Monte Carlo N-particle simulation of neutron-based sterilisation of anthrax contamination

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Objective: To simulate the neutron-based sterilisation of anthrax contamination by Monte Carlo N-particle (MCNP) 4C code.

Methods: Neutrons are elementary particles that have no charge. They are 20 times more effective than electrons or γ -rays in killing anthrax spores on surfaces and inside closed containers. Neutrons emitted from a ²⁵²Cf neutron source are in the 100 keV to 2 MeV energy range. A 2.5 MeV D–D neutron generator can create neutrons at up to 10^{13} ns^{-1} with current technology. All these enable an effective and low-cost method of killing anthrax spores.

Results: There is no effect on neutron energy deposition on the anthrax sample when using a reflector that is thicker than its saturation thickness. Among all three reflecting materials tested in the MCNP simulation, paraffin is the best because it has the thinnest saturation thickness and is easy to machine. The MCNP radiation dose and fluence simulation calculation also showed that the MCNP-simulated neutron fluence that is needed to kill the anthrax spores agrees with previous analytical estimations very well.

Conclusion: The MCNP simulation indicates that a 10 min neutron irradiation from a 0.5 g ²⁵²Cf neutron source or a 1 min neutron irradiation from a 2.5 MeV D–D neutron generator may kill all anthrax spores in a sample. This is a promising result because a 2.5 MeV D–D neutron generator output $>10^{13} \text{ ns}^{-1}$ should be attainable in the near future. This indicates that we could use a D–D neutron generator to sterilise anthrax contamination within several seconds.

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Anthrax is a serious disease caused by *Bacillus anthracis*, a bacterium that forms spores. Anthrax spores are the dormant form of anthrax bacteria, but may be reactivated under the right conditions [1]. *B. anthracis* differs very little from the common soil bacterium that is its near relative; however, scientists have discovered that a slight genetic difference is enough to give *B. anthracis* its disease-causing properties [2].

The anthrax spore consists of several distinct structural layers, which form a highly protective barrier for the spore's genetic material [3]. Because of their unique structural properties, anthrax spores are long-lived and extremely resistant to adverse environmental conditions [4]. Once inside the host, the same structures allow anthrax spores to survive host immune surveillance and to germinate, leading to rapidly replicating bacilli and production of toxins that kill the host. Because of their hardiness, ease of production and spread, and high infectiousness and fatality rate, anthrax spores are a potential terrorist biological weapon. With anthrax attacks having occurred in postal systems and other public areas, it is very important to have an effective way to sterilise areas contaminated by anthrax.

The medical procedures generally used to kill bacteria, such as pasteurisation, alcohol and ultraviolet irradiation [5],

do not work effectively for anthrax sterilisation. For the past 100 years, the treatments or agents commonly used to decontaminate anthrax spores have included heat, formaldehyde, hypochlorite solutions, chlorine dioxide [6, 7] and radiation [8]. The technique to sterilise anthrax contamination through the use of heat is feasible in some situations [9, 10]; however, it is not possible for post offices to steam all mail before delivery. Historically, formaldehyde solution or gas has been used as both a disinfectant and chemical sterilant. Formaldehyde was used as a disinfectant as early as the late 1880s and is still used to process haemodialysers for reuse in the same patient and to decontaminate biological safety cabinets and laboratories. Fumigation with formaldehyde vapour has also been used to treat a textile mill contaminated with *B. anthracis* spores [11, 12]. In this instance, contamination was greatly reduced immediately after treatment. However, the possible role of formaldehyde as a carcinogen has limited its use. The concentration, relative humidity, temperature and carrier material affect the gaseous sterilisation of anthrax spores. The amount of contamination and level of cleanliness of surfaces will also contribute to the effectiveness of formaldehyde vapour as a sporicide. All of the above procedures do not work for decontamination of buildings after intentional release of anthrax in a large public area, and no accumulated scientific knowledge exists on the subject up to now.

