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Methods to minimise effective public dose in the event of an accident at a fusion power plant

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ABSTRACT

An investigation was conducted into minimising effective dose to members of the public in the unlikely event of an accident by optimising design parameters and site locations of future fusion power plants. This is part of the defence in depth approach for tritium safety that also includes significant work on the prevention of accidents. Calculations were performed using Atmospheric Dispersion Modelling System (ADMS 5), a validated software package that models plume dispersion with inputs including buildings, stack height, terrain topography and meteorological data. To decrease the effective dose to on-site workers and the public, stack height, release duration and site boundary should be maximised. The minimum recommended stack height and site boundary distance are 60 m and 250 m, respectively. It was also found that very unstable weather conditions that cause enhanced vertical mixing, Pasquill-Gifford Stability Class A, minimise effective dose to members of the public. The impact of these changes on effective doses are demonstrated quantitatively. Analysis of tritium dispersion and dose rates provides upper bounds on releasable tritium inventories that can be stored on site. It is envisaged that future fusion power plants such as DEMO can use this information when designing and choosing a location for their site.

1. Introduction

Fusion energy is seen as a contender to provide baseload power to the grid in the future. A large part of enabling the viable use of fusion energy is the public perception of fusion energy as a safe alternative to nuclear fission and other fossil fuel powered methods of electricity generation. As a result of this DEMO, a European DEMOnstration power plant for fusion energy, has a requirement to minimise effective dose to members of the public to as low as reasonably achievable (ALARA).

Very few studies have been conducted on the effective dose due to an accident at a fusion power plant. Some studies have been conducted for ITER; however, the results are not publicly available. It is therefore important for the public perception of fusion energy to increase the awareness of the layers of safety utilised in a fusion power plant design and have published work demonstrating its effectiveness.

For the work in this paper, it was assumed that the public dose must be kept below 50 mSv however, this limit is continually being assessed. In any case the results discussed in this paper can be used to design fusion power plants in way that minimises effective dose to members of the public. To confirm that DEMO can meet these requirements, the effects of the following design and location parameters have been investigated:

- Tritium source term
- Stack height
- Site boundary distance
- Release duration/Emission rate of tritium
- Weather
- Terrain
- Building locations.

The implications for the design of the fuel cycle were also determined. Note that tritium source term in the context of this paper refers to the amount of tritium lost to the environment and not the total DEMO plant inventory.

Analysis was carried out using a dispersion modelling software developed by Cambridge Environmental Research Consultants (CERC) called Atmospheric Dispersion Modelling Software version 5 (ADMS 5) to provide estimates for effective dose and to suggest stack heights and site boundary distances.

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The accident was assumed to be a beyond design basis accident (BDBA) which specified a 50 mSv total predicted early dose from exposure over a 7-day period. BDBAs or beyond design basis events (BDBEs) are defined as “hypothetical accidents” that have a frequency of occurring of less than 10^{-6} per year. They are studied to determine the ultimate safety margins against accidents that have an extremely low probability of occurring. Typically, sequences of failure based on design basis accidents and probabilistic safety analysis are specified, known as a Fault Sequence. These are used to produce figures of estimated source terms, reduced due to the safety measures in place, which are used to calculate the potential dose to on-site workers (OSWs) and to members of the public [1]. However, in this case, as the fuel cycle and tritium building design are not finalised and the full safety functionality of the plant is unknown, this report studies an accident with no safety measures in place in order to determine the ultimate safety margins. The aim of this study is to optimise variables such as stack height, site boundary distance and site layout in order to minimise effective dosage to members of the public.

2. Methodology

2.1. Assumptions

All assumptions made for this study are conservative.

For this study 100% of the released tritium source term was assumed to spontaneously convert from HT (hydrogen-tritium) to HTO (tritiated water) vapour due to oxidation with air. This decision was made as the percentage of HT that converts to HTO will depend on the temperature, external conditions and exposure distance; but lack of data means holding a conservative view is more appropriate. The 100% conversion to HTO is also typically assumed in the event of a fire or explosion which also come under a BDBE. This allowed for a conservative estimate of the estimated effective dose as the dosage due to HTO is approximately 10,000 times worse than a dosage due to HT, as demonstrated by the inhalation committed dose coefficient values [2]. This is similar to safety calculations carried out for the International Thermonuclear Experimental Reactor (ITER) in its Preliminary Safety Report summarised in [3,4] with further details in [5].

Some initial assumptions were made when using the modelling software. In an accident scenario the worst-case pathway is assumed to be a release of tritium from the DEMO Tritium Building stack. In certain accident scenarios the tritium source term may not be released from the stack and could be released from ground level. For example, an aeroplane crash into the tritium plant could result in a ground level release. This has been modelled and would result in a high on-site dose but a low off-site dose, reducing the risk to members of the public. For the purpose of this investigation, a member of public is defined as a person positioned at the site boundary. On-site worker dosage has not been considered in this paper. As a site location for DEMO has not been confirmed Culham terrain and meteorological data was used to carry out this investigation.

