore, there is approximately one GLE event per year,[1] with some alignment with solar maximum, how-

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[1] Although GLE events may occur yearly, ‘very weak’ GLE events are not considered within this paper, as they would only have a minor impact on potential radiation doses. The lowest level of GLE considered is a ‘weak’ event - see Table 3 for further details on the classification, frequency, and intensity of potential GLEs.

ever GLEs are extremely difficult to predict with constantly varying solar conditions. Since 1940 the largest ever recorded GLE was in 1956, during this GLE the observed count rate at one station (Leeds) increased by ~4760 % (15-minute average) [11].

4.2. Space weather scenarios / ground level enhancements events

Based on works by Dyer [10] on extreme atmospheric radiation environments and single event effects, an analysis of GLEs extreme solar energetic particle events, which have a hard spectra [12], has been conducted. From these works the following event-integrated intensity classification s for GLE events have been defined [1].

4.3. Very high altitude 'Near space' exposure environment

The influence of potential GLE events makes the exposure environment presented for very high altitude 'near space' flights unique, and unlike the environment for astronauts and those in LEO. To adequately assess the risks associated with this environment, and ensure a safe flight, the impact of GLEs and the atmospheric conditions must be accurately modelled (G. Griffith, [13]). Previous modelling of such events and the particle spectrum for potential GLEs has been noted as being challenging due to predicting SEP event energy levels.

Historically, there has been very limited assessment of this very high-altitude 'near space' flight exposure environment. This is partly due to the perceived protection provided from the Earth's magnetic field during SEP events, a lack of craft exploring this flight level environment and a historic focus on astronauts during such events. Further, there has been a focus on conditions from GCR exposure, rather than the potential effects of GLEs and the ability for incident particles to overcome the rigidity of the Earth's magnetic field.

4.4. Radiation risk

The risk to health from low levels of radiation i.e., less than 1mSv per year, are deemed to be negligible [14]. However, elevated levels of radiation or prolonged exposure can increase the risk of cancer, health conditions and other genetic defects. The average dose for a nominal commercial airline passenger from flying from the UK in 2010 was estimated by Public Health England [2] to be 0.03mSv, and 2.4mSv per year for commercial airline crew, this is in addition to the ~2.7mSv average annual dose in the UK from natural terrestrial sources per year (Radiation Protection Services, UK Health Protection Agency). The International Commission on Radiological Protection (ICRP) notes that for 1 Sv effective dose exposure there is a 5 % risk of detrimental health effects. This includes damage to DNA, hereditary defects and malignancy/cancer (ICRP Publication 103, 2007).

For astronauts and those in LEO there is an acknowledged constant risk from radiation exposure from space weather [6]. However, the focus has been on GCRs and solar output, with no discussion of potential GLEs and their impact at lower altitudes. Thus, there is still significant work to be done to assess the unique risk of the exposure environment for very high altitude and space tourist flights.

5. Deterministic risk assessment

Deterministic risk assessment is used to assess the acceptability of risks associated with non-nominal conditions, i.e., accident scenarios, associated with radiation exposure. The use of deterministic risk assessment aims to demonstrate that the risk is Tolerable/ALARP and identify potential protection measures against exposure to elevated radiation levels.

For those working in environments with potential radiation exposure, companies are required to manage the risk associated with that exposure, e.g., UK the Ionising Radiation Regulations (IRRs) and Safety Assessment Principles (derived from ICRP guidance). The following figure forms the basis of the current radiation workers and nuclear industry deterministic risk assessment for dose consequences. The chart denotes the requirements for potential protection measures to be put in place to mitigate potential doses to workers and members of the public.

Passengers on very high altitude 'near' space flights would be classed as members of the public (blue "hashed" section on Fig. 1). Hence, on the above chart protection measures would need to be considered for doses under 1mSv for frequent scenarios. For doses above 1mSv, protection measures would be required to ensure that doses are ALARP. Very high altitude near space flight crew would be classified as occupationally exposed workers and hence would be in the red "hashed" section of the Figure, which denotes that protection measures should be considered for doses under 20mSv and shall be required above this.

