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Radiation risk assessment for varying space weather conditions for very high altitude 'near space' tourism balloon flights

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A R T I C L E I N F O

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Acronyms:
CAA, UK Civil Aviation Authority
CARI, Civil Aviation Research Institute
GCR, Galactic Cosmic Ray
GLE, Ground Level Enhancement
FAA, US Federal Aviation Authority
HSE, UK Health and Safety Executive
HZE, High Nuclear Charge, Z, and Energy Particles
ICRP, International Commission on Radiological Protection
IRRs, Ionising Radiation Regulations
LEO, Low Earth Orbit
MAIRE, Models for Atmospheric Ionising Radiation Effects
NM, Neutron Monitor
SAIRA, Smart Atmospheric Ionizing Radiation
SSC, Surrey Space Centre
SEP, Solar Particle Events
UK, United Kingdom
VHABF, Very High Altitude Balloon Flight

A B S T R A C T

Within the next decade it is likely that the space tourism industry will grow dramatically and the number of humans travelling into, and beyond, the stratosphere via commercial entities such as World View and Space Perspective will increase. Current space tourism ventures focus on long duration very high altitude balloon flights; also known as 'near space' flights, sub-orbital flights and visits to Low Earth Orbit (LEO). In the next few decades space tourism is ultimately likely to become routine. During these new commercial ventures the effects of cosmic radiation exposure, especially during sudden changes in space weather, such as ground level enhancement (GLE) events, could have significant health implications for crew and passengers. The risks from these rapid changes in space weather and potential radiation exposure during flights is not currently fully understood or even acknowledged. Legislation and regulation for such enterprises is also in its infancy with little or no guidance for commercial entities or potential passengers. Initial work at the University of Surrey has focused on very high altitude 'near space' balloon flights. World-wide launch locations for flights have been modelled using MAIRE and CARI-7 computer programs. Flight routes have been monitored, for current commercial and higher flight levels, using the Smart Atmospheric Ionizing Radiation (SAIRA) detector. The modelled flight profiles have been compared with detector data, up to a maximum flight altitude of 30 km (100,000 ft), with varying space weather conditions, from norms to extreme events, to assess the radiation risk presented by potential exposure.

Plain Language Summary: An assessment of the risks and potential radiation exposure from flying to 'near space' within newly designed observation balloons at very high altitude in the upper atmosphere above the Earth. Looking at the impact of radiation from the sun and sources outside the solar system, and critically when these conditions vary which could result in high levels of exposure.

1. Introduction

During current commercial air travel, at around ~11 km (~35,000 ft) in altitude, passengers and crew are subjected to low levels of radiation exposure from natural non-terrestrial sources, i.e., galactic cosmic rays (GCRs). Due to the protection provided by the Earth's atmosphere and magnetic field, the levels of exposure from cosmic radiation are normally low (UK Health Protection Agency, 'Radiation Risks from Low Levels of Ionising Radiation', 2008). However, 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). Aircraft and spacecraft are especially vulnerable to these changes due to the altitudes they fly at.

Exposure to elevated levels of ionising radiation (mSv range), such as those possible during GLE events, has been noted by the UK Health Protection Agency [12], 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 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. Initial work at the University of Surrey has focused on the potential radiation risk associated with very high altitude or 'near space' observation balloon flights.

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1.1. 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. 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.

1.1.1. 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.

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. Normally the Earth's magnetic field would largely protect us from lower energy particles. 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. However, 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 [7].

Dyer [7] noted that there are "few calculations or observations on solar particle enhancements at aircraft altitudes", this finding has not changed in the subsequent two decades. Further, only a small number of SEPs events have the joint properties of high intensity and hard spectra required to result in significant increases in radiation exposure at aircraft altitudes, such events would be detectable on the surface of the Earth as GLEs.

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, however GLEs are 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) [4].

1.2. 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 risk of such exposure on our health. Initial works have shown that during a survey of current commercial airline crew most[2] were aware of the potential radiation exposure and its associated risk, and most members of the public[3] were not aware of the effect on them as passengers, e.g., ~80μSv effective dose from a commercial flight from UK to USA (Public Health England, 2010).

The risk to health from low levels of radiation i.e., less than 1mSv, are deemed to be negligible [19]. 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 (2010) to be 0.03mSv, and 2.4mSv for commercial airline crew, this is in addition to the ~2.7mSv average 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 6% risk of detrimental health effects. This includes damage to DNA, hereditary defects and malignancy/cancer [14].

There has been significant terrestrial work on probabilistic risk of radiation exposure as part of the evolution of the nuclear industry and its risk assessment process [16]. This is unlike the very high altitude flight and space tourism industry. M. Kim [17] discussed probabilistic 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 or those flying at very high altitude.

For astronauts and those in LEO there is an acknowledged constant risk from radiation exposure from space weather (S. [10]). 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.

1.2.1. Tolerability of risk

The world-wide 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.

'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 (The Tolerability of Risk from Nuclear Power Stations, UK HSE 1992). 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). ALARA/ALARP is expected to show that an operator/site has conducted all reasonably practicable steps have been taken to prevent and mitigate the risk associated with potential radiation exposure (UK IRR17 Regulations 2017).

This tolerability of risk and demonstration of ALARA/ALARP is a key requirement for nuclear licensing and enabling safe operations involving radioactive materials. Although legislation for Spaceports and their flight operations are still in their infancy, similar tolerability of risk assessments will be requirements for regular flights to operate under future licenses.

[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.

[2] 56% of 30 crew surveyed

[3] 60% of 250 members of the public surveyed.