A standard procedure for killing bacteria in animal carcasses or anthrax in envelopes is to use ionising

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radiation or γ -ray irradiation from electron beams. This is reasonable since the bacteria are on the surface of the animal, and deep penetration into envelopes is not required, but radiation techniques using electrons encounter problems when anthrax spores are hidden too deep [13]. For example, terrorists may bring anthrax into public areas by hiding anthrax spores in sealed metal containers or in large pieces of luggage. The γ -ray irradiation is much more penetrating than electron beams, so γ -ray irradiation can be used to sterilise anthrax spores that are hidden in sealed metal containers or large pieces of luggage [8]; however, an earlier theoretical study showed that the efficiency of sterilisation of anthrax spores by γ -ray irradiation is not as good as that of neutron irradiation [14].

Neutron irradiation can be a powerful tool in defending against anthrax contamination. Neutrons are elementary particles that have no charge. This allows neutrons to be very penetrating. They can penetrate into sealed containers, killing both anthrax spores on surfaces and those hidden inside containers and luggage. Neutrons interact with the nuclei within the anthrax spores, and the materials around the anthrax spores can also create γ -ray irradiation that is both lethal to anthrax spores [8] and penetrating. Neutrons have an advantage over other forms of radiation and other chemical procedures if deep penetration and sterilisation are required over a large area.

The most effective neutron energy to use is between 100 keV and 2 MeV, which has a weighting factor [13, 15] of 20, in comparison with electrons and γ -rays, which have a weighting factor of 1, meaning that neutrons are 20 times more damaging to biological organisms for the same energy deposition (Table 1).

Neutrons can be generated by a ^{252}Cf source [16], a D-D neutron generator or a T-D neutron generator [17]. In this study, a Monte Carlo N-particle (MCNP) code was used to simulate neutrons from a ^{252}Cf neutron source, or a D-D neutron generator, and to calculate the neutron energy deposition, neutron fluence and neutron radiation dose that are needed to sterilise anthrax contamination.

The ^{252}Cf neutron sources are low cost and portable, and, most importantly, most of the neutrons emitted from a ^{252}Cf source are within the 100 keV to 2 MeV energy range. The radioisotope ^{252}Cf is an intense neutron emitter that is routinely encapsulated in compact, cylindrical source capsules [16]. Decay by α emission and spontaneous fission result in an overall half-life of 2.645 years and neutron emission of

$2.314 \times 10^9 \text{ s}^{-1} \text{ mg}^{-1}$. The neutron energy spectrum is similar to a fission reactor, with a probable energy of 0.7 MeV. For the spontaneous fission of ^{252}Cf , the energy spectrum of the neutron is approximated by the expression [14]

$$\frac{dN}{dE} = CE^{\frac{1}{2}}e^{-\frac{E}{T}} \quad (1)$$

where N is the neutron number and E is the energy of neutrons; the constant T in Equation (1) has the value of 1.3 MeV. Therefore, the average energy of the neutrons $\bar{E}$ can be calculated by

$$\bar{E} = \frac{\int_0^\infty E dN}{\int_0^\infty dN} = \frac{3}{2} T \quad (2)$$

The average energy of the neutrons obtained from Equation (2) is approximately 2 MeV.

Scientists at the Lawrence Berkeley National Laboratory, Berkeley, CA, have developed an innovative coaxial radiofrequency-driven plasma ion source for a compact cylindrical neutron generator; this single target coaxial neutron generator that is 26 cm in diameter and 28 cm in length can produce a 2.5 MeV D-D neutron yield of $1.2 \times 10^{12} \text{ ns}^{-1}$ or a 14 MeV D-T neutron yield of $3.5 \times 10^{14} \text{ ns}^{-1}$. D-D neutron generator outputs $>10^{13} \text{ ns}^{-1}$ and D-T neutron generator outputs of 10^{15} ns^{-1} will be attainable in the near future [17–19].

In MCNP [20] simulation calculations, we consider the effects of the real experimental set-up; this includes the shielding materials, the exact chemical components of the anthrax spores, the effects of the different neutron sources, the distance between the samples and the neutron sources, and so on.

