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A sensitivity analysis of the factors that influence the hazard potential of fusion power plants

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ABSTRACT

A robust safety case for a fusion power plant for electricity generation must demonstrate that the radiological risk to workers and the public under any credible accident scenario is as low as reasonably practicable (ALARP). Whilst the hazard potential of a fusion power plant is significantly less than that of a fission power plant, a fusion power plant will still contain radiological inventories. From the work done in previous fusion safety studies and the current work being undertaken for the ITER project, it has been established that there are certain accident scenarios in which a part of these radiological inventories can be released into the atmosphere, potentially posing a risk to workers and members of the public. The actual radiological risk to an exposed person depends on a multitude of factors including type of inventory released, quantity released, height of release, weather conditions and age of person exposed, amongst others. The aim of this paper is to assess the radiological dose received by an exposed population under a variety of conditions, to put these releases into context by comparing them with sheltering and evacuation emergency reference levels (ERLs) and to discuss the impact of siting a fusion power plant near local populations.

1. Introduction

As things stand, there is currently no detailed final design of a fusion power plant for electricity generation. Work on the EU-DEMO (DEMO) facility is at a very early stage with the current aim of having DEMO operational in 2050. However, it is increasingly likely that designers will wait for the results of key experiments scheduled for ITER before deciding on a final design (the first experiments at ITER are not scheduled to begin until 2025) which could delay this date. More rapid progress is being made on a number of smaller spherical tokamak ventures and it is reasonable to expect that the first commercial fusion power plant may have a design that is markedly different to that of DEMO. Nevertheless, whatever the design solution, it is important to understand the size and nature of the hazard posed by fusion power plants.

As detailed in [1], the radiological inventories expected in a fusion power plant that have the potential to give rise to an off-site hazard are tritium (used in fuel), activated dust (formed due to the erosion of plasma facing components) and activated corrosion products (formed due to corrosion within the water cooling loops if water is chosen as the primary coolant). Depending on the breeding blanket type chosen for the fusion power plant, there may be additional source terms that are not mentioned here. In this paper, the atmospheric dispersion modelling tool ADMS-STAR is used to evaluate the impact of a release of radionuclides on the risks to workers and the public. Given that the radioactivity of the tritium and activated dust inventories is generally orders of magnitude higher than that of ACPs, this paper focusses on the impact of releases associated with tritium and dust.

Note this paper is not meant to be part of a safety case for any design of a future fusion power plant, nor is it meant to strongly influence fusion power plant architecture. The authors are not implying that fusion power plants are capable of releasing the identified quantities of radioactive materials or that offsite emergency countermeasures will be required. Whether the release of the quantities of radioactive materials identified in this paper is feasible or realistic will depend upon the fusion power plant design and the measures that are taken to control the radioactive inventory. The sheltering and evacuation emergency reference levels (ERLs) referred to are meant to be reference dose values, which (for the purposes of this paper) would result in the countermeasure being implemented (see Section 7.1). We believe the information provided in this paper is important for designers and operators given that the stated safety goal for fusion power plants is to avoid the need to

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implement any off-site emergency countermeasures to protect the public in the event of an accident. It will be up to designers to demonstrate that (for their fusion power plant designs) any release of HTO or dust will not be sufficient to trigger off-site countermeasures or show that the probabilities of the releases that would trigger off-site countermeasures are acceptably low in order to demonstrate that the doses to the public meet the ALARA/ALARP requirements. The purpose of this paper is simply to illustrate the factors that can influence the relationship between the quantities of radioactive materials (in the form of HTO and activated dust) that need to be released to trigger the lower sheltering and evacuation ERLs.

2. Background

2.1. Overview of model

ADMS-STAR (Short-Term Accidental Releases) [2] is a relatively nascent atmospheric modelling tool developed as part of the ADMS suite, which is used by a number of regulatory authorities in the UK including the Health and Safety Executive (HSE), the Environment Agency (EA), the Scottish Environmental Protection Agency (SEPA) and the Northern Ireland Environment Agency (NIEA). ADMS-STAR differs from standard air dispersion modelling tools in that standard models use a single parameter Pasquill-Gifford stability class to define dispersion parameters. ADMS-STAR, however, characterises the boundary layer structure with two parameters: the boundary layer height and the Monin-Obukhov length; this allows for more accurate dispersion modelling particularly when elevated sources are considered. It is worth noting that ADMS-STAR can only model short-term releases and doesn't factor in processes such as ingestion or re-emission. However, for the purpose of this work, illustrating the quantities of radioactive materials in the form of HTO and activated dust that would need to be released in order to trigger the lower sheltering and evacuation ERLs, this limitation was deemed an acceptable omission.

2.2. Atmospheric stability classes

The transport and dispersion of radionuclides through the atmosphere depends primarily on the speed and direction of the wind, but the vertical mixing of pollutants is strongly influenced by differences in temperature with altitude (known as the lapse rate) [3]. The lapse rate is generally used as an indicator of atmospheric stability, which can essentially be thought of as the tendency of the atmosphere to enhance or resist vertical mixing [3]. Simple dispersion models use stability categories to define atmospheric stability, with the most common being the Pasquill-Gifford (PG) scheme [4]. The PG scheme defines seven atmospheric stability categories ranging from A (very unstable) to G (very stable). These are displayed in Table 1.

Table 1
Pasquill-Gifford stability classes [3].

Stability class	Definition	Most likely occurrence	Frequency of occurrence in central England (%)
A	Extremely unstable	Late morning to mid-afternoon in spring and summer	0.6
B	Moderately unstable	Daytime transitions all year	6
C	Slightly unstable	Daytime transitions all year	17
D	Neutral	Daytime/cloudy; night-time/cloudy; high wind, day transition all year	60
E	Slightly stable	Night-time transition all year	7
F	Moderately stable	Night, clear skies, light winds, all year	8
G	Extremely stable	Night, clear skies, light winds, all year	1.4

Traditional approaches to dispersion modelling used the seven PG stability classes to define boundary layer stability. The advantage of this method is that it requires minimal input data and is a typically empirical approach. It is based on the assumption that the plume (in our case the volume of air that is contaminated with the radionuclides that have escaped from a facility following an accident) concentration distribution follows a normal (or Gaussian) distribution in both the horizontal and vertical directions in all stability conditions (see Section 3). However, field experiments have shown that this is an overly simplistic model, as the lapse rate results in convective eddies of turbulence that grow and rise over time and this adjusts the vertical mixing of pollutants [5]. A more modern approach to dispersion modelling, used in ADMS-STAR and led by recent advances in the field of atmospheric physics, characterises the boundary layer using different parameters. The ADMS-STAR approach does not require PG stability categories as inputs as it combines a range of meteorological conditions to represent different atmospheric stabilities [5]. The two most important parameters in the ADMS-STAR model are the Monin-Obukhov length L_{MO} and the boundary layer height h.

2.2.1. The atmospheric boundary layer

The atmospheric boundary layer, also known as the planetary boundary layer, is the lowest part of the troposphere that directly experiences surface effects due to friction (cause by roughness at the earth's surface) and heating or cooling [3]. The boundary layer generally exhibits turbulence and has a strong diurnal cycle of temperature, wind and related meteorological variables [6]. Changes across the boundary layer occur with timescales typically between a fraction of a second and an hour, whilst the height of the boundary layer also exhibits a pronounced diurnal cycle and varies between tens of metres up to kilometres. The main meteorological factors affecting the depth of the boundary layer are the amount of insolation (sunshine) and wind speed. The state (or stability) of the boundary layer (amount of turbulence, meteorological conditions, etc.) will greatly influence the dispersion characteristics of any plume within it.

From a modelling perspective, the most important atmospheric processes that need to be parametrised are vertical mixing and the formation, sustenance and dissipation of clouds [7]. Surface properties that also have a significant effect on boundary layer stability include albedo (fraction of incident sunlight that the surface reflects), roughness, moisture content and vegetation cover [7]. There are two types of turbulence that dominate throughout the boundary layer: convective turbulence (due to surface heating) and mechanical turbulence (generated by shear at surface). The state of the boundary layer and dispersion behaviour of any pollutants within the boundary layer depend significantly upon which turbulence effect is dominant.

2.2.2. The Monin-Obukhov length

The Monin-Obukhov length gives a relative measure of the significance of buoyancy (generated by heating of the surface) and mechanical turbulence (generated by friction at the surface) and is given by

$$L_{MO} = \frac{-u_*^3}{\kappa g F_{\theta_0} / (\rho c_p T_0)} \quad (1)$$

in which u_* is the friction velocity at the earth's surface, κ (= 0.4) is the von Karman constant, g is the acceleration due to gravity, F_{θ_0} is the surface sensible heat flux, ρ is the density of air, c_p is the specific heat capacity and T_0 is the near surface temperature.

To simplify, we can substitute in a term for buoyancy B, given by

$$B = \kappa g F_{\theta_0} / (\rho c_p T_0) \quad (2)$$

Therefore, the Monin-Obukhov length becomes

$$L_{MO} = \frac{-u_*^3}{B} \tag{3}$$

Physically, the Monin-Obukhov length can be thought of as representing the depth of the boundary layer in which mechanical turbulence dominates [5]. Note in Eq. (3), the friction velocity will increase with increasing wind speed and surface roughness, whilst the buoyancy will increase with increasing surface heat flux. From these parameters, we can define three main categories of stability: unstable, neutral and stable.

2.2.3. Unstable conditions

Convective (unstable) conditions (PG cat A–C) tend to occur on hot sunny days with light winds and strong heating of the earth's surface. This generates warm thermals which rise from the ground and form large convective eddies, resulting in strong convective turbulence. This results in both a large vertical and lateral spread of the plume as it travels downwind. In unstable conditions, the Monin-Obukhov length is negative and the magnitude of L_{MO} represents the height above which convective turbulence dominates over mechanical turbulence. Typically, $|L_{MO}|$ is < 10 m in unstable conditions, whilst the boundary layer depth is large (usually between 1000–2500 m). Therefore, convective turbulence dominates throughout almost the entirety of the boundary layer, with only a shallow layer close to the surface in which mechanical turbulence has a significant role. The more unstable the conditions, the shallower the layer dominated by mechanical turbulence, and the smaller the magnitude of L_{MO}. Note extremely unstable conditions are infrequent in the UK, occurring for less than 1 % of the time.