1.3. Radiation protection quantities

The International Commission on Radiation Units (ICRU) and ICRP provide definitions on the units, description and quantification of exposure to humans from ionizing radiation.

Human exposure to ionising radiation can occur from incident radiation on the body, denoted 'external exposure' or from the ingestion/intake of radionuclides, denoted 'internal exposure'. For space tourism participants internal exposure is not considered further, as participants will be within a spacecraft or aircraft with no route for ingestion/intake of radiation nuclides.

Radiation protection quantities largely relate to occupational and public exposure on Earth, e.g., monitoring for terrestrial radiation workers concentrates on alpha (two protons & two neutrons), beta particles (electron) and gamma rays. Radiation limits are defined in terms of preventing stochastic and deterministic effects.

Radiation exposure for very high altitude and space tourism flights are different to those on the surface of the Earth or flying at commercial altitudes. The higher altitudes for proposed flights means they are vulnerable to a higher radiation exposure environment and are more vulnerable than astronauts at even higher altitudes due to the exposure times. This is especially true during GLE events, where showers of secondary particles at higher altitudes can result in significant rapid increases in radiation levels.

The ICRP recommends the following radiation exposure quantities for various operation types and radiation working environments. Note: the ICRP recommends that general information about cosmic radiation exposure to aircraft passengers should be available to all.

1.3.1. Ambient dose equivalent H*(d)

Ambient Dose Equivalent, defined H*(d) is an operational quantity used for radiation protection for monitoring of ambient doses aviation altitude flights resulting from strongly penetrating radiation. It is used here for a single dose equivalent, which approximates exposure to a phantom approximating the human body at a depth 'd', nominally 10 mm, hence is often presented as H*(10).

ICRP noted that in most practical situations on Earth, and within the atmosphere, the ambient dose equivalent provides a conservative estimate of the effective dose to a person (ICRP Publication 123 & Pellicioni, 1998).

1.3.2. Equivalent dose

ICRP notes that for radiation protection "the main interest is directed not to the absorbed dose at a point in the human body, but to the absorbed dose average over a tissue or organ volume" (ICRP Publication 123). It follows that the mean absorbed dose in an organ or tissue 'T' due to radiation of type 'R' is defined as $D_{T,R}$. For radiation protection equivalent dose is used for doses in an organ or tissue.

The Equivalent Dose is denoted HT is defined as the sum of all radiation types involved:

$$H_T = \sum_R w_R D_{T,R}$$

Where, w_R is the radiation weighting factor for radiation 'R'. Equivalent dose is recorded in Sieverts (Sv).

Operational quantities such as Dose Equivalent are measurable, and as such can enable an assessment to be made of the effective dose (which is not measurable, but calculated based on tissue weighting factor).

1.3.3. Effective dose

The ICRP introduced effective dose as a radiation protection quantity in its 1990 recommendations [13]. The ICRP continues to recommend effective dose as a radiation protection quantity for general application, including aviation at high altitudes [15], with the use of ambient dose rates for validation of any calculations. The effective dose is noted by ICRP as an appropriate quantity to assess the risk for occupational and public exposure. Further, in the nuclear industry, as well as the aviation industry, it is used worldwide for radiation protection, licensing and hazard identification purposes. Noting the ICRP recommendations, effective dose is deemed appropriate for the assessment of potential radiation exposure of very high altitude aviation and the associated radiation exposure environment.

1.4. Radiation exposure limits

The ICRP specifies an occupational effective dose limit for radiation workers of 20mSv per year and a 1mSv limit for members of the public [14]. These ICRP limitations and associated guidance feed directly into worldwide regulation regarding control of radiation exposure.

Within the UK, the Air Navigation Order (ANO, 2019) was published by the Civil Aviation Authority (CAA); it places 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[4] member. The ANO forms the basis of regulation in the UK for very high altitude flights and potential future space tourism. The effective dose limits are summarised below:

Table 1
Statutory effective dose limits, per year, for crew from the Air Navigation Order 2019.

No. 1115 Civil Aviation – The Air Navigation Order 2019	
Effective Dose Limits per Calendar Year (mSv)	
Crew Member (CAA Non-Authorised operator)	1
Crew Member (CAA Authorised Operator)	6
Classified Crew Member	20

Table 1 summarises that for a CAA non-authorised operator, (i.e., no Space Industry Act Licence, (or equivalent), approved training or declaration to the CAA), the dose limit to a crew member would be 1mSv (members of the public would be treated as "non-authorised" crew). This is consistent with the limits placed on a UK member of the public under the Ionising Radiation Regulations (IRRs). Further, the exposure limit for a CAA Authorised Operator Crew Member is 6mSv. Under the IRRs (2017) this is more consistent with trainees working with radiation sources or those required to be 'Classified Workers'.

Under the ANO there is no current requirement for real-time 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 of 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.

[4] 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.

2. Atmospheric radiation monitoring, modelling and risk assessment

2.1. Flight radiation detector

There are multiple types of detectors and methods for monitoring radiation exposure depending on the type of radiation and the exposure environment. Tissue-equivalent proportional counters (TEPCs) have served as radiation monitors on-board the ISS and historically on the Space Shuttle. TEPCs are used to monitor the equivalent dose uptake by a function of time, monitoring the energy transfer from incident radiation. TEPCs utilise a sealed gas chamber to monitor ionisations, silicon-based detectors have also been developed and made simpler for flight radiation monitoring [18].