2.2. Atmospheric dispersion modelling system (ADMS 5)

The software used to model the plume dispersion was developed by Cambridge Environmental Research Consultants (CERC) in collaboration with the UK Meteorological Office, National Power plc and the University of Surrey. The software uses inputs of terrain, meteorological and surface roughness data to determine where the highest concentration of tritium will be. The software allows a maximum of 25 buildings surrounding the stack (i.e. site buildings) to be included in the model in order to determine their effects on the plume dispersion. A summary of the technical specification is included in the ADMS 5 User Guide and further details are on the CERC website [6,7].

2.2.1. Puff model

The puff model is used to model short duration releases. It is used when a fixed quantity of contaminant is released over a specified time. In general, it can be used to model a release at the end of a batch process or blowdowns, the venting of gas accumulated in equipment. However, in this paper it is used to model accidental discharges as it provides a good bounding case and allows assessment of the worst case scenario. The output of this model calculates the time-integrated concentration or dose. This equates to the total quantity of discharge a person would be exposed to at a particular location as the plume passes over that point. It is therefore ideal for determining the effective dose due to an accidental tritium release.

The puff model has very simple input data. No buildings, surface roughness or terrain data are included in the simulation. More detail on these data inputs is provided in Section 2.2.2. The meteorological data used in this model are called the Pasquill-Gifford stability categories which characterise the boundary layer, the region within the troposphere that is affected by the Earth’s surface and which extends about 2.5 km above it. They are traditionally used to model plume dispersion. The Pasquill-Gifford stability categories, described in Table 1, is a seven class scheme used to characterise the atmospheric stability and potential for vertical mixing [8]. As the stability categories model does not take into account any variations over time this is a very simple way of looking at the effect of initial weather conditions on the effective dose. However, it has been the standard method used to calculate public doses for the nuclear licensing process since its inception in the NRPB-R91 report purely because it is simple and conservative to use [9].

2.2.2. Long term concentration model

The Long Term Concentration Model calculates the concentration for every hour of meteorological data and displays the average for every specified mesh point. This model is typically used for annual releases and is useful for comparing predicted concentrations with Air Quality Standards. This model does not tend to be used to model emergency releases as it assumes a static output grid rather than one that moves with the plume trajectory.

The Long Term Concentration model requires location specific meteorological and terrain data. It also has added inputs, that the puff model does not provide, of building layouts and surface roughness. The meteorological data was taken from Benson weather station as it is the closest station to Culham, roughly 11 km away from the site. The meteorological data contained hourly weather parameters that ADMS 5 uses to model plume dispersion, such as the wind speed and direction, ambient temperature and cloud cover.

The terrain data is used by ADMS 5 to localise the weather data even further by calculating the changes in the wind flow field due to the surface elevation. Surface roughness from the Culham site was also used to model the turbulence caused by the surface features such as trees and houses. This could be used as a more generic approach to terrain in future work, as it models the typical features of a power plant site, i.e. a built-up site location with lots of fields and country surrounding it with some towns nearby.

Table 1
Summary of the Pasquill-Gifford stability classes.

Stability Class	Definition	Description
A B C	Very unstable Unstable Slightly unstable	Hot, sunny, clear skies and still weather cause enhanced vertical mixing
D	Neutral	Cloudy, windy conditions
E F G	Slightly stable Stable Very stable	Night time or winter conditions and clear skies suppress vertical mixing

An image of the meteorological data is shown in Fig. 1. The 2010 data represented wind direction that was more spread out and was selected for use in the model as it had the most extreme wind rose out of the 5 years of data.

Due to the use of local data this paper provides indicative results for the distance to the site boundaries and neighbouring villages. These deposition analyses should be repeated when DEMO site information is narrowed down or confirmed.

Fig. 2 shows the building layout that was used as a reference for the buildings included in the simulation [10]. The dimensions of the buildings were provided in the ITER Preliminary Safety Report [5]. ADMS 5 allows a maximum of 25 buildings to be included in the simulations, therefore, the buildings thought to have the highest effect on the dispersion of the tritium plume were included. The Preliminary Safety Report also referenced a requirement for the Tritium Building to have a minimum of two air changes per hour. Using this information along with the building dimensions a minimum emission rate was calculated.

2.2.3. Model comparison

A summary of the positive and negative aspects of the ADMS 5 models used is described in Table 2.

2.3. Dosage calculations

For both methods the output data needs to be converted into a dosage. In order to do that an inhalation committed effective dose coefficient must be used. It is the committed effective dose over 50 years or from the age at intake (if less than 20 years) to age 70 of an individual arising from the inhalation of a unit of activity (1 Bq). It depends on the type and form of radionuclide inhaled and the age group of the individual [2].