2.2.4. Neutral conditions

Neutral conditions (PG cat D) commonly prevail on cloudy days with medium to strong wind speeds which cause vigorous mixing of the lower atmosphere. In this case, mechanical turbulence dominates throughout most or all of the depth of the boundary layer, whilst the cloud cover inhibits any heating or cooling off of the ground, reducing any convective eddies of turbulence that would otherwise occur [5]. The vertical and lateral spread of the plume is lower under neutral conditions than in the convective case. In neutral conditions L_{MO} may be either positive or negative but the magnitude of L_{MO} will be very large, demonstrating that mechanical turbulence dominates throughout most or all of the boundary layer, with little effects due to convective turbulence. The magnitude of L_{MO} is generally greater than the height of the boundary layer (typically around 800 m) meaning buoyancy effects do not dominate at any height [5]. Note this is the broadest category and neutral conditions occur over a wide range of times of day and times of year.

2.2.5. Stable conditions

Stable conditions (PG cat E–G) occur on clear, calm nights with strong cooling of the ground and the lower layer of the atmosphere caused by long wavelength radiation to space. In stable conditions the boundary layer tends to form into layers of different densities, such that the denser layers are closer to the ground. These layers act to resist any vertical motion caused by friction effects at the surface, although these layers assembling on top of each other will cause weak turbulence [5]. Temperature inversions typically occur in stable conditions, due to the strong cooling at the surface, and the vertical and lateral spread of the plume is lower in the stable case compared to the neutral and unstable cases. In this case, L_{MO} is a measure of the height above which vertical turbulent motion is considerably suppressed by the stable stratification. Despite the small value of L_{MO} (typically less than 20 m) in stable conditions, mechanical turbulence still dominates throughout a significant portion of the boundary layer due to the reduced boundary layer height (typically between 100–200 m) [5]. Note in the UK very stable conditions occur only a few percent of the time.

3. Methodology

3.1. Puff dispersion model

ADMS-STAR employs a puff model to simulate the dispersion of a release. The release is represented as a series of instantaneous puffs, which may increase in number over time; these puffs are then advected independently in a manner defined by the local meteorological conditions. In order to calculate the activity/concentration field at any particular time, the model simply sums the activity/concentration field from each puff at that time [2]. The instantaneous puffs are characterised by their position and size, which are given as spread parameters; these spread parameters are updated on a timescale shorter than the timescale on which the meteorology changes.

3.1.1. Concentration

Each individual puff is described by its centre position (x_c, y_c, z_p) and spread parameters σ_x, σ_y, σ_z. The model represents the activity/concentration distribution for each individual puff as Gaussian in the along-wind and cross-wind directions and Gaussian or skewed-Gaussian in the vertical. The concentration due to an individual puff at a given time is given by

$$C(x,\ y,\ z,\ t) = \frac{M_s}{(2\pi)^{3/2}\ \sigma_x\ \sigma_y\ \sigma_z}\exp\left(\frac{-(x-x_c)^2}{2\sigma_x^2}\right)\exp\left(\frac{-(y-y_c)^2}{2\sigma_y^2}\right)$$
$$\left\{\exp\left(\frac{-(z-z_p)^2}{2\sigma_z^2}\right) + exp\left(\frac{-(z+z_p)^2}{2\sigma_z^2}\right) + exp\left(\frac{-(z-2h+z_p)^2}{2\sigma_z^2}\right)\right.$$
$$\left. + \exp\left(\frac{-(z+2h-z_p)^2}{2\sigma_z^2}\right)\exp\left(\frac{-(z-2h-z_p)^2}{2\sigma_z^2}\right)\right\}$$

in neutral and stable conditions in the presence of an inversion, where M_s is the total mass in the puff and h is the boundary layer height [2]. For convective conditions, stable conditions with no inversion, or for a puff that penetrates through the boundary layer the term in curly brackets is replaced with appropriate vertical terms for plumes.

3.1.2. Advection

The model then updates the puff properties based on the meteorological conditions at the position of the puff at that time at the mean puff height. In the presence of an inversion, the mean puff height z_m is given by

$$z_m(t) = \frac{\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_0^h z\ C(x,\ y,\ z,\ t)dz\ dy\ dx}{\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_0^h C(x,\ y,\ z,\ t)dz\ dy\ dx}$$

Note the upper limit of the integral in z is given by h as material that passes through the boundary layer height is dealt with separately.

3.1.2.1. Position. The position of the centre of the puff is given by

$$x_c(t+\Delta t) = x_c(t) + \Delta t U_x(z_m,\ t)$$
$$y_c(t+\Delta t) = y_c(t) + \Delta t U_y(z_m,\ t)$$
$$z_c(t+\Delta t) = z_c(t) + \Delta t(\mathrm{U}_z(z_m,\ t) - v_s + w_{pr})$$

where U_x, U_y, U_z represent the wind speed components at the mean puff height at time t, and the vertical term contains components for gravitational settling v_s and plume rise w_{pr}. The vertical position must always be greater than or equal to 1.5 z_0 where z_0 is the local roughness length [2].

3.1.2.2. Spread parameters. To update the spread parameters, the model calculates the change in the standard ADMS spread parameters that would have occurred during the same time step assuming the current meteorological conditions (at the mean puff height) experienced by the puff had been experienced since the start of the release. The spread parameters are given by

$$\sigma_x^2\left(t+\Delta t\right) = \sigma_x^2(t) + \Delta t\ \frac{\partial \sigma_x^2}{\partial t} + \Delta \sigma_{pr}^2$$

$$\sigma_y^2\left(t+\Delta t\right) = \sigma_y^2(t) + \Delta t\ \frac{\partial \sigma_y^2}{\partial t} + \Delta \sigma_{pr}^2$$

$$\sigma_z^2(t+\Delta t) = \sigma_z^2(t) + \Delta t\ \frac{\partial \sigma_z^2}{\partial t} + \Delta \sigma_{pr}^2$$

where σ_{pr} is the change due to plume rise.

3.2. Dry deposition

In the model, the rate of dry deposition is assumed to be proportional to the near-surface concentration, as given by

$$F_{dry} = v_d C(x,\ y,\ 0)$$

where F_{dry} is the rate of dry deposition per unit area per unit time, v_d is the deposition velocity (either specified or calculated within the model), and $C(x,\ y,\ 0)$ is the predicted concentration at ground level [2]. The deposition velocity actually contains two components, the diffusive velocity $v_d^{'}$ (usually referred to as deposition velocity only), and an additional element due to gravitational settling that in the model depends on a single parameter v_s, the terminal velocity of a particle. Note in all releases considered, v_s was not a fixed parameter and was calculated within the model as a function of the diameter and density of the particles released.

The overall deposition velocity v_d is expressed as

$$v_d = \frac{v_s}{1 - \exp(-v_s/v_d^{'})}$$

Note in the limit $v_s \to 0$ we find $v_d \sim v_d^{'}$.

3.3. Wet deposition

As the plume travels, the amount of material incorporated into any falling precipitation is ΛC per unit area per unit vertical distance per unit time, where Λ is the washout coefficient and C is the local airborne concentration [2]. Assuming no re-emission, the total wet deposition rate per unit horizontal area per unit time is expressed as

$$F_{wet} = \int_0^\infty \Lambda C\ dz$$

where z is the vertical direction. It follows that the plume strength decreases with downwind distance. Note in the model, Λ takes into account both in-cloud scavenging (rainout) and below-cloud scavenging (washout). The washout coefficient Λ varies with the nature of the isotope modelled, precipitation rate, droplet size distribution, and isotope concentrations in the air and in raindrops. In the model, it is estimated as

$$\Lambda = AP^B$$

where P is the precipitation rate and the values of A and B for all isotopes are 0.0001 and 0.8, respectively [2].

3.4. Radiological dose

The short-term (early) dose is calculated for an exposure time of 48 h and takes into account the following:

- internal exposure induced through inhalation of radioisotopes
- external exposure to deposits on the ground
- external exposure to radioactive plume
- absorption of tritium through skin

The calculations involved in these processes will be discussed briefly here.

3.4.1. Inhalation dose

The model calculates the inhalation dose (ID) for each isotope as follows

$$ID = TIC \times ir \times DCF$$

where *TIC* is the time integrated concentration for the isotope, ***ir*** is the inhalation rate, and *DCF* is the dose conversion factor for inhalation of the isotope. The default inhalation rate (1.2 m^3/hr in accident conditions) and dose coefficients are taken from ICRP 119 [8]. In this section, the dose coefficient values are taken from Table G.1 – the effective dose coefficients for inhalation (activity median aerodynamic diameter =1 μm) of radionuclides for members of the public up to 70 years of age, with the worst cases for adults selected. Note for tritiated water (HTO) the inhalation dose is multiplied by 1.5, in order to account for the dose due to absorption of HTO through the skin [9].

3.4.2. External exposure to ground deposits

To calculate this dose contribution, we must first calculate the total ground deposition by integrating over the exposure time

$$\text{Time integrated ground deposition} = \int_0^t D(x,\ y,\ z,\ t)\ dt$$

where $D(x,\ y,\ z,\ t)$ is deposition as a function of position and time. Then for each isotope we must introduce a dose coefficient for exposure to contaminated ground surfaces $h_{T_{ground}}$ (taken from Federal Guidance Report No. 12 [10]) to calculate

$$\text{Dose due to ground deposits} = \text{Time integrated ground deposition} \times h_{T_{ground}}$$

3.4.3. External exposure to plume

Similar to above, for each isotope we must introduce a dose coefficient for air submersion $h_{T_{air}}$ (taken from Federal Guidance Report No. 12 [10]). Then

$$\text{Dose due to exposure to plume} = TIC \times h_{T_{air}}$$

The total dose is then calculated by summing all these doses.

4. Model validation

In order to validate the model, it should, ideally, be compared with either experimental data, or, if this is not possible, with predictions from other models. In the case of tritium releases it was possible to validate the model by comparing its predictions with measurements derived from experimental field studies. The validation of the model for dust releases was more problematic, as it was not possible to obtain experimental release data for dust particles that are likely to be produced in fusion reactors. To get around the lack of experimental data, the model predictions were compared with the dust calculations reported in the ITER Preliminary Safety Report (RPrS), as this is regarded as the most comprehensive safety analysis for a large fusion facility that is currently available [11]. The RPrS data was also used to validate the model for tritium releases.