The Smart Atmospheric Ionizing Radiation Atmospheric (SAIRA) detector has been used to monitor the radiation environment during normal flight conditions and also aims to capture significant space weather events [3]. It has been designed and developed by the University of Surrey. The SAIRA detectors use a silicon detector, which has been demonstrated as a suitable technique for aviation dosimetry [8]. The SAIRA detector is based upon the design of the Zenith Radiosonde detectors, also produced at the Surrey Space Centre (SSC) (Dyer et al., 2018), it has been modernized and simplified for use by untrained members of the public or flight crew in a “citizen science” model. Note: the SAIRA detector applies an approximate calibration factor for equivalent radiation doses.

2.2. Atmospheric radiation modelling software

2.2.1. CARI-7 cosmic radiation computer program

CARI-7 is the latest version of the CARI series of models and has been developed by the Federal Aviation Authority (FAA) in early 2021. Like CARI-6 it allows the user to calculate the effective dose from GCR received by a person flying on an aircraft between two points around the globe. Unlike CARI-6, CARI-7 allows for users to calculate doses up to 300,000 ft (91 km). CARI-7 allows for GLEs to be modelled and for a user to input a custom primary particle spectrum.

CARI-7 generated results have been compared with historical measurements from commercial aircraft, high altitude flights and similar calculations. These have demonstrated good agreement with current commercial aircraft altitudes (K. [5]) and good validation for higher balloon flights up to ~100,000 ft.

2.2.2. Model for atmospheric ionising radiation effects [11]

MAIRE is a parametric model based on particle transport calculations in a multi-layered geometry of the atmosphere using the FLUKA (“FLUktuierende KAskade”) Monte Carlo code. The model uses incident GCR or SEPs, and heavy ions input spectra (for GCRs), to calculate fluxes of all relevant particle species for specific latitudes/flight profiles and altitudes up to 100 km. MAIRE allows the user to calculate the secondary radiation caused by GCR and GLE events at varying altitudes within the atmosphere.

The MAIRE model considers a full spectrum of particles for GCR impact events, secondary particles. During GLE events it focuses on primary protons in the GLE spectra [11]. Abundances of higher Z ions will be lower than GCR, but their omission in MAIRE is an approximation suitable for lower altitudes. Note: in MAIRE over 60,000 ft the proton dose from GLE events dominates, hence there is a possibility of underestimating the potential dose uptake. Note: MAIRE has been validated for commercial flights and is subject to ongoing development (F. Lei, 2009, A. Hands, 2017, C. Dyer, 2018).

CARI-7 and MAIRE both allow for outputs in effective dose and ambient dose equivalent.

2.3. Radiation risk assessment

Terrestrial probabilistic radiation risk exposure is used as a basis for the assessment of potential health effects for very high altitude and space tourism flights, namely:

$$R_{Prob} = E \times Drf \times SF \times PMfb$$

Where;

R_{Prob}	Risk probability of adverse health effects for crew/passenger (yr^{-1})
E	Effective Dose (mSv)
Drf	Flight Dose Risk Factor[5]
SF	Radiation Exposure Scenario Frequency (yr^{-1})
PMfb	Aircraft/Spacecraft/Operations Protection Measure Failure Probability (yr^{-1})

To demonstrate that the risk from such radiation exposure is tolerable the terrestrial radiation industry sets a R_{Prob} limit of 1×10^{-4} yr for workers and members of the public. If the risk for any exposure scenario exceeds the risk limit it is deemed intolerable and the exposure cannot be justified without the provision of additional protection measures, e.g. shielding, or mitigation measures. If the R_{Prob} is below the limit then the risk is deemed tolerable, but it is still required to demonstrate that it is ALARA/ALARP and that suitable protection measures have been considered for the identified scenario.

Future work will expand on this formula validating it for the very high altitude and space tourism environment, namely assessing the Flight Dose Risk Factor and potential risk limits for the industry to ensure that exposure during space weather scenarios are ALARA. Note: if doses for exposure scenarios are determined to be less than 1mSv then a deterministic assessment would demonstrate that the exposure is ALARA/ALARP noting that it falls below the effective dose limits. For such a scenario mitigation/protection measures for exposed persons would not necessarily be required, but could be considered as best practice.

NASA recommends a limit of 1 in 750 probability for crew risk and loss of crew [6], which equates to a risk of roughly 1×10^{-3} for flight operations. This limit is less that the terrestrial radiation industry risk limit. Future works will review this limit and the level of acceptable risk for space weather events.

3. Very high altitude flight profiles

Very high altitude balloon flights (VHABFs) 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). VHABFs are also known as “near space” flights, they have a potential duration of 6 to 12 h [20] depending on the commercial entity and proposed flight route. VHABFS are an initial form of space tourism, their pressurised observational balloons will have large viewing windows, Wi-Fi, a bar and bathroom facilities (Space Perspective proposals, 2022).

Table 2 presents the flight profiles that have been considered as part of the initial work at the University of Surrey. These represent the current launch/flight locations that are seen as the front runners in very high altitude aviation in the USA and UK.

[5] D_{rf} reflects the probability of early death per Sievert of effective dose exposure. Terrestrial experience shows that this risk factor ranges from 0.04 for radiation workers to 0.05 for the public. Note: this risk factor does not take into account heredity or other minor health effects; it is solely for the risk of death. Future work will need to review the wider radiation exposure guidance from terrestrial and space studies to determine what the dose risk factor is for the unique exposure environment for the very high altitude flight altitude envelope.

Table 2
Flight profiles VHABF1 – 4 for the USA and UK based launch origin. Flight origin location and landing/splashdown site are based on 6 hour flight time with prevailing wind direction, to a maximum flight level of 30 km. Flight profiles have subsequently been modelled in MAIRE and CARI-7 (see Section 5 for further details).