The physical mechanism of neutron radiation sterilisation of anthrax spores

The main components of anthrax spores are carbohydrate polymers, which are hydrogen (proton)-rich materials. Carbohydrates are a large group of compounds in which hydrogen and oxygen, in the proportions in which they exist in water, are combined with carbon; the formula of most of these compounds may be expressed as $\text{C}_m(\text{H}_2\text{O})_n$. When neutrons hit the anthrax spore, they will interact with the nuclei of the hydrogen, oxygen and carbon within the carbohydrate of the anthrax spores. From the viewpoint of nuclear physics, the main chemical component of anthrax spores is water. But this does not mean that the main component of the anthrax spore is in the form of natural water. Actually, anthrax spores lack water, and this provides them with their powerful resistance to environmental stress. This is the reason why we decided to use very penetrating neutron radiation to explore this issue.

The biological damage created by ionising radiation is due to the chemical alteration of the biological molecule,

Table 1. Weighting factors of radiations [15]

Radiation and energy region	Weighting factor
X-rays and γ -rays, all energies	1
Electrons and muons, all energies	1
Neutrons	
<10 keV	5
10–100 keV	10
>100 keV to 2 MeV	20
2–20 MeV	10
>20 MeV	5
Protons (other than recoils) >2 MeV	5
Alphas, fission fragments, heavy nuclei	20

Figure 1. Model of neutron radiation sterilisation of anthrax spores.

which is influenced by the ionisation or excitation caused by the radiation. The severity and permanence of these changes are directly related to the local rate of energy deposition along the particle track.

As a neutron has the same mass as a hydrogen nucleus (proton), after a neutron collides with a proton in the anthrax spore, it transfers all of its energy to the proton, and thus deposits all its energy in the anthrax spores. So, compared with other forms of radiation, the neutron can create the greatest biological damage to the anthrax spore. Neutrons also collide with the oxygen and carbon nuclei in the carbohydrates in the anthrax spore. The masses of oxygen and carbon nuclei are more than 10 times greater than that of a neutron; therefore, only a small part of a neutron's energy transfers to the oxygen and carbon nuclei. The energy transfer in neutron-proton collisions dominates the energy transfers within anthrax spores when irradiated by neutrons, so the neutron-proton collision dominates the biological damage mechanism within the anthrax spores.

The results of MCNP simulation of neutron radiation sterilisation of anthrax spores

We constructed a model (experimental set-up) to simulate neutron sterilisation of anthrax spores by MCNP code (Figure 1). This model consists of a reflector, a stainless steel frame, an anthrax layer and neutron sources. The materials used in the reflector are water, paraffin and graphite; all these materials are good neutron-reflecting and "slowing down" materials [21]. As good reflecting materials, they bounce back the neutrons escaping from the anthrax sample and enable the neutron to collide with the anthrax sample several times to increase the energy deposition in the anthrax sample. As good neutron slowing down materials, they can slow down the neutrons within the reflector; when the neutrons bounce back to collide with the anthrax sample again, most of the neutrons will be within the 100 keV to 2 MeV energy range, which is the most effective neutron energy to kill anthrax spores (Table 1). The neutron-slowness power of the reflecting materials is determined by the light element percentage in the reflecting materials, especially their hydrogen and carbon atomic mass percentage. The larger the light element atomic mass percentage, the greater the

neutron-slowness power. Table 2 lists the atomic mass percentage of the three reflecting materials. It is clear from Table 2 that paraffin has the greatest neutron-slowness power, and graphite the least.

In this model, a stainless steel frame is used to support the anthrax samples; the anthrax-contaminated area is 20×20 cm² and the thickness of the anthrax layer is 4 μm. The neutron sources used in the MCNP simulation are a radioisotope spontaneous fission ²⁵²Cf neutron source [16] and a 2.5 MeV D-D neutron generator [17–19].