The inhalation committed effective dose coefficient is 1.8×10^{-15} Sv Bq^{-1} for HT and 1.8×10^{-11} Sv Bq^{-1} for HTO, showing that the effective

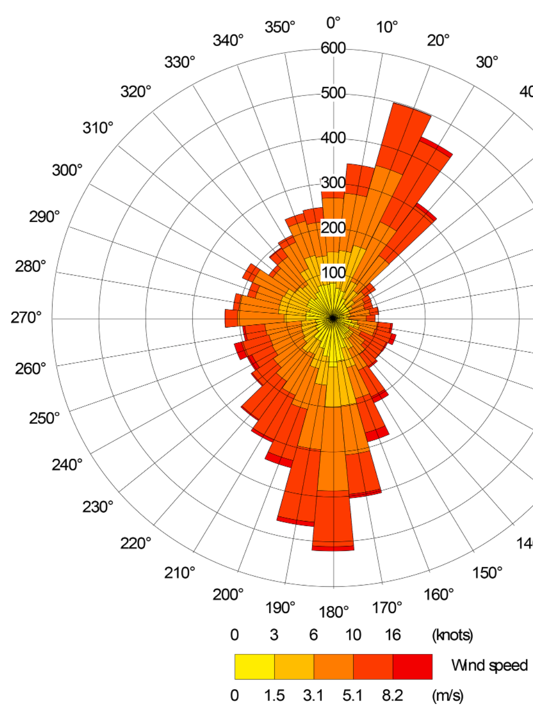

Fig. 1. A years' worth of meteorological data, from 2010 at the Benson site 11 km from Culham, shown in the form of a wind rose. The wind rose shows the wind direction and speed over 2010. The spokes are every 10° and the legend represents the windspeed. The length of each sector shows the number of occurrences of wind in each direction.

dose due to HTO is 10,000 times worse. This value was chosen because it was assumed that all of the HT was converted into HTO when released into the environment. The coefficient for HTO was increased by 50% to 2.7×10^{-11} Sv Bq^{-1}, before being used to provide conservative estimates for effective dose. The coefficient was increased by 50% because when a person is immersed in the HTO vapour the coefficient needs to account for the absorption of tritium through the skin [2,11-13]. The HTO dose coefficient also assumes that all inhaled HTO is absorbed by the body and that none of it is released when exhaling.

The breathing rate used in all calculations was 3.3×10^{-4} m^3 s^{-1}, this is the best practice value for design basis accidents and probabilistic risk assessments [14].

The total dose, shown in Eq. (2-1), is given by multiplying the output of the puff model by the breathing rate and inhalation committed effective dose coefficient.

$$Total\ Dose = B \times e_i \times C_{P,} \quad (2.1)$$

Where:
B = breathing rate (m^3 s^{-1}),
e_i = inhalation committed effective dose coefficient (Sv Bq^{-1}),
C_P = output of the puff model (Bq s m^{-3}).

The dose rate, shown in Eq. (2-2), is given by multiplying the output of the long term concentration model by the breathing rate and inhalation committed effective dose coefficient.

$$Dose\ Rate = B \times e_i \times C_{LT,} \quad (2.2)$$

Where:
C_{LT} = output of the long term concentration model (Bq m^{-3}).

The total dose can be calculated in the case of the puff model as the exposure time to the plume is known and calculated by ADMS 5 which is not the case for the long term concentration model.

3. Results

The stack height and release duration variables were studied as they can be modified during the design phase and operational phases of DEMO respectively. For each variable the results from both the puff model and the long term concentration model will be considered.

A stack height of 60 m was chosen for the simulations in which the stack height is a constant as this is an initial estimate for the stack height to be used in future UK nuclear power plant designs. These power plants were designed knowing that there is a possibility of tritium leaks occurring which will then pass through the HVAC and HEPA filtration systems to then be discharged from the stack [15].

A 700 g tritium source term was used in the simulations as the dosage due to this amount released in 60 s with a stack height of 60 m kept the dosage below 50 mSv under the worst case weather scenario.

3.1. Effect of release duration on dosage

3.1.1. Puff model

Release duration does not seem to have a significant effect on the maximum dosage assuming the other variables remain constant. See Figs. 3 and 4. The maximum dose is very similar – 49.07 mSv for the 1 hour case and 50.42 mSv for the 15 min case both at 111.08 m due to Category A stability conditions. Although the release duration reduces, from 1 hour to 15 min, the dosage is similar and the distance at which the maximum effective dose occurs is the same.