Flight Profile ID	Flight Type	Flight Origin (Latitude, Longitude)	Flight Destination (Latitude, Longitude)	Peak (max) Altitude of Flights (km)	Vertical Rigidity Cut-Off (GV)
VHABF1	Very high altitude observation balloon flight	Cape Canaveral, Florida, USA (28.5, −80.6)	Atlantic Ocean (28.9, −79.5)	30	5.0
VHABF2	Very high altitude observation balloon flight	Spaceport America, New Mexico, USA (33.0, −107.0)	New Mexico, USA (34.0, 104.1)	30	4.1
VHABF3	Very high altitude observation balloon flight	Spaceport Cornwall, Newquay, UK (50.4, −5.0)	English Channel, UK (50.6, −0.8)	30	2.8
VHABF4	Very high altitude observation balloon flight	Sutherland Spaceport, UK (58.5, −4.5)	North Sea (59.8, 0.1)	30	1.3

4. Space weather events

The initial works to date have focused on radiation exposure during very high altitude flights, as a result of sudden changes in space weather, namely GLEs, which could dramatically effect VHABF profiles identified in Table 2. The spectrum and severity of these potential GLEs events has been defined in the following subsection.

4.1. Particle energy spectrum

Based on works by Dyer [7] on extreme atmospheric radiation environments and single event effects, an analysis of GLEs extreme solar energetic particle events, which have a hard spectra [2], has been conducted. From these works the following event-integrated intensity classifications for GLE events have been defined.

4.2. Very high altitude exposure environment

The influence of potential GLE events makes the exposure environment presented for very high altitude 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 [9]. 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 [1],

Historically, there has been very limited assessment of this very high altitude 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, [1]. 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.

5. Modelling and initial detector results

5.1. SAIRA radiation detector flights

The SAIRA radiation detector has successfully been flown on a number of commercial aircraft flights, from a range of worldwide locations, up to altitudes of ∼43,000 ft. Further, the detector has also successfully been flown multiple times on a Bombardier Global 6500 business jet aircraft, which is capable of flights up 51,000ft,[6] recording radiation exposure data from higher altitudes. The future research works include further planned flights at ∼50,000 ft along with flights on very high altitude balloons up to altitudes of ∼100,000 ft. A summary of all the recent detector flight data (2021–2022) is presented here.

A comparison of SAIRA flight radiation data to modelled VHABF flight profiles is presented in Figs. 1-4:

Fig. 4 presents the initial SAIRA flight data. There is a clear correlation between higher flight levels, i.e., altitude, and the spikes in equivalent dose rates. To date, the SAIRA detectors have not flown during a GLE event, future flights will hope to increase the possibility of monitoring such an event. Further, the initial data supports the modelled profiles presented in Figs. 1-3 for normal GCR conditions, showing the susceptibility of higher altitudes flights.

5.2. MAIRE and CARI-7 modelling results

Fig. 5 shows how the initially modelled flight profiles have shown a noticeable higher dose rate for flights at higher latitudes, e.g. VHABF3 and VHABF4. This aligns with the reduction in protection provided by the Earth's geomagnetic field at varying latitudes, i.e., the higher latitude flight origin location, lower rigidity required for particles to penetrate further into the atmosphere.

Modelling solar conditions as they were in 2020 (emerging from a solar minimum) and noting most current high altitude balloon flights are proposed to fly at ∼30 km (World View Flight Proposals, 2022), the lowest total dose uptake was calculated to be 47μSv. This dose reflects a single 6 hour flight at 30 km from Cape Canaveral modelled in MAIRE (flight profile VHABF1). The highest calculated dose under 2020 GCR conditions was 150μSv, which reflects a single 6 hour flight at 30 km from Sutherland Spaceport (flight profile VHABF4 modelled in CARI-7).

Under these GCR conditions, i.e., where solar output is low and consistent, the highest single flight doses to passengers on a single trip are relatively low. However, for crew who are assumed to make as a minimum one 6 hour flight per week, over a period of a 48 week working year, these doses would equate to a minimum of 2.3mSv (flight profile VHABF1) and a maximum of 7mSv (flight profile VHABF4). This maximum dose is in excess of the level at which a crew member would be required to become a classified worker under UK regulations. Further, the GCR conditions calculated dose rate does not take into account any changes in space weather.

When the GCR doses are combined with the GLE event of 1956, we see that during a strong GLE VHABF4 exceeds the yearly limit for passengers during a single flight of 6 hour duration. Further, during an extreme GLE all flight profiles will exceed the yearly exposure limits for passengers during a single flight. Thus, the effect of GLEs on a single flight and yearly radiation exposure are significant.

The exposure to a GCRs and GLEs for all potential exposure scenarios identified in Table 3 cannot be demonstrated determinis-

[6] Note: flights over 49,000ft are required by aviation regulations to carry a radiation detector.

Table 3
GLE Event Classification compared to 1956 GLE 05 event, frequency of such events, comparison to historically recorded events and estimation of increase on background.[18]

GLE Event Classification	Peak Ground Intensity (%*h) of Event[6] Compared to GLE 05 (1956)	Event Frequency	Comparison to Historic GLE Events & Estimated Increase on GCR Background
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))
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))
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))
Extreme	3000% x GLE 05	1 in 1200 year event (C. Dyer, 2003)	Extreme event, none recorded since modern NM GLE monitoring. Estimated ~ 150000% increase on background (C. Dyer, 2003)

[1] Note: this integral intensity over the whole event.

Table 4
2020 MAIRE and CARI-7 modelled VHABF1–4 effective dose for GCR conditions and varying GLE events for a single 6 hour flight at a maximum altitude of 30 km. Note: MAIRE data is in black text and CARI-7 data is in blue text. Data cells highlighted in red are modelled to be in excess of an effective dose of 20mSv and data highlighted in orange is in excess of 1mSv.