In the simulation calculations, the MCNP v. 4C code was used to calculate the single neutron energy deposition on anthrax spores. The neutron sources, the thickness of the reflector, the materials of the reflector and the distance between the anthrax sample and the neutron source were varied in the MCNP simulations to study the single neutron energy deposition (radiation dose) on the anthrax spores. To simplify these complicated processes and save computation time for easy calculation of the neutron radiation dose to the anthrax spores, we ignored the energy deposition from the associated γ-ray irradiation that is created when neutrons interact with anthrax spores and the reflector around them in the model. This approximation will not make a significant difference to the final MCNP calculated radiation dose because the neutron-proton collisions dominate the energy transfers within the anthrax spore, and the weighting factor of neutron is 20 times that of γ-rays at the same energy depositions, so it is reasonable to ignore the energy deposition from γ-rays in the MCNP simulations.

MCNP simulation results are shown in Figures 2–6. Figure 2 shows the MCNP simulation results of using radioisotope spontaneous fission ²⁵²Cf as the neutron source; Figures 3–6 are the MCNP simulation results of using a 2.5 MeV D-D neutron generator as the neutron source. MCNP simulation results can be summarised as follows.

- (1) *The effect of the thickness of the reflector on the neutron energy deposition on anthrax spores.* The simulation results of using ²⁵²Cf as the neutron source are

Table 2. Atomic mass percentage of the reflecting materials

Material	Hydrogen	Carbon	Oxygen
Graphite	0	100%	0
Water	11.1%	0	88.9%
Paraffin	15.0%	85%	0

shown in Figure 2. From these results, we can conclude that, regardless of the materials (water, paraffin or graphite) used in the reflector, the energy deposition in the anthrax sample parallels the thickness of the reflector. However, when the reflector reaches a certain thickness, further increases in the thickness of the reflector will not result in a higher energy deposition in the anthrax sample. We call this reflector thickness the saturation thickness. There is no increased effect on the energy deposition in the anthrax sample when using a reflector thicker than its saturation thickness, so it is meaningless to have a reflector thicker than its saturation thickness in the neutron radiation sterilisation of anthrax spores. This is also true for Figures 3–6, which show the results of using a neutron generator as the neutron source. The results in Figures 2–6 indicate that the saturation thickness is closely related to the reflecting material of the reflector, with the saturation thicknesses for graphite, water and paraffin being approximately 20, 15 and 5 cm, respectively. The saturation thickness for all three reflecting materials is independent of the type of neutron source used, and of the distance between the anthrax sample and the neutron source. The distinct saturation thickness differences of the three reflecting materials are not surprising, as these saturation thickness differences arise from the distinctly different chemical compositions of the three reflecting materials: paraffin has the greatest neutron-slowing power and graphite has the least (Table 2).

- (2) *The effect of the distance between the anthrax sample and the neutron source on the neutron energy deposition on anthrax spores.* It is clear from the results shown in Figures 3–6 that the closer the anthrax sample is to the neutron source, the greater the neutron energy deposition on the anthrax spores. For all three different reflecting materials, when the distance between the anthrax sample and the neutron source is 5 cm, the energy deposition on the anthrax sample is almost twice the energy deposition when the distance is 10 cm. Although this result differs somewhat from the inverse square law, it is still reasonable because of the use of the reflector in the model. This result once again proves that the reflector plays an essential role in the neutron-based sterilisation of anthrax contamination. In real neutron-based sterilisation of anthrax contamination, it would be necessary to place the neutron source as close as possible to the anthrax-contaminated area and to use the reflector to increase the energy deposition in the anthrax spores.
- (3) *The effect of the different reflecting materials on the neutron energy deposition on anthrax spores.* The results from Figures 2–6 indicate that the reflector can greatly enhance the energy deposition in anthrax spores, with different reflecting materials resulting in striking differences in the energy deposition in the anthrax spores. From Figures 2 and 6, we can conclude that, after reaching its saturation thickness, using graphite as the reflecting material can maximise the neutron energy deposition in the anthrax spores because it has the highest density

(1.7 g cm^{-3}). The neutron energy deposition in the anthrax spores using water and paraffin as the reflecting material are approximately 88% and 77% that of the graphite, respectively. This is also true for both neutron sources. Based on the neutron energy deposition calculation results, all three materials can be used in the reflector, but paraffin has the thinnest saturation thickness. Although the density (0.93 g cm^{-3}) of the paraffin is lowest, the content of the hydrogen in the paraffin is highest (approximately 15%); graphite does not have any hydrogen at all, which means that paraffin has the greatest neutron-slowing power. Although paraffin's saturation thickness is only 5 cm, it would be the reflecting material of choice in a real neutron-based sterilisation of anthrax contamination, as it is lightweight and easy to machine.