4.1. Model validation using the Canadian HT study

An experimental release of tritium (in the form HT) was carried out at the Chalk River Meteorological Field in Canada in June 1987 [12]–[14]. The purpose of this experiment was to understand how tritium would behave if released under accident conditions, and to develop further knowledge about the dose conversion values of HT. Around 3.54 T Bq of HT was released at 15:20 on June 10th 1987 at a steady rate over a 30 min period from a height of 1 m above the surface. The whole field consisted of a grassy circular section with a diameter of 183 m and a sparsely vegetated patch 226 m long [13]. The temperature and humidity were measured at a distance of 100 m from the release point and had values of 21 °C and 34 %, respectively. The mean wind speed was measured at 2.4 m/s and was roughly 20° off the field centreline (see Fig. 1).

Air samplers for tritium gas (HT) and tritiated water vapour (HTO) were located at distances ranging from 50 m to 400 m from the release point. Japan Atomic Energy Research Institute (JAERI) also participated in this experiment to compare HT concentrations with those predicted by its Gaussian plume dispersion model and to observe HT and HTO deposition and re-emission rates from soil [13]. Fig. 2 shows the results generated by the ADMS-STAR model when these source terms and meteorological parameters are inputted.

It can be seen from Fig. 2 that the model agrees well with experimental data at all distances from the source. It is worth noting that whilst a fraction of the released HT is converted into tritiated water (HTO) in air, this fraction is relatively small, and has no significant effect on the average HT concentration in air. A process that may have a significant effect on dose, however, is the conversion of HT to HTO in soil, followed by re-emission of HTO to the atmosphere (HTO's dose conversion factor is 10,000 x larger than HT's) - a process that ADMS-STAR does not account for. Nevertheless, it will be shown that, as a conservative assumption, any tritium released from a fusion reactor in an accident scenario is assumed to already be in HTO form. In this case, deposition and re-emission of HTO does still occur; however, it results in a negligible increase in dose received by an exposed person [9]. For the purposes of this work, assessing the magnitude of risk to workers and the public that a fusion power plant poses, this re-emission process can be overlooked.

4.2. Model validation using the ITER RPrS

The RPrS [11] used the CERES and GAZAXI codes to study the effects of tritium and dust releases (these are established codes and are approved for use by the French regulatory authority ASN) [15].

4.2.1. Weather and dose assumptions

The RPrS incorporates the Doury dispersion parameter set [16], which consists of only two different stability categories: normal diffusion and weak diffusion. Normal diffusion corresponds to unstable or neutral atmospheric conditions (PG classes A to D) and is characterised by a vertical temperature gradient less than or equal to -0.5 °C/100 m. Weak diffusion corresponds to stable or very stable atmospheric conditions (PG classes E to G) and is characterised by a vertical temperature

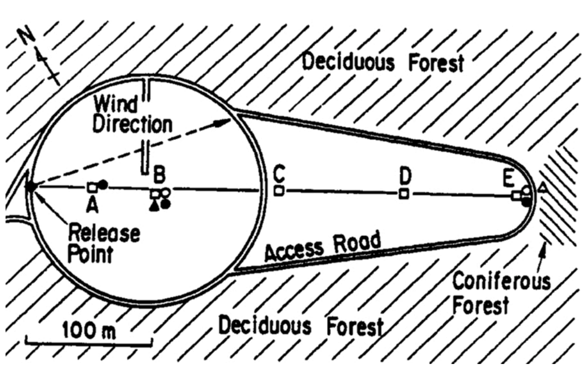

Fig. 1. Chalk River Meteorological Field illustrating field centreline and various receptor points. Source: [13].

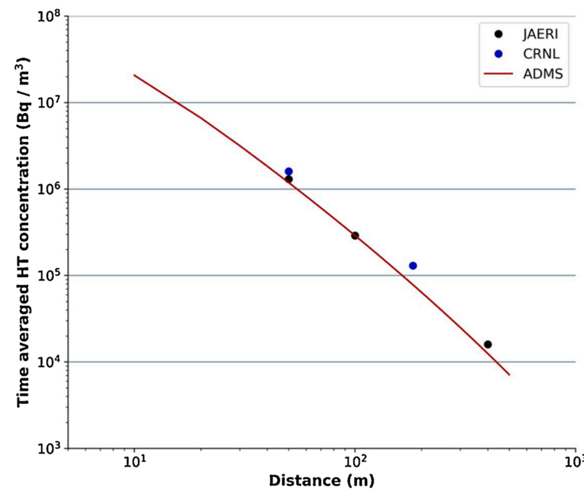

Fig. 2. Comparison of ADMS-STAR model with Chalk River National Laboratories (CRNL) and JAERI's experimental results. Note both axes are on a logarithmic scale.

gradient greater than -0.5 °C/100 m [17]. In the RPrS, calculations are performed for:

- weak atmospheric diffusion and a wind speed of 2 m/s, so called DF2;
- normal atmospheric diffusion DN and a wind speed of 5 m/s, so called DN5;
- normal atmospheric diffusion DN and a wind speed of 5 m/s, with rain (5 mm/hr), so called DN5P

In addition to this, the air temperature and relative humidity are assumed to be 20 °C and 80 %, respectively.

Early dose (as defined in the RPrS) considers an exposure time of 48 h at a short distance. Receptor points are located at distances of 200 m, 1 km, 2 km, 2.5 km, and 3.5 km; however, only the measurements at 200 m consider wholly early dose effects; measurements at all other distances take into account long-term effects such as ingestion. Early dose takes into account:

- internal exposure induced through inhalation of radioisotopes
- external exposure to deposits on the ground (dust only)
- external exposure to radioactive plume
- absorption of tritium through skin (HTO only)

4.2.2. Release characteristic assumptions

If the ratio between stack height and height of the surrounding buildings is less than 2.5, building wake effects can potentially occur. This creates a turbulent zone in the near-field, resulting in increased vertical mixing close to the building, effectively creating a downwash effect and dragging the plume down in the near-field [15]. In order to account for this, the effective release point is calculated by dividing the stack height by a factor of 2.

In the design of ITER considered in the RPrS, the release is from a stack that protrudes about 4 m above the roof of the tokamak building, which itself is 54 m above ground, giving a release height of 58 m. The surrounding buildings, however, have a height of around 54 m, meaning building wake effects have to be considered. In the RPrS, the effective release height is taken to be 30 m (roughly half of the actual release height). Note in certain accident scenarios, some of the release may be leakage through building walls; this is represented as a ground level release [11]. For all releases considered, a nominal release duration of one hour and an adult breathing rate of 1.2 m^3/hr have been assumed.

4.2.3. Source term assumptions

A number of assumptions have been made in the RPrS in relation to the source terms for tritium and activated dust.

4.2.3.1. Tritium. Whilst there is only expected to be a very small amount of tritium actually in the plasma at any one time (~1–2 g), tritium can accumulate both on the surface of and inside plasma facing materials. In the event of an accident, this tritium can mobilise and potentially follow a release pathway out to the environment. In the RPrS, the tritium source term is estimated at 1 kg with an activity of 3.57E+17 Bq (note this takes into account both tritium in the cryopumps and tritium in the co-deposited layer of plasma facing components). In each accident scenario considered, this source term is mobilised and assumed to be entirely in the form of HTO. This is a conservative estimate, as HTO is not only the most mobile form of tritium but also has the largest inhalation dose coefficient (1.8E-11 Sv/Bq) [8]. Note only a fraction of this 1 kg source term is assumed to escape to the environment in the scenarios considered, as the ITER design employs multiple engineered barriers and defence in depth.

4.2.3.2. Activated dust. In the RPrS, the activated dust is assumed to be tungsten from within the vacuum vessel (VV) as this provides conservative radiological consequences (due to the high activation of tungsten). The maximum dust inventory that can be accumulated inside the VV in ITER is assumed to be 1000 kg, and this is used to determine the dust source term considered [11]. Note if the accident scenario also triggers a large plasma disruption, an additional 5 kg of tungsten dust is assumed to be produced, increasing the dust inventory to 1005 kg. Similar to the tritium case, it is assumed that only a fraction of this 1000 kg source term actually escapes to the environment in the scenarios considered, because of the effectiveness of ITER's engineered barriers.

Generally, the dust found in fusion devices has the composition of the walls that make up the plasma-facing surfaces [18]. The wall of the plasma facing components (PFCs) in ITER will be made of tungsten and beryllium; however, the isotopes generated from the activation of tungsten dominate over those from activated beryllium (in terms of activity released). Therefore, neutron activation calculations have been performed on tungsten (as part of the ITER safety case) in order to estimate the quantities of each expected radionuclide present in activated tungsten dust (see Table 2). Note in the RPrS the dust particles are all assumed to be 1 μm in diameter.

Table 2
Nuclide composition of activated dust source terms in RPrS. Note activity is given in Bq per gram of dust released; dose conversion factor for inhalation of particles of diameter 1 μm taken from ICRP 119. Source: [8,15].

Nuclide	Activity (Bq/g)	Dose conversion factor for inhalation (Sv/Bq)
W187	1.04E+11	2.00E-10
W185	3.72E+10	1.40E-10
Re186	1.97E+09	1.10E-09
Ta182	1.67E+08	9.70E-09
Re188	1.19E+09	5.50E-10
W181	1.43E+10	2.80E-11
Ta183	6.40E+07	2.00E-09
Co60	1.27E+06	2.90E-08
Re184	1.99E+07	1.80E-09
Ta184	4.33E+07	4.40E-10
Ta179	2.74E+07	5.20E-10
Ag110m	3.72E+05	1.20E-08
Co58	1.14E+06	2.00E-09
Ta186	6.40E+07	1.90E-11
Mn54	2.57E+05	1.50E-09

4.2.4. Additional input assumptions

On top of the release characteristics (see Section 4.2.2) and radionuclide source term inventories detailed above, it is worth noting any additional assumptions made in the model. For all releases, surface roughness length is set at 0.3 m (standard value for this parameter), surface albedo is set at 0.23 (model default), and deposition velocity is calculated within the model for each run. The boundary layer h and the Monin-Obukhov length L_{MO} values depend significantly on the atmospheric stability type being simulated and were initially set as follows

DF2 (weak diffusion/stable conditions): $h = 100$ m, $L_{MO} = 20$ m

DN5 (normal diffusion/neutral conditions): $h = 800$ m, $L_{MO} \to \infty$

DN5P (normal diffusion/neutral conditions with rain at 5 mm/hr): $h = 800$ m, $L_{MO} \to \infty$

In both DN5 and DN5P stability conditions, L_{MO} tending to infinity is a representation of mechanical turbulence dominating throughout the entirety of the boundary layer, with little effects due to convective turbulence. Note these values are merely input values for these parameters; as the model iterates through time these values will change. DF2 conditions are represented by relatively clear skies (1 okta), whereas DN5 and DN5P conditions are characterised by cloudy skies (8 oktas). For a release of dust, the half-life, density, particle size, and inhalation dose coefficient of each radioisotope had to be entered. All dust particles were assumed to be 1 μm in diameter (as in the RPrS) and their respective half-lives and inhalation dose coefficients were taken from ICRP 119 [8].