VHABF 6hr Flight Profile at a Maximum Altitude of 30km		Single Flight Effective Dose (µSv)				
		Space Weather Conditions				
MAIRE Modelled CARI-7 Modelled	Flight Origin Latitude[9]	GCRs	GCRs + Weak GLE	GCRs + Strong GLE	GCRs + Severe GLE	GCRs + Extreme GLE
VHABF 1	28.5	4.7E+01	4.8E+01	6.2E+01	1.2E+02	2.3E+03
		6.7E+01	7.8E+01	1.7E+02	5.9E+02	1.6E+04
VHABF 2	33.0	4.9E+01	5.1E+01	6.6E+01	1.3E+02	2.6E+03
		7.4E+01	8.8E+01	2.1E+02	7.5E+02	2.0E+04
VHABF 3	50.4	6.7E+01	7.7E+01	1.6E+02	5.5E+02	1.5E+04
		9.6E+01	1.3E+02	4.4E+02	1.8E+03	5.1E+04
VHABF 4	58.5	1.0E+02	3.7E+02	2.7E+03	1.3E+04	3.9E+05
		1.5E+02	5.7E+02	4.3E+03	2.1E+04	6.2E+05

[1]Note: Table 2 provides full flight path details. Including the latitude and longitude for the flight origin and destination.

Table 5
2020 MAIRE and CARI-7 modelled VHABF1–4 effective dose for GCR conditions and varying GLE events for a weekly 6 hour flight over 48 weeks, at a maximum altitude of 30 km. Note: MAIRE data is in black text and CARI-7 data is in blue text. Data highlighted in red is modelled to be in excess of a yearly effective dose of 20mSv, data in yellow is in excess of 6mSv and data highlighted in orange is in excess of 1mSv.

VHABF 6hr Flight Profile (48 Flights per Year)	Total Yearly Effective Dose (µSv)				
	Space Weather Conditions (Single Yearly Event)				
MAIRE Modelled CARI-7 Modelled	GCRs	GCRs + Weak GLE	GCRs + Strong GLE	GCRs + Severe GLE	GCRs + Extreme GLE
VHABF 1	2.3E+03	2.3E+03	2.3E+03	2.3E+03	4.5E+03
	3.2E+03	3.2E+03	3.3E+03	3.8E+03	1.9E+04
VHABF 2	2.4E+03	2.4E+03	2.4E+03	2.4E+03	4.9E+03
	3.6E+03	3.6E+03	3.7E+03	4.2E+03	2.4E+04
VHABF 3	3.2E+03	3.2E+03	3.3E+03	3.7E+03	1.8E+04
	4.6E+03	4.6E+03	4.9E+03	6.3E+03	5.6E+04
VHABF 4	5.0E+03	5.2E+03	7.6E+03	1.8E+04	4.0E+05
	7.1E+03	7.5E+03	1.1E+04	2.8E+04	6.3E+05

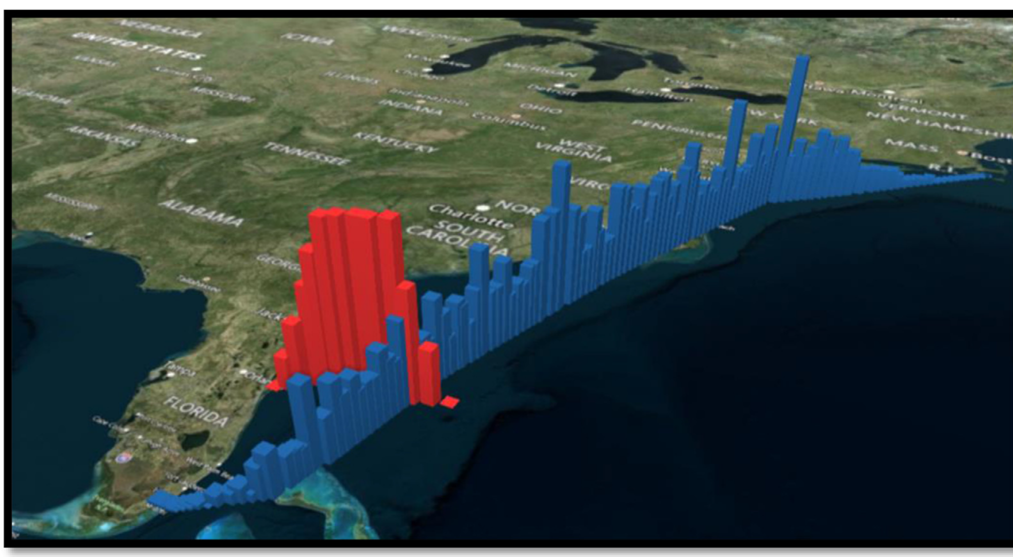

Fig. 1. VHABF1 – SAIRA equivalent dose commercial flight from Miami to Boston at maximum cruise altitude of 33,000 ft, (blue bar chart) during 2021 solar conditions. Compared to the MAIRE-calculated ambient dose equivalent for VABF1 from Cape Canaveral (red bar chart), under 2020 normal GCR conditions, at a maximum cruise altitude of 100,000 ft (30 km).

tically as ALARA/ALARP, i.e., less than 1mSv. Utilising the probabilistic assessment described in Section 2.3 the exposure to severe and extreme GLEs, for VHABF3 and 4, show that potential doses would not be ALARA/ALARP (this notes that there are currently no proposals for safety/protection measures for VHABFs, i.e. radiation shielding,[7] hence a PMfb of 1 is assumed). Therefore, potential mitigation measures and further assessment would be required to ensure the risks associated with possible exposure are ALARA/ALARP.