This lack of significant effect may be due to the duration of release not having much effect on the mixing of the tritium with the air when it comes out of the stack. This suggests that no matter how long the plume takes to pass over the person the same amount of tritium is inhaled, therefore resulting in a similar dosage. Another, more significant, reason as to why the release duration does not have a large impact on the dosage is that this model only uses one specific wind direction and speed

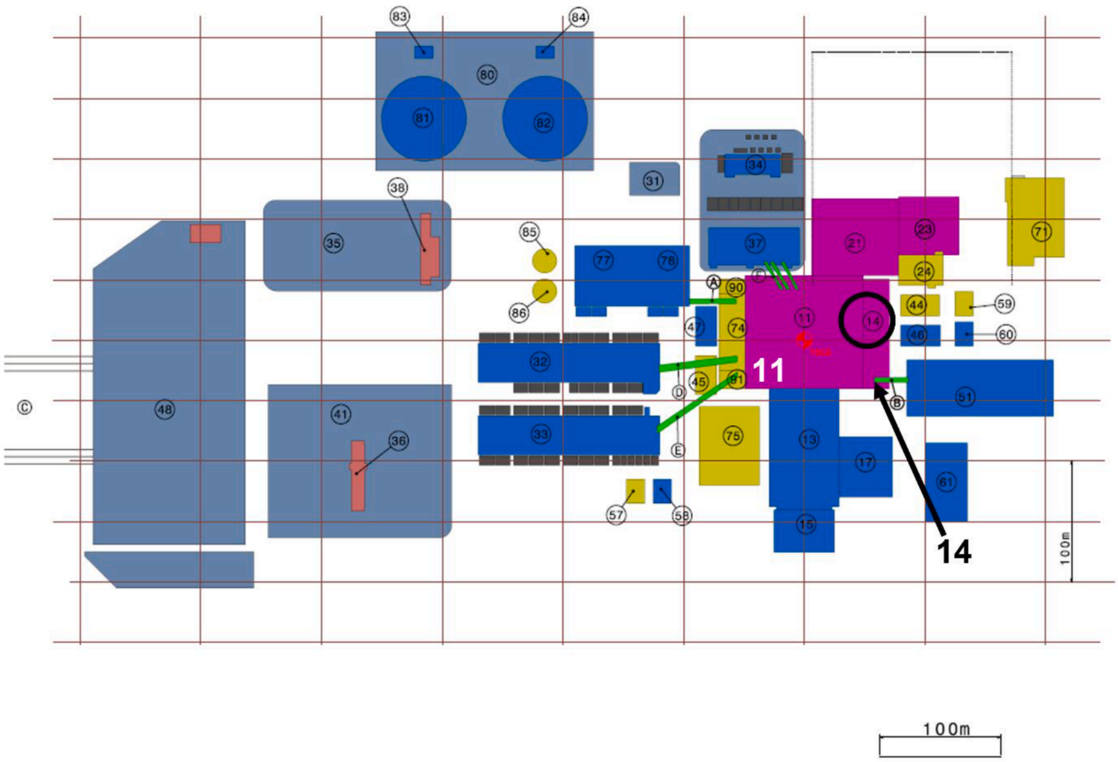

Fig. 2. The DEMO building layout [10]. The black circle highlights where the stack would be. Buildings 11 and 14 are the Tokamak and the Tritium Buildings with heights of 59 m and 34 m respectively.

Table 2
The positive and negative features of the model types with respect to the purpose of this investigation.

Model Type	Positives	Negatives
Puff	Calculates total dosage Used to model accidental releases Calculates time evolution of the plume	Does not allow building or terrain data to be used Limited amount of meteorological data can be used
Long Term Concentration	Can use building, surface roughness and terrain data Can use real meteorological data	Calculates average dosage rate during first hour of release, so is not useful for calculating total dose received Primarily used to model continuous releases during normal operations Slightly pessimistic as assumes person is in static plume

over the whole release time. As these are short release durations this may not have a significant effect overall, however, as the weather is modelled from the Pasquill-Gifford stability categories there is no spread in the data over time. Real meteorological data would shift directions over time, therefore causing the plume to disperse further, reducing the concentration of tritium in the air. This would result in the amount of tritium inhaled by a person to decrease, therefore they would receive a lower dosage. Whereas the Pasquill-Gifford stability categories repeat themselves hour to hour, with no change in direction, and therefore the plume does not disperse as much as it would in a real-life scenario.

3.1.2. *Long term concentration model*

The release duration has an inversely proportional impact on dosage using this model as can be seen in Table 3 and Fig. 5. When halving the release duration, the dose rate roughly doubles in the areas where significant deposition is occurring. This can be seen in Table 3 where the distance from the stack to the maximum dose rate remains unchanged with decreasing release duration. This occurs when all other variables remain unchanged, such as the amount of tritium being released, the meteorological data used and the stack height.

This seems contradictory to the results produced by the puff model, however, it can be explained due to the way this model is run. The long term concentration model shows the average possible dosage over the first hour after the initial release of tritium. Whereas, the puff model shows the effective dose if a person is static as the plume passes over them, potentially hours after the tritium is released from the stack. A possible way to check that this is due to the limitations of the model rather than a limitation on the data is to buy meteorological data that is measured more than once an hour. As the release duration is shorter than an hour the way it spreads in this simulation is not modelled completely. Additionally, the difference in results between the puff and long term concentration model show that the total dose may not change with release duration, but the rate at which the dose is received is dramatically altered.