4.2.5. ADMS-STAR model comparison with ITER RPrS predictions

4.2.5.1. Elevated releases. Table 3 shows a comparison between the model and the RPrS early dose predictions for a 1g release of both tritium (in HTO form) and activated dust from a 58 m stack (30 m effective) under DF2, DN5 and DN5P conditions.

The table shows that for an elevated release the model is in reasonable agreement with the ITER RPrS early dose predictions for both HTO and dust at a distance of 200 m. It can be seen that for DF2 weather conditions, the model and the RPrS agree well. For DN5 weather conditions, however, the model overpredicts the doses at 200 m by a factor of about 2. For DN5P weather conditions, the model again overpredicts the HTO dose at 200 m by a factor of 2, but slightly underpredicts the

Table 3
Comparison of ADMS-STAR and RPrS early dose (mSv) predictions for a 1 g release from 58 m stack; dose is calculated at a distance of 200 m from the source.

	Weather conditions					
	DF2		DN5		DN5P	
Source	ADMS	RPrS	ADMS	RPrS	ADMS	RPrS
HTO	2.81E-08	2.50E-08	5.40E-02	2.10E-02	5.33E-02	2.10E-02
Dust	1.91E-10	1.80E-10	4.15E-04	2.00E-04	3.17E-03	4.00E-03

Table 4
Comparison of ADMS-STAR and RPrS early dose (mSv) predictions for a 1 g release from ground level; dose is calculated at a distance of 200 m from the source.

	Weather conditions					
	DF2		DN5		DN5P	
Source	ADMS	RPrS	ADMS	RPrS	ADMS	RPrS
HTO	4.79	4.50	0.20	1.90	0.20	1.80
Dust	3.05E-02	3.80E-02	1.55E-03	1.70E-02	3.53E-03	2.40E-02

dust dose. Given the uncertainty in the meteorological conditions considered in the RPrS calculations, this seems an acceptable level of accuracy for the model. Hence, the model can be considered validated for elevated releases for all weather conditions.

4.2.5.2. Ground releases. Table 4 shows a comparison between the model and the RPrS early dose predictions for a 1 g release of both tritium (in HTO form) and activated dust from ground level under DF2, DN5 and DN5P conditions.

Table 4 shows that for ground level releases under DF2 conditions, the model slightly overpredicts the HTO dose and slightly underpredicts the dust dose at 200 m when compared with the RPrS values. For the DN5 and DN5P conditions, the ADMS model underpredicts both the HTO and dust doses by a factor of about 10. This may be due to the uncertainty in the meteorological conditions considered in the ITER RPrS, or due to the advanced modelling processes that are taken into account in the model and absent from the CERES/GAZAXI codes (such as characterising the boundary layer using h and L_{MO}). Nevertheless, a robust safety analysis of any potential releases of radionuclides should take into account worst-case weather conditions. Table 4 shows that for the ground level worst-case weather conditions (DF2), the model can be considered validated for the use in the analysis of risk in this paper.

5. Reference case

Before performing any sensitivity analysis, it is necessary to present a reference case. This reference case should be based on realistic assumptions that are expected to be present in a fusion power plant, which then allows individual parameters to be modified and the effects observed. Given the validation results in Section 4.2.5, the following scenario has been used as the reference case for a representative fusion power plant:

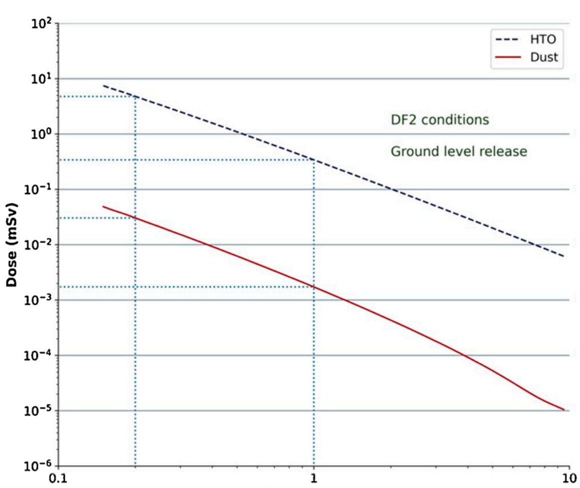

Fig. 3. Early dose for 1 g release of dust and HTO from ground level under DF2 conditions.

- Release of 1 g of activated dust/tritium in HTO form
- Release period of 1 h
- Ground level release
- DF2 weather conditions
- Particle size of 1 μm
- Dust nuclide composition (see Table 2)
- Adult breathing rate of 1.2 m^3/hr

This scenario can be considered a best estimate calculation for a representative fusion power plant, as it provides a realistic set of assumptions that result in a maximum dose to exposed individuals. Fig. 3 illustrates the early dose received by an adult as a function of distance from the source for this reference scenario – the distances of 200 m and 1 km have been highlighted to represent the site boundary and the closest expected population, respectively.

6. Sensitivity analysis

Given the lack of a detailed design for a fusion power plant, it is important to consider the sensitivity of the risks predicted in the reference case to changes in the key assumptions in order to see if any have a significant effect on the risk outcome. The key parameters investigated in the sensitivity study are:

- Release height;
- Dust particle size;
- Release time; and
- Weather conditions

6.1. Release heights

6.1.1. Overview

The results given in Section 4 show that release height can have an effect on the dispersion behaviour of a release of HTO or dust which in turn impacts the dose received by an exposed population. The purpose here is to investigate the effect of the release height on the dose received by the public. Various release heights have been investigated rather than just the two release heights considered in the RPrS [11].

In a number of accident scenarios considered in the RPrS, hot water enters the vacuum vessel (VV) and undergoes rapid evaporation, producing steam which pressurises the vessel. As a result, any mobilised inventories of tritium and dust are initially transferred to the drain and suppression tanks. Given that there is no failure of the primary confinement barrier and hence there are no leaks into adjacent rooms and no uncontrolled leaks into the environment, the only potential environmental releases are controlled releases via the suppression tank vent system (ST-VS) and associated detritiation systems, i.e. via the stack. It is therefore crucial to understand what effect the stack release height has on any potential releases. This information will be useful to fusion power station designers whose challenge involves ensuring the radiological consequences of any accident scenarios are minimised.

6.1.2. Release characteristics

If the ratio between stack height and height of the surrounding buildings is less than 2.5, building wake effects can potentially occur [15]. In order to account for this, the approach taken in the ITER RPrS was to calculate the effective release height by dividing the stack height by a factor of 2. As there is currently no detailed design for a fusion power plant for electricity generation, the plant layout and the relative heights of the discharge stack and surroundings buildings is unknown; hence, it is not possible to accurately model building wake effects. Therefore, for the purposes of these calculations, it is assumed that no building wake effects occur. The release heights considered were ground level, 5 m, 10 m, 20 m and 30 m.

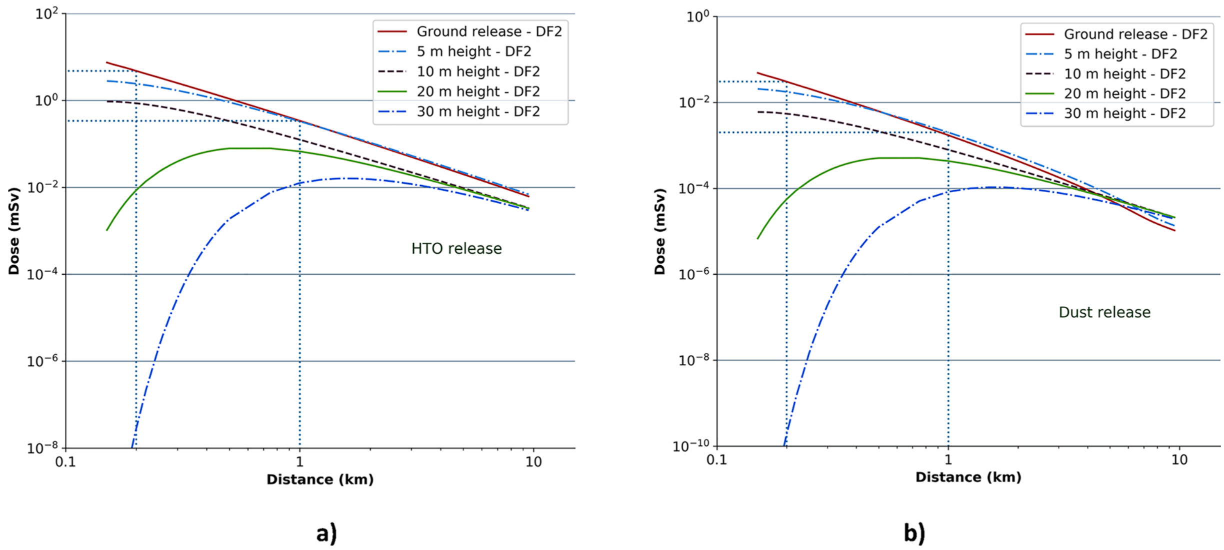

Fig. 4. Early dose for 1 g release under DF2 conditions for a range of release heights for **a)** HTO and **b)** dust.

All calculations assume DF2 weather conditions, a release of 1 g of tritium in HTO form or 1 g of activated dust, a nominal release duration of one hour and an adult breathing rate of 1.2 m^3/hr.