Noting that for near space flights participants are equally exposed, i.e., crew and passengers, from a space weather event, a limit of 100mSv is deemed appropriate for the purposes of the boundary between the requirements for deterministic and probabilistic assessments. Thus, all potential effective doses above 100mSv will require a probabilistic risk assessment.

6. Probabilistic risk assessment

6.1. Background

PRA is a systematic and comprehensive methodology to evaluate risks associated with engineering systems, e.g., nuclear facilities, spacecraft, etc. PRA can be applied throughout the lifecycle of the selected system, i.e., from design, construction, operation and decommissioning (M. [15]). PRA originated in the mid-20th century, it gained prominence after the Three Mile Island incident in 1979 highlighted the need to assess not just potential accidents [16] but also their probabilities and consequences [4].

In the use of PRA risk is defined as the potential occurrence of an identified hazard, e.g., failures during launch of a spacecraft. In a PRA, risk is assessed in the magnitude of the hazard (severity) that can result from the selected system (activity), and the likelihood of the event occurring. Thus, PRA can be a powerful analytical tool to assess the potential safety performance for a chosen system / acivity. Note: PRA is a quantitative assessment of the potential risk, as both the severity and likelihood of the scenario are expressed numerically.

PRA is designed to demonstrate:

- What can go wrong with the studied system/process, and/or what the initiators or initiating events are that lead to an adverse (non-nominal) condition.
- What and how severe are the consequences associated with the adverse (non-nominal) condition.
- The frequency and probability of the identified adverse (non-nominal) conditions, to determine the tolerance of the associated risk.

6.1.1. PRA in aerospace

PRA of aircraft and associated operations grew in the late 20th century. With the FAA requiring the use of fault trees and probabilistic analysis of aircraft to identify single point of failures and reduce the chances of failures to less than one-in-a-billion flight hours. These requirements have been updated over the years to include a greater breadth of aircraft systems to be considered as part of any PRA assessment.