3.2. *Effect of stack height on dosage*

3.2.1. *Puff model*

The effect of stack height on dosage was studied using the puff model to demonstrate the increased dispersion of the tritium plume with increasing stack height. These results are independent of the effects of the site buildings, terrain and surface roughness data. These simulations model the release of 700 g of tritium from the stack with a release duration of 1 hour. The meteorological data used was the Pasquill-Gifford stability categories in a fixed direction. The results in Figs. 6 and 7 show that increasing the stack height significantly decreases the dosage to OSWs and members of the public. Table 4 summarises the main results.

Table 4 shows that increasing the stack height decreases the effective dose to members of the public. However, as the ADMS 5 model does not

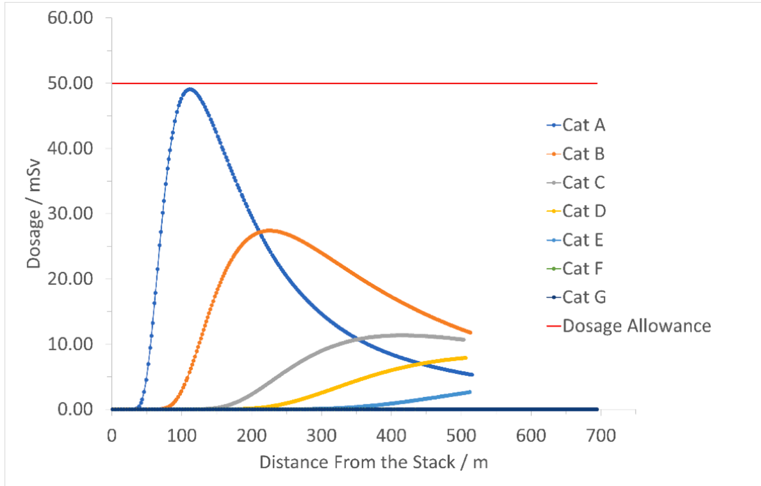

Fig. 3. Effective dose against distance from the stack for a release duration of 1 hour with a source term of 700 g and a stack height of 60 m.

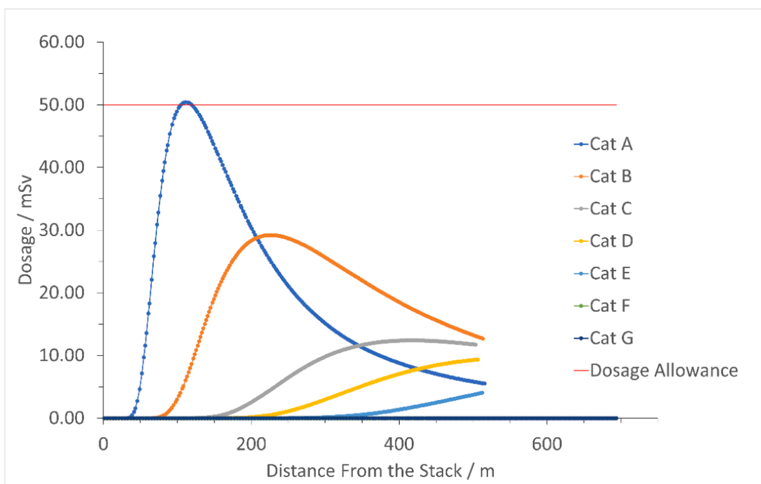

Fig. 4. Effective dose against distance from the stack for a release duration of 15 min with a source term of 700 g and a stack height of 60 m.

Table 3
The effect of release duration on dosage rates.

Release Duration (minutes)	Maximum Dose Rate (mSv h^{-1})	Distance from Stack to Location of Maximum Dose Rate (m)
60	8.3	57
30	17.0	57
15	33.0	57

show the effective dose caused past 600 m, we cannot be certain whether the more stable weather categories, F and G, cause doses above 50 mSv at large distances from the site. This is because these weather categories do not encourage dispersion of the plume and therefore high concentrations of tritium could be deposited far away from site. Further research should be done into the dosages caused by the stable weather categories. They were not carried out in this investigation due to computational limitations.

Figs. 6 and 7 show that as you move away from the stack location, for the more unstable weather categories A – C, the dosage is minimised. The turning points for weather categories A and B can be seen at less than 300 m from the stack.