- (4) *The effect of the different neutron sources on neutron energy deposition on anthrax spores.* Comparing Figures 2 and 6, it is very clear that the neutron energy depositions on anthrax spores are not significantly different when using two different neutron sources with the same reflecting materials. Actually, all the neutrons created by the D–D neutron generator have energy in the 2.5 MeV region. The radioisotope spontaneous fission ^{252}Cf neutron source emits neutrons with a neutron energy spectrum similar to a fission reactor, from 0 to 10 MeV [21]. The average energy of the neutrons emitted from a ^{252}Cf neutron source is approximately 2 MeV [14]. After the neutrons slow down and bounce back from the reflector, the neutron energy spectrum from the two different neutron sources is not too different. This explains why the MCNP simulation results of neutron energy deposition on anthrax spores from the ^{252}Cf neutron source are almost the same as the MCNP simulation results from the D–D neutron generator. If ^{252}Cf is used as the radioisotope spontaneous fission neutron source, regardless of whether it is being used or not and despite its neutron yield reducing by half every 2.645 years, shielding materials will be required to shield the penetrating neutrons and associated γ -rays all the time. In contrast to the ^{252}Cf neutron source, the D–D neutron generator creates neutrons only when it is plugged into a power source; when it is unplugged, the neutrons stop. With improvements in technology, the 2.5 MeV D–D neutron generator neutron yield may reach 10^{13} ns^{-1} or higher [17–19]; therefore, it may be the ideal neutron source in real neutron-based sterilisation of anthrax spores.

Calculation of neutron radiation dose and neutron fluence on anthrax spores

The main chemical components of the carbohydrate polymers in anthrax spores are hydrogen and oxygen, in the proportions in which they exist in water, combined with carbon. To make calculations easier, we assume that the main component of the anthrax spore is water and its density is approximately the same as that of water. If

Figure 2. Energy deposition on anthrax with ^{252}Cf as the neutron source for three reflecting materials.

water is substituted for an anthrax spore in the following calculation, its absorption properties per unit mass do not differ greatly because the average atomic number of water is similar to that of anthrax spores.

It is straightforward from the results in Figures 2–6 that, as the neutron sources are 10 cm away from the anthrax spores, the neutron energy deposition on the anthrax spores is of the order of magnitude $\Delta E = 1.0 \times 10^{-4} \text{ MeV}$ per neutron. If we assume that the spore's density is 1000 kg m^{-3} , which is the same as that of water, the radiation dose (Gy) absorbed by the anthrax spores as a result of neutron irradiation is

$$D = \frac{\Delta E}{\text{mass}} \times \left(\frac{1 \text{ Gy}}{6.24 \times 10^{12} \text{ MeV/kg}} \right) = 1.6 \times 10^{-13} \text{ Gy} \quad (3)$$

γ -ray irradiation was used in the 1960s and 1970s to disinfect anthrax-contaminated imported goat hair bales

[8]. This study suggested that a dose of $1.5 \times 10^6 \text{ rad}$ from a $200\,000 \text{ rad h}^{-1}$ cobalt source was sufficient to kill most resistant anthrax spores when mixed with goat hair, and $2.0 \times 10^6 \text{ rad}$ was recommended to include a margin of safety. The SI equivalent of $2.0 \times 10^6 \text{ rad}$ is $2.0 \times 10^4 \text{ Gy}$. From Table 1, the weighting factor for γ -ray irradiation is 1, and the weighting factor for neutron radiation within the energy range of 100 keV to 2 MeV is 20. This means that, if anthrax spores are irradiated by neutrons, no anthrax spores can survive at a dose level above $1.0 \times 10^3 \text{ Gy}$, so the no survival dose level, $\tilde{D}$, for anthrax spores under neutron irradiation is

$$\tilde{D} = 1000 \text{ Gy} \quad (4)$$

By using Equations (3) and (4), the neutron fluence that is needed to kill anthrax spores is:

Figure 3. Energy deposition on anthrax with a 2.5 MeV neutron generator as the neutron source and water as the reflector.