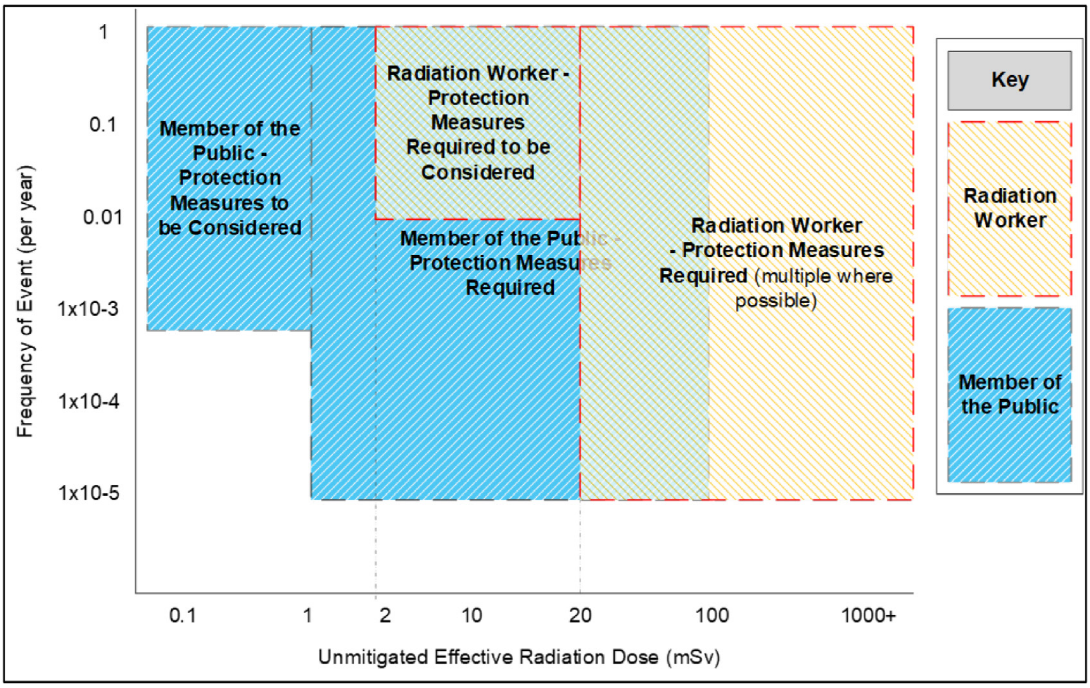

Fig. 1. Terrestrial nuclear industry design risk assessment chart for radiation doses. Noting boundaries between protection measures recommended and where protection is required for radiation workers and members of the public to ensure that doses are ALARP.

6.1.2. PRA in space industry

NASA began using PRA in the late 1960′s following the capsule fire during the Apollo program [17]. This focused on the use of a fault tree analysis of the entire Apollo system. However, NASA did not fully embrace PRA until after the Space Shuttle Columbia break-up in 2003, where investigations identified the need for accurate risk assessment.[2] It is now widely used for space missions, including the International Space Station (ISS) programs and activities. However, there has been little work on space tourism and the affects on radiation risk assessment from changes in space weather on future space exploration missions [5].

7. Civil nuclear probabilistic fault assessment process

For terrestrial radiological risk assessments, probabilistic safety assessment is only used where the deterministic requirements cannot be fully met, nominally where the dose from an identified non-nominal scenario could exceed 100mSv for a member of the public (Fig. 1).

7.1. Civil nuclear PRA methodology

Current terrestrial nuclear assessments use the following formula is used to calculate the risk of early death based on the potential radiation exposure during an identified scenario:

$$R_{Prob} = E \times D_{RF} \times SF \quad \times PM_{FP}$$

Where:

- $\mathrm{R_{Prob}}$ = For each scenario the probability of early death.
- E = Effective dose in Sieverts (Sv).
- DRF = Dose Risk Factor - which reflects the probability of early death per Sievert. For terrestrial civil nuclear a figure of 0.05 (ICRP 2017), i.e., 5 % risk of death per Sievert. Note: these factors are only applicable up to doses of 1 Sv.
- SF = Sequence Frequency/Scenario Frequency per year.
- $\mathrm{PM_{FB}}$ = Protection Measure Failure Probability (per year).

7.2. Civil nuclear dose risk factors

The key part of the formula is dose risk factor. This is based on the potential exposure environment and incident radiation for terrestrial nuclear operations.

ICRP 2017 provides a dose risk factor of 0.05, i.e., 5 % risk of early death per Sievert.

7.3. Civil nuclear dose risk limits

If the determined risk for any accident / non-nominal scenario exceeds the allocated risk limit then it is deemed intolerable and the proposed activity cannot be justified without additional protection etc. If the risk is determined to lie between the limit and target, the risk is deemed tolerable, but it remains necessary to demonstrate whether the risk is ALARP [18]. If the risk is determined to be lower than the target, the risk is tolerable and may be considered to be broadly acceptable.

The terrestrial nuclear industry risk limits are displayed in Table 2 below, these risks reflect the limits and targets for all of a nuclear site's operations. They support that no worker or member of the public shall be exposed to multiple sources of potential risk:

8. Near space flight probabilistic risk assessment (RQ2)

Noting the approach taken for PRA in the civil and aerospace industries, the proposed assessment methodology, formula and risk limits for exposure to space weather events are described in the following subsections.

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[2] PRA predicted a failure rate of approximately 1 in 100 launches of the space shuttle, however this was dismissed by NASA management as being too pessimistic [17], and only later accepted as a more realistic risk assessment of the associated potential risks.

8.1. Near space probabilistic risk assessment methodology (no protection measures)

Most current ‘near’ space flight craft, such as Space Perspective’s Neptune capsule, do not feature any specific radiation protection measures as the level of risk posed from space weather is deemed to be very low. Thus, the following PRA formula is suggested for a craft without any defined protection measures.

$$R_{Prob} = E \times D_{NSRF} \times S_W F$$

(Near Space PRA - Formula 1) Where:

- R_{Prob} = For each flight scenario the probability of early death.
- E = Predicted effective dose in Sieverts (Sv).
- D_{NSRF} = ‘Near Space’ Dose Risk Factor - which reflects the probability of early death per Sievert.
- $S_W F$ = Space Weather Frequency per year.