[7] NASA has flown a potential wearable space radiation protection suit, 'AstroRad', for astronauts on the Artemis I flight in 2022 (https://stemrad.com/astrorad-4/). This suit has been designed for flights beyond LEO and thus would be unlikely to be provided to very high altitude flight crew or passengers.

6. Initial work conclusions

The initial VHABF profiles modelled have shown a noticeable higher dose rate at higher latitudes, e.g., VHABF4. This aligns with the reduction in protection provided by the Earth's geomagnetic field at varying latitudes, i.e., the higher latitude flight origin location, the lower rigidity required for particles to penetrate further into the atmosphere. MAIRE and CARI-7 models indicate that VHABFs are very susceptible to changes in space weather, during stronger GLE events. This is largely due to their flight profiles, altitude and long cruise time at high altitude.

Going forward VHABF enterprises will be equally affected by the very limited availability of radiation exposure data and modelling of the flight exposure environment, especially during events such as the 1956 GLE; which can occur with no warning. Hence, there is currently insufficient data for commercial or indepen-

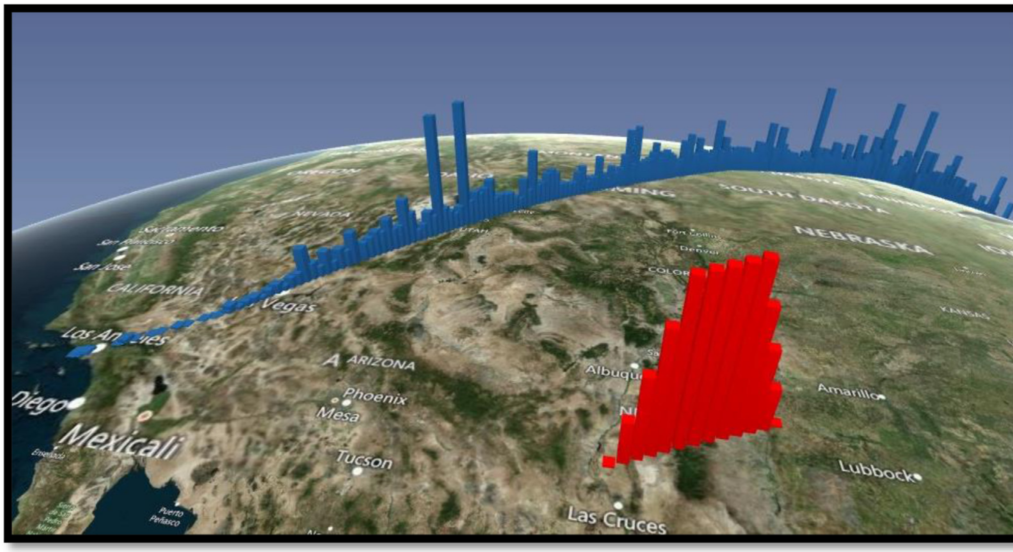

Fig. 2. VHABF2 – SAIRA equivalent dose for a commercial flight from Los Angeles to London at maximum cruise altitude of 33,000 ft, (blue bar chart) during 2022 solar conditions. Compared to the MAIRE calculated ambient dose equivalent for VABF2 from Spaceport America (red bar chart), under 2020 normal GCR conditions, at a maximum cruise altitude of 100,000 ft (30 km).

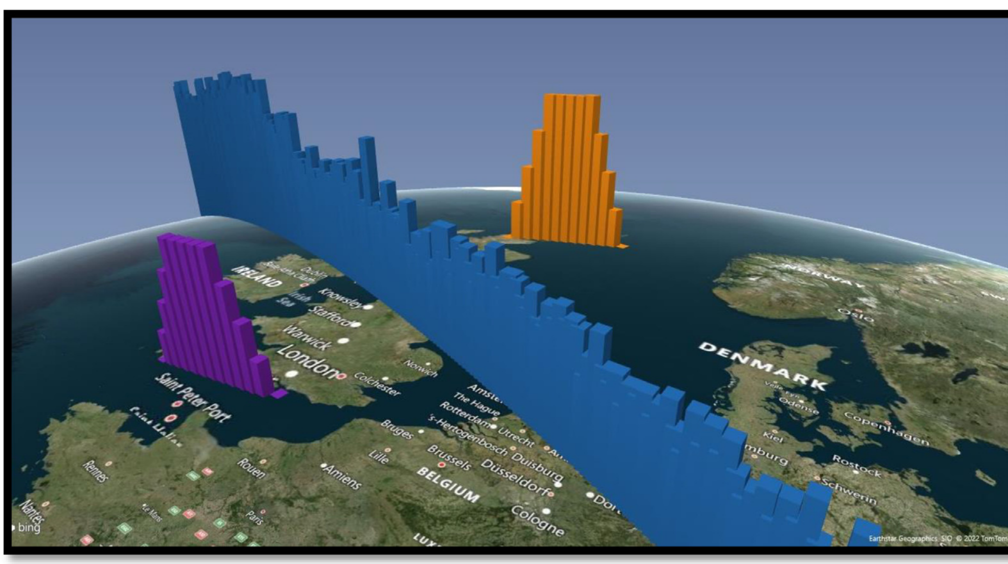

Fig. 3. VHABF3 – SAIRA equivalent dose for a flight from Budapest to New York City at maximum cruise altitude of 43,000 ft (blue bar chart) during 2022 solar conditions. Compared to the MAIRE calculated ambient dose equivalent for VHABF3 from Spaceport Cornwall (purple bar chart) and VABF4 from Sutherland Spaceport (orange bar chart), under 2020 normal GCR conditions, at a maximum cruise altitude of 100,000 ft (30 km).

dent bodies to accurately assess the level of risk from exposure on either type of flight. Further, on-board monitoring should be conducted to increase the available data and ensure/validate that these models are accurate. SAIRA flights to date have not recorded any GLE events, further flights will increase the likelihood of possible detection, especially as the solar maximum approaches.