6.1.3. Results

Fig. 4 illustrates the early dose (mSv) received by an adult as function of distance from the source for a range of release heights under DF2 conditions. On each of the plots the distances of 200 m and 1 km are highlighted to reflect a nominal person located at the site boundary and in the surrounding area.

For HTO releases, Fig. 4a shows that as the release height increases, the dose to the exposed person decreases at all distances. This is most notable as the release height is increased above 10 m, as there is a sharp reduction in dose to the exposed person at all distances up to around 500 m. In the case of activated dust, Fig. 4b again shows that at distances up to around 6 km from the source, the dose to the exposed person reduces as release height increases. However, there is a crossover around this point, and beyond this distance the higher release heights show an increase in dose compared to that of the reference case.

These results are explained primarily due to the reduced vertical mixing that takes place in DF2 conditions: the plume undergoes little dilution and so, as the release height is increased, less of the plume is mixed and brought down to ground level, resulting in a smaller dose to any exposed persons near the source. In the case of HTO, this effect is less pronounced as distance from the source increases, as the plume has travelled further downwind and so has undergone further dilution and is eventually brought to the ground. In the case of dust, as distance increases beyond 6 km the trend seems to reverse, i.e. the 20 m and 30 m release heights result in a larger dose compared to the release heights closer to the ground. There are two primary reasons for this: 1) at these distances the plumes that were released from the elevated heights have travelled a sufficient distance in order to be brought down to ground level, increasing the dose received and; 2) the increased deposition that occurs close to the source from near-ground releases results in a plume of much lower concentration travelling downfield. Hence, at a distance of around 6 km the plumes from near-ground releases have a lower concentration than plumes from elevated releases that have been brought to the ground. This results in the lower dose received from near ground-level releases.

In virtually all cases, as the release height is increased, the doses at 200 m and 1 km decrease[1] . Further, in both the HTO and dust cases, there is a considerable drop in dose received at 200 m and 1 km as release height is increased to 30 m; however, this margin reduces as distance from the source increases.

6.2. Dust particle size

6.2.1. Overview

Developing a source term for activated dust in a fusion power plant is problematic as the dust inventory depends on a multitude of factors. Estimates of dust production rates depend upon the material type, location, plasma pulse length and disruption frequency [18]. In the RPrS it is assumed that the dust particles are all spherical with a diameter of one micron; however, in reality this is not the case. *Sharpe et al.* participated in a study in which they compared collected dust from a number of research devices including the Tokamak Fusion Test Reactor (TFTR) at Princeton, Alcator C-Mod at MIT, JET at Culham, ASDEX-Upgrade at the Max Planck Institute and the NOVA laser facility at the Lawrence Livermore National Laboratory [18]. Collection took place during periods of schedule maintenance, when the vacuum chamber is vented, and personnel can access the plasma chamber. They found that whilst most dust particles found in present fusion devices do generally exhibit a roughly spherical surface-to-volume ratio, the diameter of the particles span a range of values (see Fig. 5).

The size distribution shown in Fig. 5 was obtained with dust collected at the lower divertor region of ASDEX-Upgrade. The figure shows measured size frequency data together with a fitted lognormal distribution [18]. *Sharpe et al.* also compared average dust sizes from different regions of the various fusion devices and found that the average particle size for this data is 2.8 ± 2.4 μm [18]. However, due to the lognormal nature of the size distribution, it is expected that dust found in fusion machines will typically range from 0.5–10 μm in diameter [18]. They concluded that the similarity in the dust size distributions for the various devices suggests similar processes are involved in their production, mainly via condensation of material eroded during plasma-surface interactions [18].

[1] The only exception to this is at a distance of 1 km, the dose due to a release of dust from a height of 5 m is slightly higher than the dose due to a ground level release

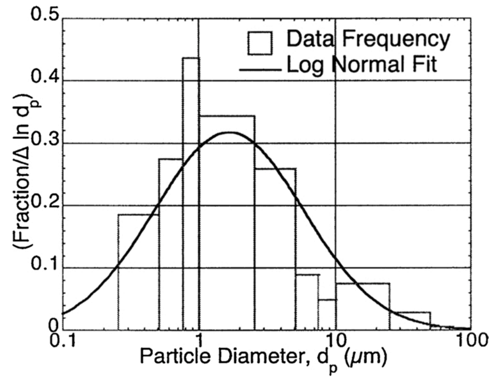

Fig. 5. Typical count-based size distribution of dust from a fusion device. Source: [18].

6.2.2. Release characteristics

In order to investigate the effect of particle size on radiological dose, the model was used to simulate a 1 g release of dust particles of the following sizes: 1, 2, 3, 4 and 5 μm. These sizes were chosen as they cover a significant range of the particle sizes expected in a fusion power plant (see Fig. 5) and any trends between sizes should be discernible.

Given that dust particles have potential release pathways at ground level and via the stack, both ground level and elevated releases (30 m) were considered. For both release heights worst-case weather conditions were assumed: for ground level releases DF2 conditions were assumed (to allow comparison with the reference case); for elevated releases DN5P conditions were assumed. All calculations assume a nominal release duration of one hour and an adult breathing rate of 1.2 m^3/hr.

6.2.3. Results

As shown in Fig. 6b, for elevated releases as the size of the dust particles increase the dose received also increases up to a distance of around 8 km. This seems to be a product of the increased deposition that occurs as the particle size increases, contributing to the overall dose (note this trend was seen in both cases where wet and dry deposition was accounted for and dry deposition only). As a comparison, an elevated release of 1 g of dust particles of diameter 1 μm under DN5P conditions results in a dose of 3.17E-03 mSv at 200 m and 6.05E-04 mSv at 1 km; whilst a release of particles of diameter 5 μm under the same conditions results in a dose of 5.82E-03 mSv at 200 m and 1.12E-03 mSv at 1 km – an increase of nearly 85 % at both distances. Note that at a distance beyond 8 km there seems to be no distinction between the doses due to the various particle sizes.

The effect of particle size on dose is more complex for ground level releases under DF2 conditions. Fig. 6 shows that whilst the dose received up to a distance of around 400 m shows the same trend as for elevated releases (dose increases as particle size increases), the size of this increase was significantly lower than in the elevated case. On top of this, beyond this distance the trend is reversed, i.e. dose decreases as particle size increases. This again can be explained by the increased deposition that occurs due to the larger particles: in the ground level case, the increased deposition of large particles that occurs close to the source results in a plume of significantly lower concentration travelling downfield, hence a reduction in dose received.

In the RPrS it is assumed that all dust particle released are 1 μm in diameter; however, the results of this analysis suggest that, at least for an elevated release, a range of particle sizes should be taken into account in any comprehensive safety analysis. Whilst the effect of particle size on dose seems modest for a ground level release, for an elevated release under DN5P conditions particles of diameter 5 μm result in a dose almost twice as large as particles of diameter 1 μm (up to a distance of around 1 km). As particles of this size are expected to be produced in a fusion power plant, any robust safety case will either need to provide confidence that this assumption is incorrect and any particles produced are 1 μm in diameter (or close to), or it will need to take into account dust particles of different sizes.

6.3. Release time

6.3.1. Overview

Varying the length of the release time may have an effect on the dose received. All accident scenarios considered in the RPrS have a release time of one hour; however, it is possible for accident scenarios to have different release times. One such factor that can influence release time is the rate of thermal outgassing of tritium from hot surfaces, which appears to be highly dependent on factors such as temperature and humidity [19].

6.3.2. Release characteristics

In order to establish any effects of release time on dose, the following release times were considered: 1 min, 1 h, 2 h and 5 h. These choices were considered sufficient to cover a range of potential scenarios, from

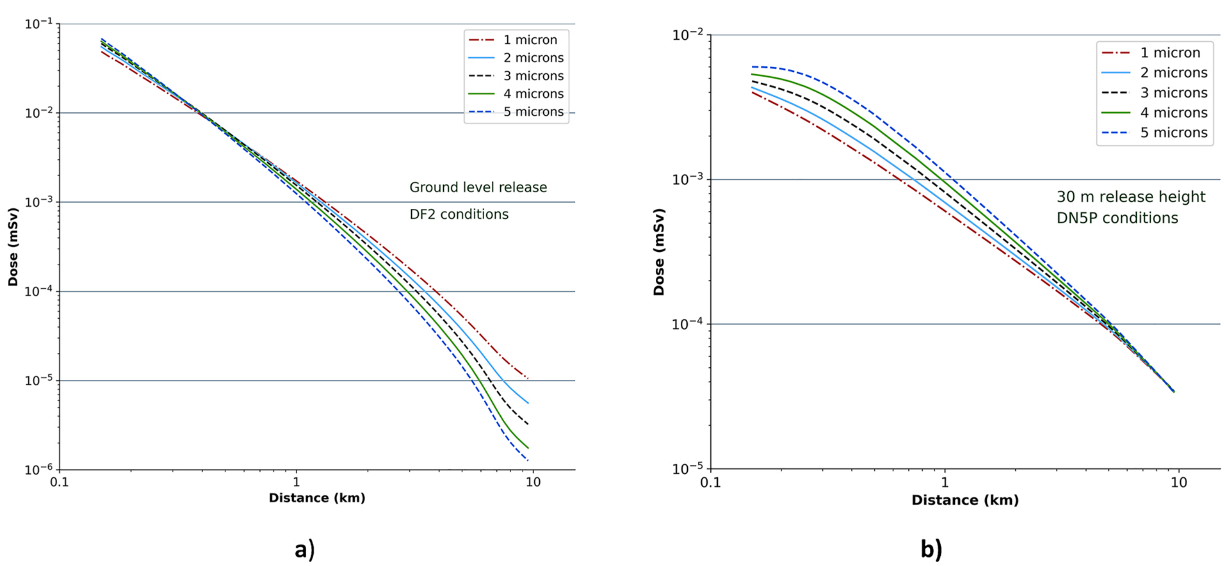

Fig. 6. Early dose for 1 g of activated dust released for a range of particle sizes for **a)** ground level release under DF2 conditions and **b)** elevated (30 m) release under DN5P conditions.

an almost instantaneous release of the source term to a prolonged release that may either go unnoticed by operators or take a considerable length of time to rectify. As radionuclides in a fusion power plant are expected to have multiple release pathways, both ground level and elevated (30 m) releases were considered here.