Formula 1 is based on the experience / research into the terrestrial PRA formula. However, it has some key differences, most notably the dose risk factor is revised for the unique near space environment. Further the abnormal event that influences the scenario risk is based on the space weather (GLE) event frequency.

8.1.1. Near space dose risk factor (RQ1)

The key considerations in determining a Near Space Dose Risk Factor (D_{NSRF}) are:

- The radiation types and proportions within the mixed exposure radiation field for near space flights.
- The energy of each incident radiation type for the near space exposure environment.

The dominant incident particles during a GLE / SPE are overwhelmingly protons [9], thus, pessimistically, for the risk factor calculation only protons are considered for such space weather events.

The energy of incident protons during GLE events typically involve the incidence of energetic particles over ~350MeV into the Earth’s magnetic field. For dose risk calculations, it is noted that protons with an energy of greater than 2MeV have a radiation quality factor (QF) of 5.

The ICRP defines the terrestrial DRF, for radiation workers, as 0.05 within ICRP Publication 103, per Sievert, for a varying radiation field / various incident particles. However, for a GLE event, dominated by protons, and noting a QF of 5 for the incident particles, the Space Dose Risk Factor (D_{NSRF}) is revised to upwards to 0.25 (0.05 × 5). Thus, for energetic high energy protons an annualised risk of death would equate to 1 in 2000 flight participants, per sievert of exposure.[3]

8.1.2. Space weather frequency

The space weather event frequency is for abnormal events, i.e., SPE/GLEs, not normal GCR conditions. It is based on the yearly likelihood of an event, as defined in Table 1. Note: for risk assessment purposes this event frequency should be a pessimistic estimate of potential SPEs/GLEs.

8.2. Near space probabilistic risk assessment methodology (craft with protection measures)

Where near space flights will incorporate protection measures, such as shielding, the following revised formula is proposed for PRA on flights.

$$R_{Prob} = E \times D_{NSRF} \times S_W F \times P_S M_F$$

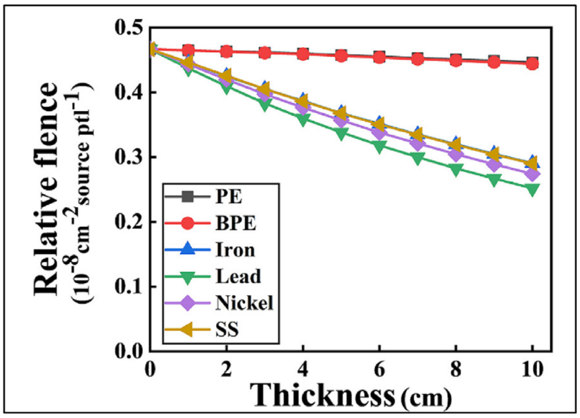

Fig. 2. The attenuation of protons associated with a space weather event, with the energy of 100MeV–1 TeV for various materials (J. [19]).

Where:

$$P_S M_F = \left(\prod_{1}^{N} P_S M_{F_i} - \sum_{1}^{N} \left(1 - P_S M_{F_i}\right) \right)$$

Note: $P_S M_F$ is the probability of failure of each protection barrier, which are discussed in the next section.

If we define $R_{NSRF} = E \times D_{NSRF} \times S_W F$, the risk associated with a flight, with single or multiple protection measures, can be calculated using:

$$R_{Prob} = R_{NSRF} \times \left(\prod_{1}^{N} P_S M_{F_i} - \sum_{1}^{N} \left(1 - P_S M_{F_i}\right) \right)$$

(Near Space PRA - Formula 2)

8.2.1. Flight protection measures

Where a proposed flight has an identified protection measure this can be claimed to reduce the severity of the probabilistic risk identified via Formula 2.