3.2.2. Long term concentration model

Stack heights of 0, 40, 60, 80 and 100 m were modelled to show their effects on the dispersion of tritium. The effect of buildings surrounding the stack were also displayed through these contours. 700 g of tritium was modelled to be released over an hour under the 2010 meteorological conditions which was consistent throughout the runs. As shown in Fig. 8 and Table 5, even a stack height of 40 m, just above the height of the tritium building (34 m), makes a significant change in the distribution of the tritium and ultimately the dose received. As the stack height increases, the dosage decreases significantly and the distance from the stack to the location of the maximum dose rate increases as shown in Table 5.

A stack height of zero, i.e. a ground level release, was simulated as shown in Fig. 8 and Table 5. This shows the potential outcome of a tritium release in circumstances such as an aeroplane crash at the tritium building, although, the increase in temperature, velocity of the plume and effective stack height due to an explosion or crash is not included in the model. The increase in these characteristics of the plume are likely to increase its dispersion and therefore decrease the tritium concentration and dosage received. The contour shows that a release below the height of the surrounding buildings contains the tritium plume to the site. This would reduce the dosage to members of the public as the plume is unlikely to spread as it gets caught in the wake of the buildings. However, the dosage to OSWs is significant with a maximum of 280 mSv h^{-1} at a distance of 7 m from the stack.

The stack height was increased to 40 m, in between the height of the

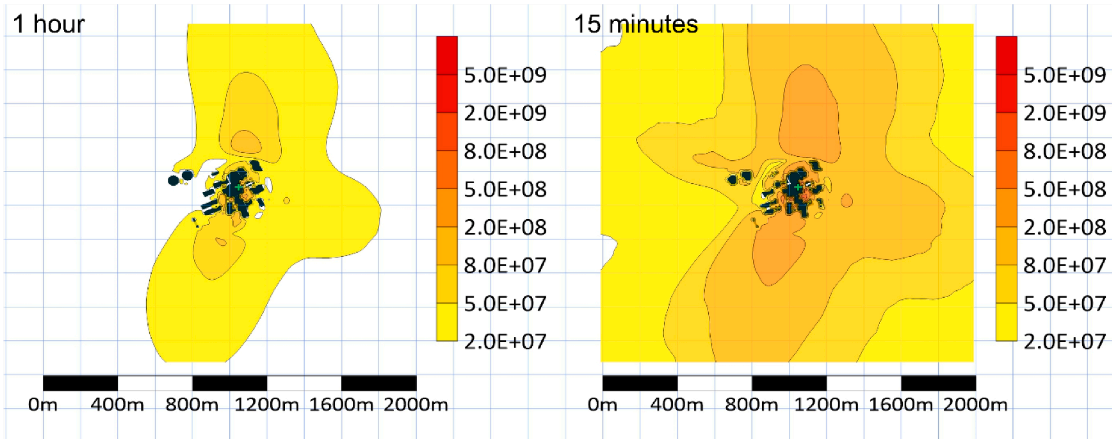

Fig. 5. Contours showing the deposition of tritium over a release duration of 1 hour and 15 min on the left and right hand respectively. The legend uses units of Bq m^{-3}.

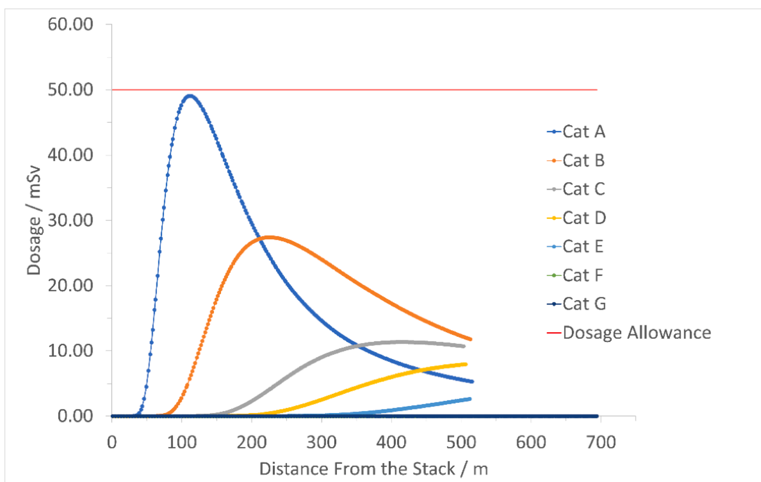

Fig. 6. Dosage as a function of distance from the stack for a stack height of 60 m for a 700 g source term.