All calculations assume DF2 weather conditions, a release of 1 g of tritium (in HTO form) or 1 g of activated dust, and an adult breathing rate of 1.2 m^3/hr. It is worth noting that in a real-world scenario there would be changes in wind direction and velocity over time, which would result in a reduction of the maximum dose received; however, for the purposes of this sensitivity study, it is assumed that the meteorological conditions are held constant throughout the modelling period.

6.3.3. Results

For all of the release times considered, there was no significant difference in dose received at all distances. This was the case for elevated releases and ground level releases for both HTO and activated dust. The consequence of this analysis is that fusion plant designers and operators must ensure that limiting the overall quantity of radionuclides released to the atmosphere is a priority, as reducing the rate of release has no significant effect on dose received (assuming the overall inventory released is the same).

6.4. Weather conditions

6.4.1. Overview

The weather conditions at the time of release play a pivotal role in determining how a plume of radionuclides are transported through the atmosphere (see Section 2.2), which may significantly affect the dose received by any exposed persons. We therefore investigated the effect of alternate weather conditions on dose received to determine the magnitude of this effect.

6.4.2. Release characteristics

Consistent with the validation process in Section 4.2, the following weather conditions were considered: DF2 (reference case), DN5 and DN5P. These choices were considered sufficient to cover a range of potential scenarios and include a range of meteorological phenomena (e.g. wet deposition). Note, as radionuclides in a fusion power plant are expected to have multiple release pathways, both ground level and elevated releases are considered here.

All calculations assume a release of 1 g of tritium (in HTO form) or activated dust and an adult breathing rate of 1.2 m^3/hr.

6.4.3. Results

6.4.3.1. Ground level releases. For HTO releases, Fig. 7a shows that DF2 conditions result in the maximum dose received at all distances considered; DN5 and DN5P conditions result in largely similar doses at all distances, with DN5 conditions resulting in a slightly increased dose at distances greater than 1 km. In the case of activated dust, Fig. 7b shows that up to around 3 km, DF2 conditions result in the maximum dose to any exposed persons; at distances beyond this, DN5P conditions result in the maximum dose. These results can similarly be explained by the reduced vertical mixing that takes place in DF2 conditions: once the plume is released from ground level, it undergoes little dilution upon reaching any exposed persons and therefore results in a larger dose. In the cases of DN5 and DN5P conditions the increased vertical mixing acts to raise the plume up into the atmosphere, resulting in increased dilution and a lower dose to any exposed persons. In the case of activated dust, beyond a distance of 3 km DN5P conditions result in a larger dose than DF2. This may be due to the increased deposition that occurs close to the source in DF2 conditions, resulting in a plume of lower concentration travelling downfield, hence a lower dose to any exposed persons.

It is clear from these figures that when considering worst-case weather conditions for ground level releases of radionuclides (e.g. conditions that will lead to a maximum dose close to the plant), DF2 conditions will need to be assumed. For HTO and activated dust (up to a distance of around 3 km), DF2 conditions result in the largest dose to any exposed persons, consistent with the findings of the RPrS [11]. It is worth noting that the early doses calculated in the model at a distance of 200 m considering a ground level 1 g release of both HTO and activated dust under DN5 and DN5P conditions are around 1/10th of the values reported in the RPrS (see Section 4.2.5.2). At this stage it is unclear which predicted values are closer to the true value, due to the number of assumptions made and lack of experimental data to validate to.

6.4.3.2. Elevated releases. As shown in Fig. 8, elevated releases tend to exhibit the opposite effect to ground level releases, i.e. for elevated releases, DF2 conditions result in the lowest dose close to the plant whereas DN5P conditions tend to result in the maximum dose close the plant. This again is primarily explained by the reduced vertical mixing that takes place under DF2 conditions: if the plume is released from a large height under DF2 conditions, the plume will travel a significant distance downfield before it is brought to the ground, resulting in an extremely low dose close to the plant and an increasing dose up to a

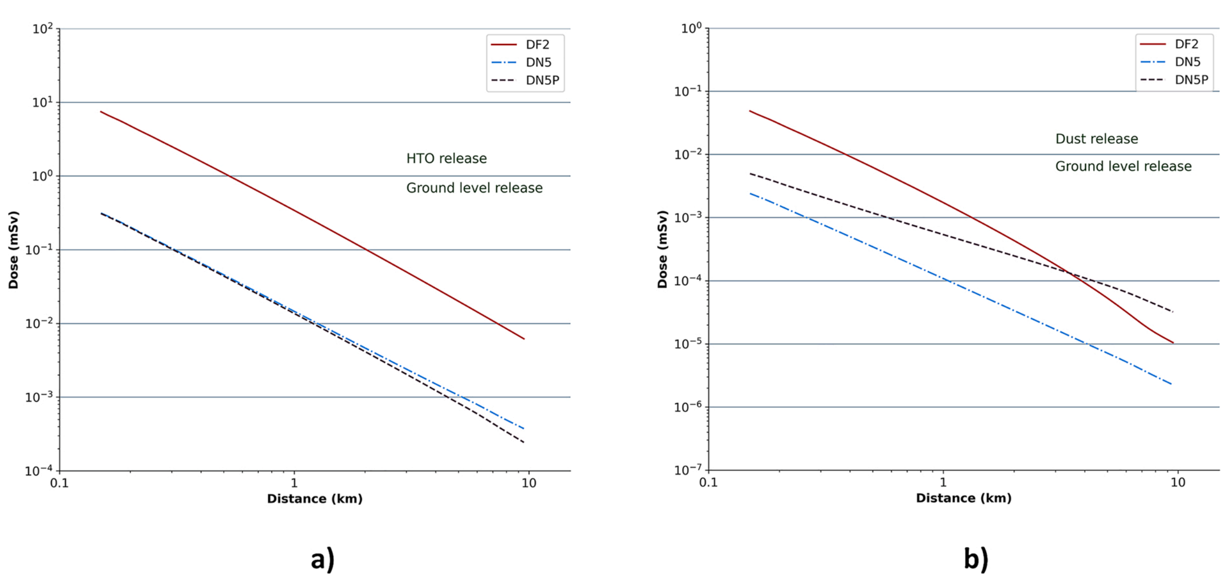

Fig. 7. Early dose for 1 g ground level release for a range of meteorological conditions for **a)** HTO and **b)** dust.

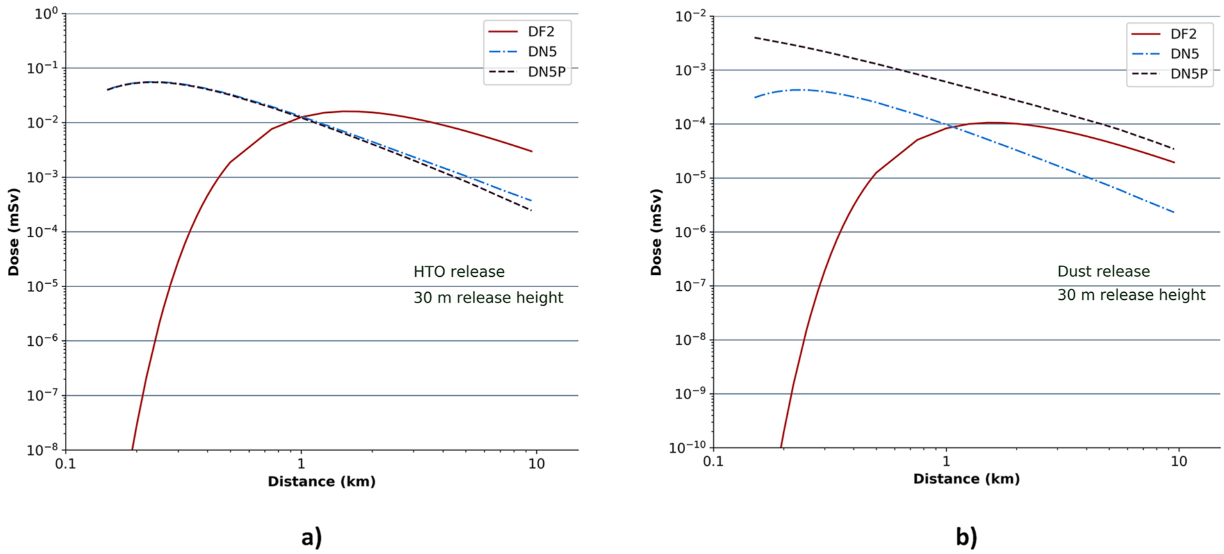

Fig. 8. Early dose for 1 g elevated (30 m) release for a range of meteorological conditions for **a)** HTO and **b)** dust.

distance of around 1.5 km. Conversely, in DN5 and DN5P conditions, the increased vertical mixing acts to bring the plume to the ground much closer to the release point, resulting in a much larger dose. In the case of dust, DN5P conditions results in a larger dose compared with DN5 as a result of the wet deposition that occurs in the DN5P case and is absent in the DN5 case - the increased quantities of dust on the ground contributes significantly to the early dose received. It is clear from these figures that when considering worst-case conditions for elevated releases, DN5/DN5P conditions will need to be assumed for HTO and DN5P conditions will need to be assumed for dust, consistent with the findings in the RPrS [11].

6.5. *Sensitivity study findings*

The sensitivity study shows that a number of parameters can influence the dose received from an accident that results in a release of HTO or activated dust. The release height is particularly important and ground level (or near ground) releases result in the highest radiation exposure at both 200 m and 1 km. Particle size has a relatively modest effect on ground level releases, but for elevated releases larger particles can result in doses up to two times greater than smaller particles at distances up to around 1 km. Release duration time has no significant effect on dose at any distance. Meteorological conditions at time of release can have a significant impact, but in a safety case analysis it is normal to use the most conservative conditions in order to provide a bounding assessment. Hence, the development of a safety case for a fusion power plant will need to be design specific.

7. Hazard potential

The above analysis shows that for a release of 1 g of tritium (in HTO form) and 1 g of activated dust under the most conservative weather and release height conditions, the radiation exposure to a worker at a distance of 200 m would be just under 5 mSv, with the major proportion of the dose coming from tritium. At 1 km a member of the public would receive a dose of around 0.34 mSv, with the major proportion of the dose again coming from tritium. The risk of harm is dependent upon the probability of occurrence x consequence and hence in the absence of a detailed design (from which the probability could be determined) the acceptability of these levels of exposure cannot be determined.