$P_S M_F$ can consist of a single or multiple protection barriers. The minimum requirements / effectiveness for these barriers is detailed in the following subsections. The level of the protection provided by the identified measure(s) does not feature in the risk calculation (Formula 2), rather the failure probability of the claimed measure to prevent or mitigate potential radiation dose uptake. The claims around the substantiation / reliability of identified protection measures is detailed in the following subsections.

8.2.1.1. Aircraft / spacecraft shielding. Aircraft or spacecraft shielding shall encompass the whole craft and be permanently affixed. The material / design of the shielding shall be selected to reduce incident radiation levels, for a potential SEP / GLE event, by a minimum factor of 50 %.

The potential thicknesses and shielding materials (e.g., polyethylene (PE), borated polyethylene (BPE), iron, nickel, lead and stainless steel (SS)) is discussed in Fig. 2. The recommended $P_S M_F$ for aircraft / spacecraft shielding is > 1×10^{-5} per year.

Note: shielding for high energy particles from a space weather event as a mitigation measure would be likely difficult, from a practicality standpoint, as the thickness of shielding required to reduce dose rates would be significant in mass / size. Other more cost-effective protection methods such as space weather forecasting, termination of flights, altitude reduction etc. should be considered prior to looking at potential shielding.

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[3] This D_{NSRF} is pessimistic for risk assessment purposes, as unlike terrestrial nuclear risk environment, where known exposure constituents, space is a harsh exposure environment.

Table 1
GLE Event Classification compared to 1956 GLE 05 event, frequency of such events, comparison to historically recorded events and estimation of increase on background.[4] Maximum estimated effective doses are based on modelling conducted by Rees, 2023, specifically a very high altitude flight at 30 km from Sutherland Spaceport, UK (58.5, −4.5) into the North Sea (59.8, 0.1); which represents a pessimistic high latitude flight during a GLE event.

GLE Event Classification	Peak Ground Intensity (%*h) of Event[2] Compared to GLE 05 (1956)	Event Frequency	Comparison to Historic GLE Events & Estimated Increase on GCR Background	Estimated Maximum Effective Dose from Event
Weak	2% x GLE 05	1 in 10 year event (on average 1 per 11 solar cycle, (E. Asvestari, 2017))	GLE 59 - 14th July 2000 - ~92% ± 5, (h) increase on background (E. Asvestari, 2017))	~0.06mSv (Rees, 2023)
Strong	20% x GLE 05	1 in 50 year event (2 such events recorded over past ~70 years of data (E. Asvestari, 2017))	GLE 42 - 29 September 1989 - ~1200% ± 60, (h) increase on background (E. Asvestari, 2017))	~4.0mSv (Rees, 2023)
Severe	= GLE 05	1 in 100 year event (1 event recorded over past ~70 years of data (E. Asvestari, 2017))	GLE 05 - February 1956 - ~5200% ± 104, (h) increase on background (E. Asvestari, 2017))	~21.0mSv (Rees, 2023)
Extreme	3000% x GLE 05	1 in 1200 year event (C. Dyer, 2003)	Extreme event, none recorded since modern NM GLE monitoring. Estimated ~ 150,000% increase on background (C. Dyer, 2003)	~620mSv (Rees, 2023)

Table 2
Dose risk limits and targets for the probability of an early death for, workers and members of the public, as a result of activities at a single terrestrial nuclear site [7].

Risk of early death	Radiation workers	Members of the public
Dose risk limit	10^{-4}/year	
Dose risk target	10^{-6}/year	

Note: that figures quoted in Table 2 are for risk of death per annum. To summarise the factors, 10^{-4} reflects a risk that 1 in 10,000 people will die per annum due to the industrial hazard / nuclear plant.

8.2.1.2. Radiation hardened / protected areas. Like aircraft / spacecraft shielding, a radiation hardened, or protected area, shall incorporate sufficient shielding to potentially reduce incident radiation from space weather events by a factor of 50 % (see Fig. 2 for potential materials). This area shall be permanently available / accessible within the craft and participants will be instructed on the it's use and functionality as part of pre-flight briefings.