The probabilistic risk assessment has initially shown that the risks associated with severe and extreme GLE are not tolerable for either crew or passengers, i.e., a risk of significant health effects in excess of 1×10^{-4} yr. However, this formula is based on terrestrial radiation exposure. The probabilistic assessment will be developed further with the focus on the near space environment, with comparisons made to the terrestrial radiation industry to assess the tolerability of the risks associated with exposure due to changes in space weather, such as GLEs. This will include advice on deterministic assessment and potential stochastic effects of exposure.

6.1. Risk management

6.1.1. Space weather flight decisions

To ensure that the radiation risks associated with VHABFs are ALARA/ALARP evidence will need to be provided of suitable risk assessment prior to launch. Fig. 6 presents an example space weather decision tree for VAHBF operators, which could provide part of the evidence required for such a risk assessment. Further, the use of such a decision tree would allow for a ‘go/no go’

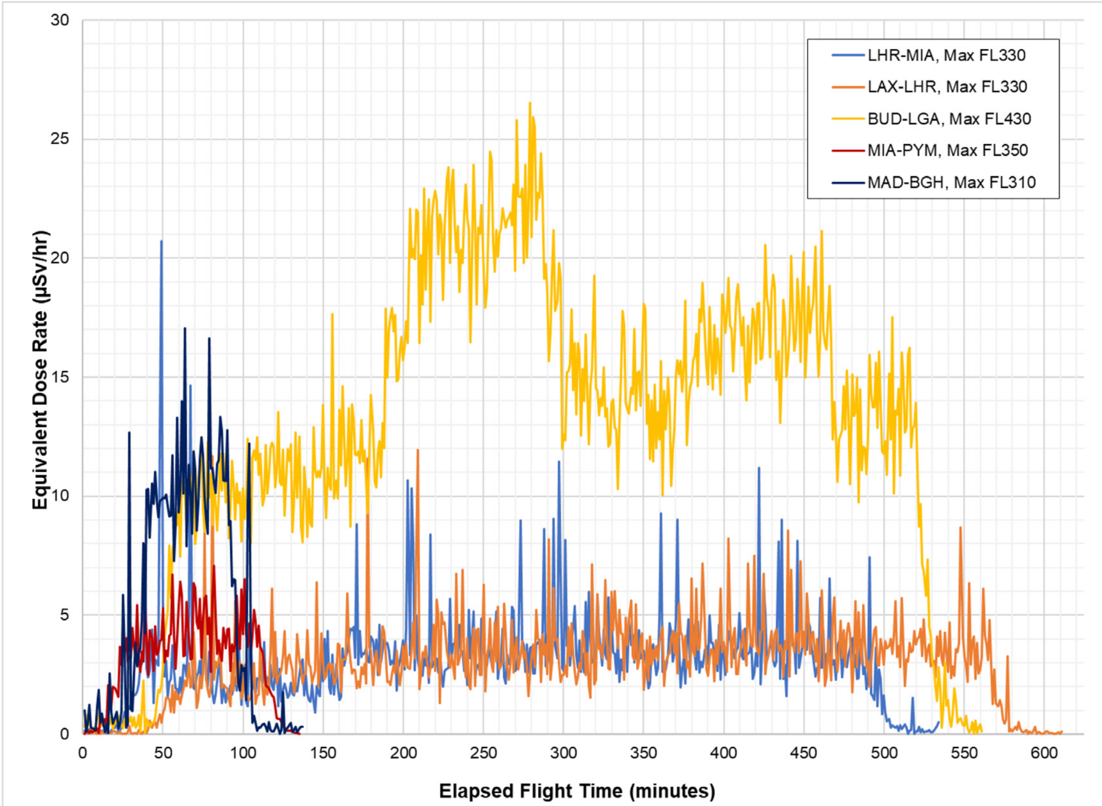

Fig. 4. SAIRA recorded equivalent dose for a number of flights, routes and varying flight levels (30,000 ft to 43,000 ft) recorded on the SAIRA radiation detector. Dose data is displayed against elapsed flight time.