Moreover, fusion power plants are expected to contain inventories much larger than the 1 g considered here (e.g. recent estimates of inventories expected at DEMO are up to 4.7 kg for tritium and up to 689 kg/year for dust [20]). In the absence of a detailed design, one way to scope the hazard potential is to consider the size of the release that would be needed to trigger emergency preparedness countermeasures such as sheltering and evacuation.

Table 5
UK Emergency Reference Levels (ERLs).

	Dose equivalent level (mSv)	
Countermeasure	Lower	Upper
Sheltering	3	30
Evacuation	30	300

7.1. *Emergency preparedness countermeasures*

In the case of nuclear fission, countries that have nuclear power programmes are required by international conventions to have emergency preparedness arrangements to mitigate the consequences in the event of a nuclear accident. These requirements are usually delivered through national legislation, although this varies between countries [21]. In the UK, the Health and Safety at Work Act 1974 [22] requires employers to protect both their employees and the public from work activities. Specific regulations are used to set out requirements and place specific responsibilities on duty holders. The regulations relating to radiation emergencies are the Radiation (Emergency Preparedness and Public Information) Regulations 2019 (REPPIR 2019) [23]. REPPIR 2019 defines a radiation emergency as an event that is likely to result in

Table 6
Inventory release quantities required to trigger sheltering.

		Quantity released to reach 3 mSv dose limit			
Release height	Inventory	At 200 m	At 500 m	At 1 km	Weather
Ground release	HTO	0.6 g	3 g	9 g	DF2
	Dust	98 g	481 g	1.7 kg	DF2
5 m	HTO	1 g	3 g	9 g	DF2
	Dust	169 g	487 g	1.5 kg	DF2
10 m	HTO	3 g	9 g	24 g	DF2
	Dust	549 g	1.4 kg	3.8 kg	DF2
20 m	HTO	25 g	73 g	211 g	DN5
	Dust	831 g	2.2 kg	5.0 kg	DN5P
30 m	HTO	56 g	91 g	231 g	DN5
	Dust	946 g	2.3 kg	5.0 kg	DN5P

Table 7
Inventory release quantities required to trigger evacuation.

		Quantity released to reach 30 mSv dose limit			
Release height	Inventory	At 200 m	At 500 m	At 1 km	Weather
Ground release	HTO	6 g	27 g	88 g	DF2
	Dust	984 g	4.8 kg	17.3 kg	DF2
5 m	HTO	12 g	33 g	91 g	DF2
	Dust	1.7 kg	4.9 kg	14.9 kg	DF2
10 m	HTO	35 g	89 g	239 g	DF2
	Dust	5.5 kg	14.2 kg	37.9 kg	DF2
20 m	HTO	250 g	729 g	2.1 kg	DN5
	Dust	8.3 kg	22.4 kg	49.9 kg	DN5P
30 m	HTO	556 g	906 g	2.3 kg	DN5
	Dust	9.5 kg	22.9 kg	49.6 kg	DN5P

Table 8
Inventory release quantities to trigger evacuation.

		Quantity released to reach 30 mSv dose limit		
Release Type	Particle size	At 200 m	At 500 m	At 1 km
Ground release DF2	1 μm	984 g	4.8 kg	17.3 kg
	2 μm	890 g	4.7 kg	18.3 kg
	3 μm	833 g	4.7 kg	19.5 kg
	4 μm	804 g	4.9 kg	21.6 kg
	5 μm	767 g	5.1 kg	24.2 kg
Elevated (30 m) DN5P	1 μm	9.5 kg	22.9 kg	49.6 kg
	2 μm	8.4 kg	19.4 kg	43.3 kg
	3 μm	7.1 kg	15.8 kg	36.8 kg
	4 μm	6.1 kg	13.0 kg	31.4 kg
	5 μm	5.2 kg	10.7 kg	26.8 kg

a member of the public receiving an effective dose in excess of 1 mSv in the period of one year immediately following the event (note this is a reduction of the 5 mSv limit previously specified in REPPIR 2001 [24]). These regulations require emergency plans to make use of countermeasures to limit radiation exposure.

The UK emergency countermeasures use "Emergency Reference Levels" (ERLs) published by Public Health England [25], which are based on the whole body dose expected to be averted if the countermeasure is deployed following a radiation emergency (see Table 5).

The dose levels in Table 5 are based on approximations and are not intended to be strict trigger values for implementing the countermeasure. However, for the purposes of this paper the lower dose levels will be used as a reference point for each countermeasure, i.e. the dose level that requires the countermeasure to be implemented.

7.2. Hazard analysis

The validated ADMS-STAR model was used to investigate the quantities of tritium (in the form of HTO) and activated dust that need to be released in order to trigger the sheltering and evacuation lower ERL countermeasures. The aim of this work was to put the release quantities into context with a view to establishing the feasibility of such releases and identify important design features that could influence the release quantities. A matrix of calculations was used to investigate the impact of release height, particle size and weather conditions on the HTO and activated dust quantities.

7.2.1. Impact of release height

For these calculations a release period of 1 h and particle size of 1 μm was assumed. Table 6 shows the quantities of tritium (in the form of HTO) and activated dust that would need to be released to trigger the 3 mSv lower sheltering ERL for a range of release heights. Table 7 shows the quantities needed to trigger the 30 mSv lower evacuation ERL. In both tables the worst-case weather conditions have been used in the model calculations for each release height (i.e. conditions that require the least amount of material to be released to trigger the ERL). This is to put into perspective the release quantities that could feasibly be released at each height and result in the triggering of sheltering or evacuation protocols.

The general trend shown in the tables is that as release height is increased, the quantity of material needed to be released in order to hit the ERL increases.

7.2.2. Impact of particle size

For these calculations a release period of 1 h was again assumed. Two release heights were adopted to investigate the effect of particle size on release quantities; for both release heights worst-case weather conditions were assumed. Table 8 shows the quantities of dust needed to be released to trigger the 30 mSv lower evacuation ERL.

For elevated releases, as the particle size increases the quantity of material needed to be released to hit the 30 mSv lower evacuation ERL decreases. For ground level releases, at a distance of 200 m this same trend is shown, i.e. as the particle size increases the quantity of material needed to trigger the ERL decreases. However, at both 500 m and 1 km as the particle size increases the quantity of material needed to be released to trigger the ERL increases: a product of the increased deposition of these larger particles close to the plant.

8. Discussion

8.1. Weather conditions

It is clear from these results that the meteorological conditions at the time of release play a crucial role in determining how a plume of escaped radionuclides will diffuse and transport through the atmosphere, thus determining the severity of the dose received by any exposed persons. If the release is from ground or near ground level, it has been shown that DF2 conditions will result in the maximum dose to any exposed persons located up to around 3 km from the plant, whilst for an elevated release DN5/DN5P conditions result in the maximum dose up to around 1 km for HTO and 10 km for dust. This is primarily due to the amount of vertical mixing (i.e. dilution) that the plume undergoes once released from the plant. This is significant as the weather conditions then determine the quantity of radioactive inventory that would need to be released to trigger sheltering or evacuation protocols. Any robust safety case would therefore need to take into account worst-case weather conditions and ensure that the design of the plant has sufficient engineered barriers and defence in depth so that the radiological consequences of any feasible accident scenario will not result in sheltering or evacuation of surrounding populations.

8.2. ADMS-STAR

In this study the ADMS-STAR model was used to model a release of radionuclides expected to be present in a fusion power plant. Prior to this, however, the model was initially validated against experimental data and, where this was not possible, with predictions from the RPrS developed for ITER. The model was successfully validated for all elevated releases and for ground level releases under DF2 conditions; however, the model significantly underpredicted the ground level doses under DN5 and DN5P conditions when compared with the RPrS. At this stage, it remains unclear which predictions are closer to the true value, as there is a lack of real-world data to validate to. Nevertheless, for the worst-case conditions for both elevated and ground level releases, the model successfully predicted the dose within a suitable degree of accuracy. The model was then used to simulate a reference case scenario, and to investigate the magnitude of the effect of changing certain parameters.

8.3. Reference case and sensitivity study

In order to investigate the effect of changing certain parameters, a reference case was used to allow a suitable comparison. The chosen reference case was based on realistic assumptions that are expected to be present in a fusion power plant and included a ground level release of 1 g of tritium (in HTO form) and 1 g of activated dust and a release period of 1 h under DF2 conditions. The sensitivity study then involved varying release heights, release duration, weather conditions and dust particle sizes to study the effect on dose to any exposed persons.

The study showed that there are a number of parameters that can affect the dose received due to a release of HTO or activated dust. The primary factors were release height and weather conditions, as together they greatly influence the transport and dispersion of radionuclides and therefore determine the dose received by any exposed persons. From this analysis the dust particle size had a modest effect on dose, and release duration had no discernible effect on dose at any distance. It is worth noting that this sensitivity study was not meant to demonstrate a rigorous analysis of a radiological release from any real-world fusion power plant; it was to demonstrate that there are multiple parameters that can have a significant effect on the consequences of any potential release and these parameters will need to be taken into account in any robust safety analysis.

8.4. Hazard potential

One of the aims of fusion power is to design a fusion power plant that will not require external countermeasures, such as the evacuation of people living in the vicinity of the plant, in the event of an accident. In the absence of a fusion power plant design, the approach to scope the hazard potential has been to evaluate the amount of tritium or activated dust that would need to be released in order to trigger the sheltering or evacuation of the local population. Such an evaluation enables the scale of the released quantities to be put into context.

For people living at a distance of 1 km from the plant, Table 6 shows that, providing the release pathways are entirely via an elevated 30 m stack (not taking into account building wake effects), it would require a release of 231 g of HTO or 5 kg of dust to consider implementing sheltering. In the case of HTO, this is a considerable release inventory, and any robust safety case should be able to demonstrate that the likelihood of a release this large is extremely low. The situation is more acute for an accident that results in a ground level release, in which only 9 g of HTO or 1.7 kg of dust is required to trigger the sheltering ERL at a distance of 1 km. In the case of evacuation, Table 7 shows that for an elevated (30 m) release, 2.3 kg of HTO or nearly 50 kg of dust would need to be released to trigger the ERL. Again, the situation is more acute for a ground level release where only 88 g of HTO or 17.3 kg of dust would need to escape.