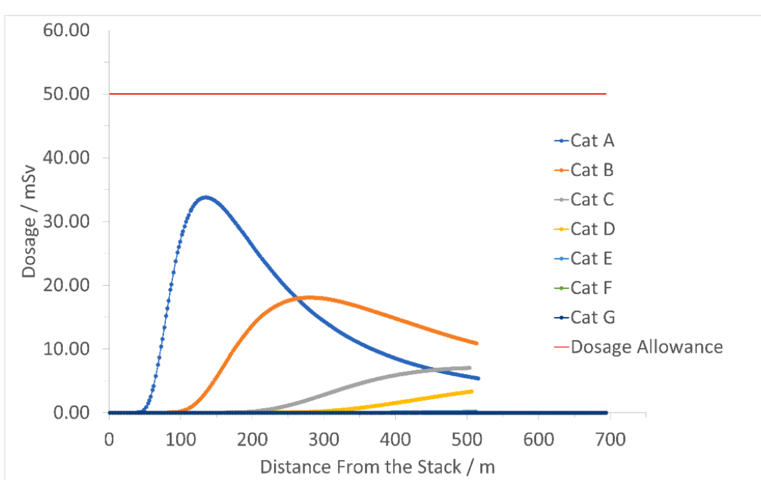

Fig. 7. Dosage as a function of distance from the stack for a stack height of 80 m for a 700 g source term.

tritium building and the tokamak building, at 34 m and 59 m respectively, as shown in Fig. 8. This contour shows that increasing the stack height increases the dispersion of the plume, thereby decreasing the dosage received. However, as the stack is still below the tokamak building, which is beside the tritium building, the plume cannot disperse well enough to leave the perimeter of the site, minimising the dosage to members of the public. This is confirmed by increasing the stack height to above 59 m, as shown in Fig. 9, where the effective dose is

Table 4
The effect of stack height on dosage.

Stack Height (m)	Maximum Dose (mSv)
0	530
40	78
60	49
80	34
100	25

significantly reduced.

The effect of the buildings can be studied further by modelling the plume spread in a fixed wind direction. This would enable the effect of each building surrounding the stack to be analysed. The building layout could be modified to enhance the dispersion of the plume to reduce the concentration of tritium, overall leading to a reduction in dosage to OSWs and members of the public.

Note that the dose rates produced by this model are the worst-case scenario as ADMS only calculates the concentration deposition over the first hour of release. As the long term model does not provide the time evolution of the plume, we assume that the plume remains static. Therefore, the overall effective dose is much larger than estimated using the puff model.

3.2.3. *Model verification*

The validity of ADMS has been studied and confirmed in previous work at UKAEA using historical JET discharge, weather data and recorded activity concentrations [16]. It has also been verified comprehensively, further details can be found at [17].

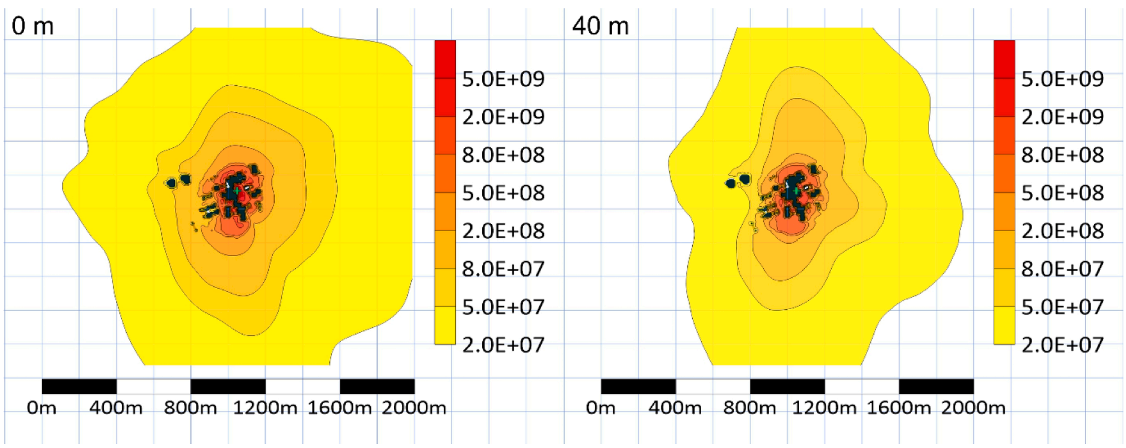

Fig. 8. Tritium deposition contour showing a stack height of 0 m and 40 m. These were modelled for a release duration of 1 hour over a period of 1 hour. The legend uses units of Bq m^{-3}.

Table 5
The effect of stack height on dosage rates.

Stack Height (m)	Maximum Dose Rate (mSv h^{-1})	Distance from Stack to Location of Maximum Dose Rate (m)
0	280	7
40	150	57
60	8.3	57
80	1.7	293
100	0.83	435