It should be noted that a radiation hardened and / or protection area is a limited area where radiation doses would be reduced, unlike whole craft shielding. Thus, any participants outside of the hardened / protected area would receive higher dose rates.

The recommended $P_S M_F$ for radiation hardened / protected areas is $> 1 \times 10^{-4}$ per year.

8.2.1.3. Emergency procedures / communication. During 'near space' flights, crew would receive regular communication from their ground control / operations. These communications would advise crew to enact emergency procedures during a detected space weather event.

These procedures would include actions to reduce potential dose uptake during a space weather event, e.g., a GLE. Specifically, they would include instructions to reduce exposure time, i.e. land at nearest spaceport, and / or increase distance from incident events, i.e. reduce altitude.

The exposure time for the peak of the 1956 Severe GLE event was over a period of 90 min [20]. In order to reduce doses by a minimum of 50 % for such an event, an emergency decent would be required, this would need to occur within 5 min, which would require a severe flight trajectory, i.e., a flight to descend from 30 km (100,000 ft) to minimum of ~15 km (50,000 ft) – see Fig. 3.

Noting that this protection measure is highly reliant on human performance, i.e., pilots take action upon receipt of emergency commands / communications, the recommended $P_S M_F$ is $> 1 \times 10^{-1}$ per year.

8.2.1.4. Space weather forecasting. The use of space weather forecasting / prediction models by operators would enable flights to tailor routes, and altitudes, to minimise radiation exposure from a detected space weather event. Such forecasting should aim to reduce effective doses, from a potential GLE event, by a minimum of 50 %. However, it should be noted that the capability for verified accurate SPE / GLE event forecasting does not yet exist.

Noting the complexity of space weather forecasting, the recommended $P_S M_F$ is $> 1 \times 10^{-2}$ per year.

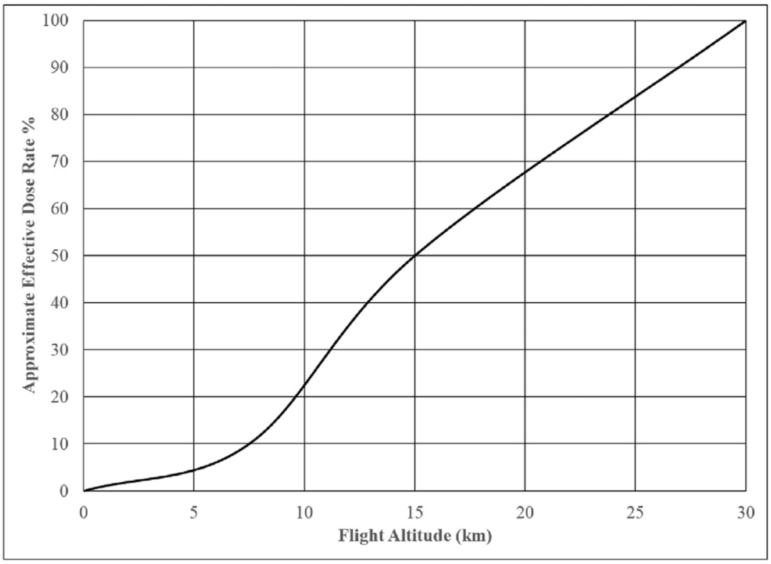

Fig. 3. Altitude against effective dose rate (%) during an extreme GLE event, for a very high-altitude flight from Sutherland Spaceport, UK (58.5, −4.5).

Table 3
Proposed dose risk limits and targets for space flight participants on 'near space' flights when at risk of potential exposure from space weather / radiation.

Risk of early death	Space flight participant
Dose risk limit	10^{-3}/year
Dose risk target	10^{-5}/year

9. Proposed near space radiation dose risk limits

NASA assessed the risk of a catastrophic failure of the space shuttle and potential fatalities from launches, as a in 1 in 100 flight event [21]. A wider review of rocket launches/failures over the last 50 years [22], shows a higher figure of 10 % and a lower figure of 4 % depending on launch location. The causes of these failures range from mechanical failures, human factors, to space weather events.