From Table 8 it can be seen that for elevated releases at a distance of 1 km, as the particle size increases the quantity of material needed to be released to trigger the 30 mSv lower evacuation ERL decreases. For ground level releases the opposite is observed: at a distance of 1 km as the particle size increases the quantity of dust needed to trigger evacuation also increases. Nevertheless, when looking at risk to populations situated at least 1 km away, it would take a significant 26.8 kg of dust for an elevated release and 17.3 kg of dust for a ground level release to trigger the lower evacuation ERL, conservatively assuming the most pessimistic case for each release height.

The results for exposed workers at a distance of 200 m are of interest as the most pessimistic ground release case requires a release of only 767 g of dust for a worker to receive a 30 mSv dose, which is in excess of the 20 mSv annual limit. Given that, in the event of air or water ingress into the VV due to an accident there is potentially hundreds of kilograms of dust transferred to the drain and suppression tanks, a release this small is conceivable.

The results for HTO releases show that there is a large margin between the amount of tritium in the plasma and the release needed to trigger either sheltering or evacuation. However, there are other sources of tritium that can potentially be released in an accident scenario (such as in the breeder blankets and in the plasma facing walls). The release of the tritium in the plasma will be instantaneous, but the release from these other sources will take time to release, allowing operators to take remedial actions to prevent any longer-term uncontrolled releases. In the case of dust, it is possible to control the inventory by the design of the plasma facing materials and operational maintenance to reduce build-up.

The results of this work pose a number of challenges to fusion power plant designers with respect to how releases of HTO and activated dust are controlled. The first challenge (option 1) is to ensure that the likelihood of accidents that can result in the significant release of HTO or dust from the vacuum vessel (VV) is suitably low to ensure the risks to both workers and the public are as low as reasonably practicable (ALARP/ALARA). The second challenge (option 2) is to ensure that if a significant release from the VV does occur, the design of the plant ensures the radionuclides are released via a high stack rather than leakage through walls. The third challenge (option 3) is that if neither of these options can be delivered, a robust, air-tight confinement building will need to be deployed to prevent an uncontrolled radioactive release.

To satisfy option 1, designers must ensure that scenarios in which the integrity of the primary confinement barrier is significantly challenged have an extremely low frequency of occurrence. Reference [1] highlights the potential accident scenarios in which the integrity of the VV is challenged including failure of the magnet systems, electromagnetic loading on the VV walls, and hydrogen and dust explosions, amongst others. In these scenarios a rupture or bypass of the VV wall will generally be followed by water or air ingress into the vessel. This in turn will cause a pressure increase in the VV which, coupled with the hot components present, could provide a driving force to propel the radioactive inventories out of the vessel. To mitigate this, it is expected that a fusion power plant will have a vacuum vessel pressure suppression system (VVPSS) that will act to reduce the potential to over-pressurise the VV and enable the inventories of tritium and dust to be transferred to drain and suppression tanks (ITER is currently expected to be the first fusion machine to test this concept).

Reference [1] has highlighted the need to investigate the scenario in which the VVPSS fails to activate following a rupture (and is therefore unavailable) to ensure the radiological consequences have no significant impact on workers or the surrounding public. What also needs to be substantiated is the capability of the VVPSS to transfer the inventories of tritium and dust to the drain tanks and ensure no leakage occurs. In the ITER RPrS there is assumed to be almost 1 kg of tritium and hundreds of kilograms of dust in the VV that is available for transfer to the drain tanks in the event of water ingress into the VV (note in the absence of a detailed design for a fusion power plant, the assumptions made at ITER are a useful guide) [11]. If 1 % of this inventory managed to escape to the environment at ground level, the 30 mSv evacuation ERL would be triggered at a distance of 200 m from the release (assuming worst-case conditions). If 10 % of the inventory escaped via the stack (elevated release), the lower evacuation ERL would be triggered.

It is therefore crucial that any events that could challenge the integrity of the VV are properly understood, and that their probabilities of occurrence and radiological consequences are calculated in order to demonstrate that the risks are ALARP/ALARA. It is also essential to investigate the scenarios in which the VVPSS system fails to activate, and to investigate the capability and reliability of the VVPSS system to ensure that the radionuclide inventories mobilised within the VV are captured and transferred to the drain and suppression tanks, and that any potential leaks are accounted for and are within an acceptable range.

In the case of option 2, if there exists any scenario in which a significant quantity of tritium or dust leaks out of the VV at ground level, and the probability of occurrence is not so low to bring the scenario into the acceptable risk region, there would need to be some kind of detritiation system in place in every room adjacent to the plasma chamber (such a system is planned for ITER). This system would ensure that any escaped tritium and dust is captured and released to the environment from a high stack, significantly reducing the radiological consequences of a release. The robustness of the detritiation systems in the rooms surrounding the VV will need to be substantiated and their probabilities of failure calculated. Given the relatively small quantity of HTO needed to be released at ground level in order to trigger the 30 mSv lower evacuation ERL, these systems may prove to be safety critical and require stricter regulatory focus.

If neither option 1 nor option 2 can be satisfied, then designers may have to consider option 3: the addition of a robust confinement structure to reduce the radiological consequences of any potential release. Whilst the majority of design basis and beyond design basis accidents identified in the RPrS do not require a mitigation solution as drastic as this, there are some scenarios that may justify the need for a confinement structure, and these therefore need further study. The scenario in which a failure of the VV causes significant air ingress resulting in a combined hydrogen and dust explosion was considered to be a beyond design basis event in the RPrS and was found to result in a dose of 0.33 mSv at 200 m and 0.20 mSv at 2.5 km from the plant [11]. Radiation doses at this level would not result in the need to evacuate people in the surrounding areas. However, given the potentially larger size and added complexity of commercial fusion power plants, the consequences of a hydrogen/dust explosion could be more severe than that shown in the ITER analysis. As avoiding ignition sources is not a practical solution (the ignition energy for a hydrogen explosion is 0.02 mJ meaning an explosion can spark on any hot surface), mitigation tactics for future fusion power plants are currently being explored which include igniters within the VV, rapid injections of inert gas to reduce the rate of pressure increase or avoiding beryllium as a plasma-facing material [26]. Given that such explosions have the potential to compromise the integrity of the VV, coupled with the relatively small radioactive inventories that need to be released to trigger the evacuation ERL at a distance of 200 m (6 g of HTO or 984 g of dust), these mitigation systems may also need to be substantiated as they are potentially safety critical systems. Further work is needed to establish the likelihood and severity of hydrogen and dust explosions to determine the radiological consequences for the surrounding public. Until it can be shown that the likelihood of these events is suitably low, or that any releases are orders of magnitude lower than the releases in Table 7, a robust confinement structure cannot be ruled out.

9. Conclusion

This work shows that any actions that may be needed to protect the public in the event of an accident at a fusion power plant depend upon the size of the radioactive source term, the nature of the release and the weather conditions at the time of the accident. The hazard potential, therefore, critically depends on the fusion power plant design and the most realistic limiting radioactive source term. In the absence of a detailed design for a fusion power plant, this paper focusses on the size and nature of the radioactive source term, i.e. the quantities of HTO and activated dust, that would need to be released to trigger both public sheltering and evacuation in the event of an accident.

The ADMS-STAR model was developed and validated to simulate accidental releases of HTO and activated dust from a fusion power plant. A reference case scenario was then used to evaluate the radiological dose that any exposed persons would receive following a release of tritium (in the form of HTO) and activated dust. Sensitivity studies were used to evaluate the impact of changing various parameters including the radioactive material release height, the activated dust particle size, release duration and weather conditions. Release height and weather conditions were found to be particularly important and ground level releases under DF2 conditions gave the most limiting results. Dust particle size was found to have a modest effect on ground level releases but slightly more of an effect on elevated releases. Release duration had very little impact on the results.

In the absence of a detailed design for a fusion power plant, the hazard potential of fusion power was evaluated by considering the quantity of radioactive material (source term) that would need to be released to trigger the UK sheltering and evacuation ERLs at various distances from the plant. The analysis showed that a release from a 30 m stack (elevated release) would require a release of 231 g of HTO or 5 kg of dust to consider sheltering at 1 km from the plant and 2.3 kg of HTO and 49.6 kg of dust to consider evacuation. For a ground level release (leakage through walls etc.), it would only require a release of 9 g of HTO or 1.7 kg of dust to trigger the lower sheltering ERL at a distance of 1 km from the plant, and 88 g of HTO or 17.3 kg of dust to trigger the evacuation ERL.

Whist the actual source terms will depend upon the size and design of a fusion power plant, the above figures can be compared with the ITER safety case maximum inventories of 1 kg of HTO and 1000 kg of dust. If these figures are representative for fusion power plants, it can be seen that for a high-level release the HTO source term has the potential to trigger sheltering but not evacuation, depending on what fraction of this inventory could be released in an accident scenario. In relation to dust the source term has the potential to trigger both sheltering and evacuation. For a ground-level release, however, the source term (HTO and dust) has the potential to trigger both sheltering and evacuation ERLs. Given the important contribution dust makes to the radiological consequences of a release, more work is needed to evaluate dust formation and build-up during operation to obtain a better understanding of the likely quantities of dust in the vacuum vessel of an operating fusion power plant. Experience gained during the initial operation of ITER will be valuable for this.

Whilst the hazard potential of a fusion power plant is considerably less than that of a fission power plant, there are radioactive materials that could be released in the event of an accident. This paper illustrates the factors that can influence the relationship between the quantities of radioactive materials (in the form of HTO and activated dust) that need to be released to trigger the lower sheltering and evacuation ERLs. This work does not imply that fusion power plants are capable of releasing the identified quantities of radioactive materials. Whether the release of the identified quantities of radioactive materials in this paper is feasible or realistic will depend upon the fusion power plant design and the measures that are taken to control the radioactive inventory.

It should be noted, however, that the amount of tritium in the plasma of a fusion power plant is expected to be on the order of grams and its instantaneous release would not trigger any of the ERLs. It is the release of the tritium that has been absorbed by the VV components and breeder blankets that has the potential to provide the main radiological HTO source term. There is therefore the opportunity for fusion power plant designers to design out or minimise both the tritium and dust source terms.

Declaration of Competing Interest

We have no conflicts of interest to disclose.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.fusengdes.2020.112183.

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