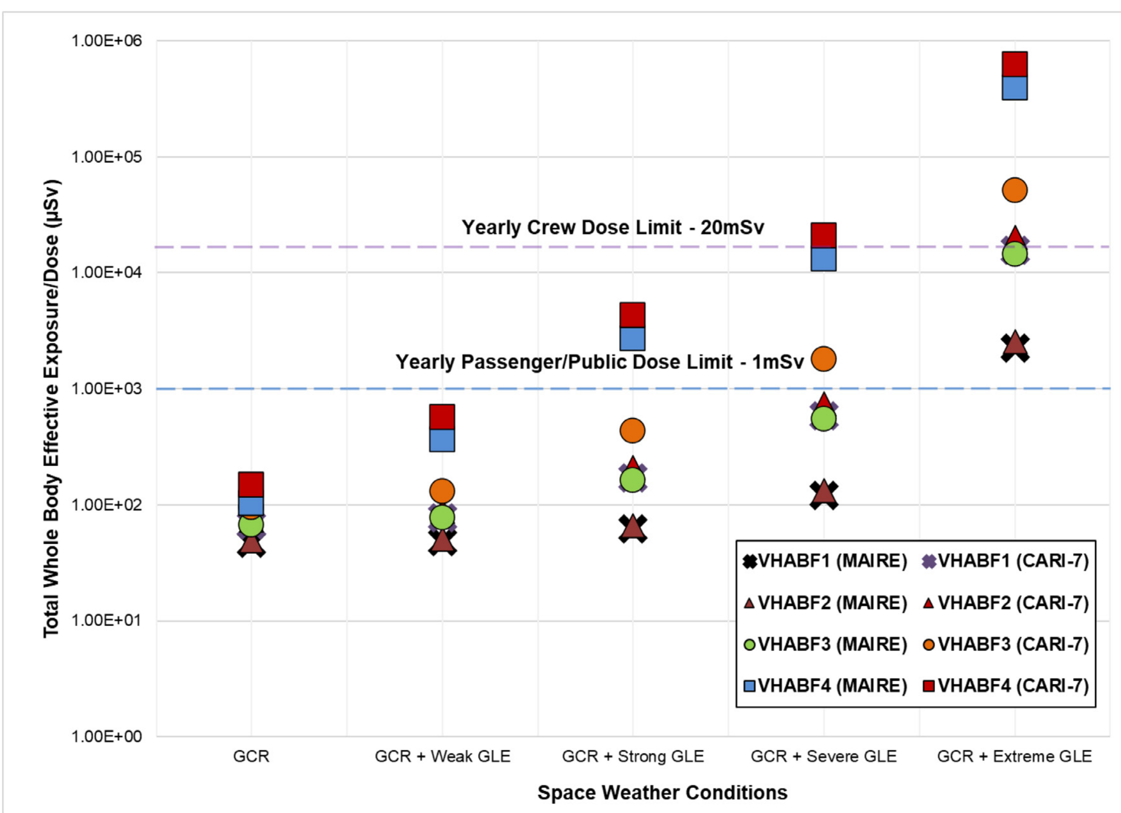

Fig. 5. VHABF1 – 4, total whole body effective dose for whole flight profile. Calculated for 'normal' GCR conditions, varying and increasing Ground Level Enhancement events. Flight profiles for a single 6 hour flight to a maximum altitude of 30 km (~100,000 ft).

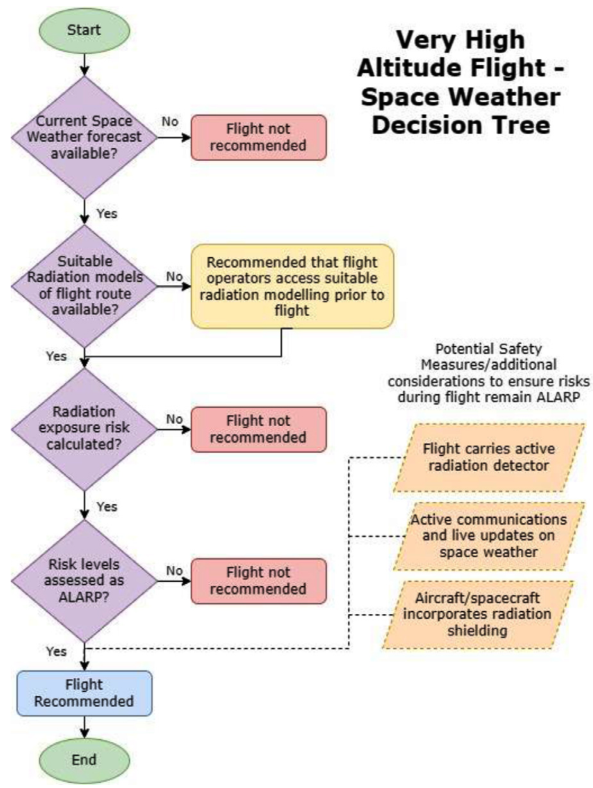

Fig. 6. Radiation risk decision tree/flow diagram for potential space weather effects during a planned very high altitude flight.

for flight operations based on potential space weather scenarios, whilst ensuring that operators acknowledge the potential radiation risks.

The identification and management of the potential space weather risks would ensure that they are ALARA/ALARP, i.e., a probabilistic risk of significant health effects is not in excess of 1×10^{-4} yr. This successful management of such risks would ensure that exposure to normal background radiation levels, and any potential changes in space weather would be addressed and potentially deemed tolerable.

6.2. Future works

The planned future works will be completed in 2024, a summary of the proposed future activities includes:

- Planned SAIRA radiation detector flights at ~15 km (50,000 ft) along with flights on very high altitude long duration (6–12 hour) balloons up to altitudes of ~40 km (130,000 ft).
- Assessment of wider VHABF profiles, in MAIRE and CARI-7, to include extended flight durations, i.e., 12 hour flights, other launch locations and varying flight altitudes.
- Assessment and review of the calculation of the probabilistic risk and overall radiation risk from the industry.
- Review of the frequency of GLE events and likelihood of impact on VHABFs.
- Regulator advice/recommendations, specifically around real time monitoring, actions upon detection of changes in space weather, potential mitigations for radiation exposure and pre-flight guidance to ensure radiation risks area ALARA/ALARP.
- Development of a guidance/template for a risk based safety assurance case for VHABFs.
- Consideration of non-GLE space weather events that could result in elevated radiation levels.(Table 4, Table 5).

Declarations of 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, Methodology, Software, Investigation, Visualization, Writing – original draft. **K.A. Ryden:** Writing – review & editing, Supervision, Validation. **A.D.P. Hands:** Writing – review & editing, Supervision, Validation. **B. Clewer:** Writing – review & editing, Resources.

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