The FAA states an acceptable risk limit of 1 death per every million commercial flights [23]. There are approximately 40 million commercial aircraft flights every year [21]. This equates to a risk of approximately 4 × 10^{-8} per flight of an early death.

We propose that due to the current experimental nature of space flight and noting the frequency of flight operations that a dose risk limit of 1 in 1000 (i.e., 1 fatality in 1000 space flight participants due to space weather / radiation exposure during flights per annum). This would be a high-level limit, the target is proposed to be 1 fatality in 100,000 flight participants per annum. This is similar to terrestrial radiation limits, however higher than the current FAA guidance for commercial flights, this is primarily due to the hazards associated with the 'near space' flight exposure environment. Table 3 summarises the proposed limits (RQ3).

The Dose Risk Limit proposed is a threshold which shall not be exceeded, as the proposed flight would result in excessive risk if above this level. The Dose Risk Target is considered a goal, if the risk is determined to be lower than the limit and above the target, the risk is tolerable and may be considered to be broadly acceptable; subject to future assessment of potential protection measures. If the risk is determined to be less than the target it is considered acceptable based on the proposed limits for potential radiation exposure.

10. Case study on the use of 'near space' PRA and associated risk levels for identified space weather scenarios

In this limited case study, Formula's 1 and 2 are used to assess the probabilistic risk from an extreme GLE / space weather event.

The flight profile assessed is single very high altitude 'near space' flight from Sutherland Spaceport, UK towards the North Sea at a maximum altitude of 30 km (Table 1). This flight represents a pessimistic high latitude flight proposal during a GLE event. Note: the calculated effective dose is in excess of 100mSv, for the flight, thus the risk cannot be deterministically assessed under the guidance presented in Section 5.

Further, an extreme GLE (space weather) event is assumed to occur approximately 1 in 1200 years (C. [10]), and result in an effective dose (E) of ~620.0mSv [1].

10.1. 'Near space' flight with no protection measures

For a craft with no protection measures, the risk associated with a single flight can be assessed using Formula 1:

$$R_{Prob} = E \times D_{NSRF} \times S_W F$$

$$R_{Prob} = 0.620 \times 0.25 \times 0.001$$

$$R_{Prob} = 1 \times 10^{-4}$$

The calculated R_{Prob} of 1×10^{-4} is below the Dose Risk Limit, thus the potential risk associated with a single flight during an extreme GLE is deemed tolerable. This equates to an early risk of death of 1 in 10,000 flight participants. Further, this calculated risk is above the Dose Risk Target, therefore a flight operator should include potential protection measures to reduce further reduce the risk to acceptable levels.

10.2. 'Near space' flight with single engineered protection measure

For a craft with a single engineered protection measure, assumed here to be radiation shielding, the risk associated with a single flight can be assessed using Formula 2:

$$R_{Prob} = R_{NSRF} \times \left(\prod_{1}^{N} P_S M_{F_i} - \sum_{1}^{N} \left(1 - P_S M_{F_i}\right) \right)$$

$$R_{Prob} = 0.620 \times 0.12 \times 0.001 \times 0.00001$$

$$R_{Prob} = 1 \times 10^{-9}$$

The calculated R_{Prob} of 1×10^{-9} is below the Dose Risk Target, i.e., the risk of early death to a flight participant is 1 in 100,000,000. Thus, the risk associated with a single flight during an extreme GLE with a permanently available radiation shielding, as a protection measure (to mitigate radiation exposure), is deemed ALARP.