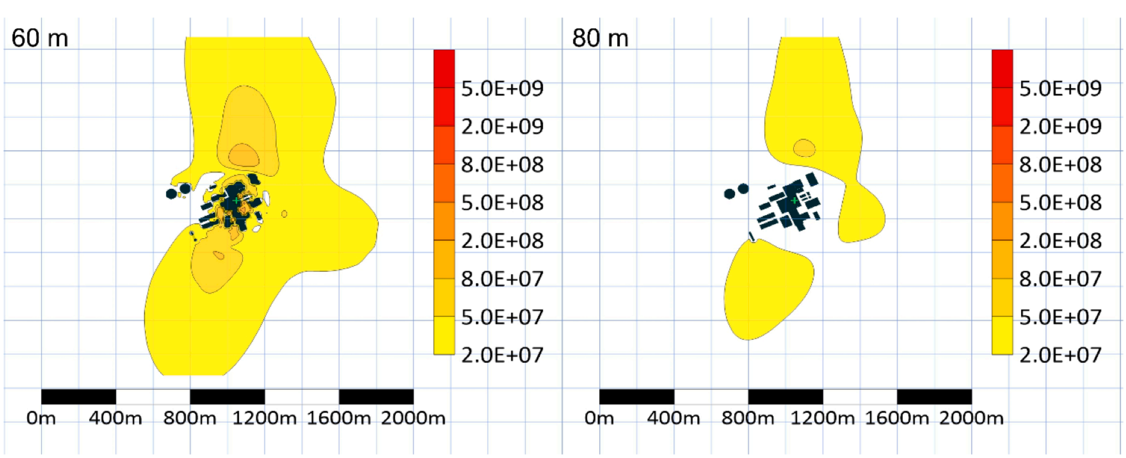

Fig. 9. Tritium deposition contour showing a stack height of 60 m and 80 m. These were modelled for a release duration of 1 hour over a period of 1 hour. The legend uses units of Bq m^{-3}.

3.2.4. Recommendations

The main recommendations coming out of this study are as follows.

The first recommendation following this study is to keep the mobilisable tritium inventory ALARA to minimise tritium lost to the environment in the event of an accident. Ensure tritium inventories are kept separate such that in the event of an accident only one containment of tritium has the potential to be lost to the environment to minimise the effective dose to members of the public.

Secondly to maximise stack height. A location with very stable weather conditions could build a stack that reaches above the atmospheric boundary layer which would significantly increase the dispersion of the plume reducing the dosage received at ground level. Typically under very stable conditions the boundary layer height ranges between 150 and 200 m. It is feasible to create a stack that is 200 m or 419.7 m tall as evidenced by the stack heights of the now demolished Didcot [18] and GRES-2 [19] Coal Power Stations, respectively. The minimum stack height should be taller than the buildings surrounding it as the higher the stack, the less the site buildings affect plume dispersion. In the case of DEMO, a stack height of 60 m should be used as then it is taller than the Tokamak and Tritium Buildings it is situated next to and on respectively.

The distance between the stack and site boundary should be maximised with no settlements down wind of the stack within a reasonable distance. The site boundary should be a minimum of 250 m from the stack radially but if this is not possible, ensure that the distance from the stack to the site boundary is at its furthest in the direction of the prevailing wind.

3.2.5. Proposed future work

Case studies for suggested DEMO sites across Europe should be carried out in future in order to choose the optimum meteorological and terrain conditions before deciding on a final site.

Further work could be done to analyse the effects of the building layout on the dispersion of the tritium plume. Simulations could be run with the wind in a fixed direction to the stack to see which buildings affect dispersion the most. The building layout could then be altered to increase plume dispersion to decrease dosage to OSWs and members of the public.

The effect of humidity on the results could be studied further. This could alter the amount of tritium deposited on to the ground and therefore alter the amount of tritium inhaled, changing the effective dose. Long term investigations into tritium deposition into the ground should also be undertaken to see how agriculture and livestock would be affected, notably because of the effect of soil on the oxidation ratio of HT. The oxidation rate of HT in the environment should be investigated to calculate more realistic dosages. These values can also be used to study the potential long-term dosage caused by an accidental tritium release. Particularly in the case of soil as a secondary source term as it can absorb HT and reemit it later as HTO [20,21].

The effects of various terrains on the deposition of tritium could be investigated as they could have a significant impact on the effective dose. For example, valleys may contain the contamination to a small area or a plant next to a hill may cause high dosages in line with the plume height.

Once a detailed design of the tritium plant is confirmed a fault sequence, a route of release of the tritium source term, can be defined. This study can be repeated when further details of the tritium building and safety systems in place at DEMO are confirmed. This will also allow assumptions about the roles of HVAC and detritiation systems to be made. Therefore, the percentage conversion from HT to HTO and percentage releases of tritium inventory can be varied depending on the scenario.

It is also important to note that estimated values in this report are **not** expected releases. They apply only to exceptionally unlikely scenarios; these scenarios must be considered to ensure that the safety requirements are met.

4. Conclusions

The main conclusions from this study are the following:

- Effective dose to the public is minimised by increasing the stack height and increasing the distance between the stack and the site boundary.
- Effective dose to the public can be further minimised by the stack height clearing the height of the surrounding buildings.
- Effective dose to members of the public is also minimised in the event of a ground level release, however, they cause the highest dose to onsite workers.

Declaration of Competing Interest

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

Data availability

Data will be made available on request.

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