10.3. *'Near space' flight with single procedural protection measure*

For a craft with a single procedural protection measure, assumed here to emergency procedures / communication (for reducing altitude / exposure time to a space weather event), the risk associated with a single flight can be assessed using Formula 2:

$$R_{Prob} = R_{NSRF} \times \left(\prod_{1}^{N} P_S M_{F_i} - \sum_{1}^{N} \left(1 - P_S M_{F_i}\right) \right)$$

$$R_{Prob} = 0.620 \times 0.25 \times 0.001 \times 0.1$$

$$R_{Prob} = 1 \times 10^{-5}$$

The calculated R_{Prob} of 1×10^{-5} is below the Dose Risk Limit, however it is in line with the Dose Risk Target. Therefore a single procedural protection measure is not sufficient to demonstrate that the risk associated with a flight during an extreme GLE is ALARP. Thus, further engineered and / or procedural protection measures should be considered to reduce the assessed risk.

11. Conclusions

In the works detailed here we present a proposed bespoke dose risk factor and associated probabilistic risk equations for initial 'near space' tourism flights, learning from the terrestrial nuclear and commercial aviation industries.

Initial use of the proposed probabilistic risk formula (Formula 1 and 2), for a limited 'near space' flight case study, has shown that for extreme GLE events that the risks are below the proposed Dose Risk Limit. For those flights with a no protection measures or a single procedural protection measure the risks are still above the proposed Dose Target and thus not ALARP. However, with the inclusion of a single engineered protection measure the risks associated with flights during an extreme GLE event can be reduced to acceptable levels and below both the Dose Risk Limit and Target.

12. Recommendations

Findings from this initial case study, for the radiation risk assessment of 'near space' flights, show that during an extreme GLE they will likely require protection measures, to ensure that the associated risks are ALARP.

This paper makes the following recommendations around types and reliability of potential protection measures, (noting the requirements detailed in Section 8.2.1):

- Aircraft / spacecraft shielding – permanently available and suitably design to prevent / mitigate against incident radiation types ($P_S M_F > 1 \times 10^{-5}$ per year).
- Radiation hardened / protected areas, e.g., space weather / storm shelter – an accessible area of the craft that is hardened / protected to temporarily reduce exposure to incident radiation ($P_S M_F > 1 \times 10^{-4}$ per year).
- Emergency procedures, e.g., early termination of flight – allows for potential reduction in exposure time during incident GLE radiation ($P_S M_F > 1 \times 10^{-1}$ per year).
- Ground communication on current space weather conditions, e.g., alerting crew to high potential high radiation levels – potentially allowing for a change in flight trajectory reducing levels of radiation exposure ($P_S M_F > 1 \times 10^{-1}$ per year).
- Use of space weather forecasting / prediction models – potentially routing flights around incident weather and / or preventing launches during space weather events ($P_S M_F > 1 \times 10^{-2}$ per year).

It should be noted that space weather events in excess of the extreme GLE, discussed in this paper, could be possible. Although they may have a significantly reduced incidence frequency, they could result in doses in excess of 1 Sv. Thus, the consideration of potential protection measures, by flight operators, will be critical to ensuring crew / flight participant protection in the future.

Acronyms

ALARA	as low as reasonably achievable
ALARP	as low as reasonably practicable
CARI	Civil Aviation Research Institute
DRF	dose risk factor
GCR	galactic cosmic ray
GLE	ground level enhancement
FAA	US Federal Aviation Authority
HSE	UK Health and Safety Executive
ICRP	International Commission on Radiological Protection
IRRs	Ionising Radiation Regulations
ISS	International Space Station
LEO	low earth orbit
MAIRE	models for atmospheric ionising radiation effects
NASA	National Aeronautics and Space Administration
NM	neutron monitor
PRA	probabilistic risk assessment
QF	quality factor
RQ	research question
SEP	Solar Particle Events
UK	United Kingdom
USA	United States of America
VHAF	very high-altitude flight

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.

CRediT authorship contribution statement

C.T. Rees: Conceptualization, Formal analysis, Investigation, Methodology, Project administration, Validation, Writing – original draft. **K.A. Ryden:** Validation, Writing – review & editing, Supervision. **T. Woodcock:** Validation, Writing – review & editing. **M. Brito:** Methodology, Validation, Writing – original draft, Writing – review & editing.

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