Figure 4. Energy deposition on anthrax with a 2.5 MeV neutron generator as the neutron source and graphite as the reflector.

$$\phi = \frac{\text{no survival dose level}}{\text{radiation dose per incident neutron}} \quad (5)$$

$$= 0.625 \times 10^{16} / \text{m}^2$$

This is the MCNP code-simulated neutron fluence that is needed to kill anthrax spores, which fully agrees with the previous analytical theoretical estimation of neutron fluence [14].

^{252}Cf can be used as a neutron source to sterilise anthrax contamination; for a 0.5 g ^{252}Cf neutron source, its neutron yield is approximately $1.157 \times 10^{12} \text{ s}^{-1}$. Therefore, if the anthrax spore sample is 10 cm away from the ^{252}Cf neutron source, and the anthrax spore sample is irradiated for 10 min, the fluence is:

$$\phi = \frac{1.157 \times 10^{12} \text{ s}^{-1}}{4\pi \cdot (0.1 \text{ m})^2} \times 600 \text{ s} = 0.56 \times 10^{16} / \text{m}^2 \quad (6)$$

In addition to the ^{252}Cf neutron source, a 2.5 MeV D-D neutron generator can also be used for sterilising anthrax contamination; its neutron yield under current technology can achieve 10^{13} n s^{-1} . If the anthrax spore sample is also 10 cm away from the neutron generator and the anthrax spore sample is irradiated for 1 min, the fluence is:

$$\phi = \frac{1.0 \times 10^{13} \text{ s}^{-1}}{4\pi \cdot (0.1 \text{ m})^2} \times 60 \text{ s} = 0.48 \times 10^{16} / \text{m}^2 \quad (7)$$

Figure 5. Energy deposition on anthrax with a 2.5 MeV neutron generator as the neutron source and paraffin as the reflector.

Figure 6. Energy deposition on anthrax with a 2.5 MeV neutron generator as the neutron source for three different reflecting materials.

Within an order of magnitude, the fluence, ϕ , needed to kill anthrax spores in Equations (6) and (7) agrees with the neutron fluence in Equation (5). This means that a 10 min neutron irradiation from a 0.5 g ^{252}Cf neutron source or a 1 min neutron irradiation from a 2.5 MeV D-D neutron generator may kill all the anthrax spores in the sample. A 2.5 MeV D-D neutron generator with an output $>10^{13} \text{ ns}^{-1}$ should be attainable in the near future. This suggests that we could use a D-D neutron generator to sterilise anthrax contamination within several seconds in the near future.

Conclusion

Anthrax spores are the dormant form of anthrax bacteria; they can germinate in tissues, producing new bacteria that release lethal toxins, causing anthrax to be harmful to humans and animal life. Neutrons are elementary particles that have no charge; this allows them to be very penetrating and to be capable of killing anthrax spores both on surfaces and inside closed containers. Neutrons have a great advantage because they are 20 times more deadly than electrons or γ -rays in killing anthrax spores. Most of the neutrons emitted from a ^{252}Cf neutron source are in the 100 keV to 2 MeV energy range. The 2.5 MeV D-D neutron generator can create neutrons up to 10^{13} ns^{-1} with current technology. All these allow an effective and low-cost method of sterilisation of anthrax contamination.

In this study, MCNP v. 4C code was used to simulate the neutron-based sterilisation of anthrax contamination. In the simulation calculations, we varied the neutron sources, the thickness of the reflector, the materials of the reflector and the distance between the anthrax sample and the neutron source to study the single neutron energy deposition and radiation dose on the anthrax spores.

Simulation results show that there is no effect on the energy deposition in the anthrax sample if a reflector is used that is thicker than its saturation thickness, so it is meaningless to use a reflector thicker than its saturation thickness in the neutron radiation sterilisation of anthrax

spores. In real neutron-based sterilisation of anthrax contamination, it would be necessary to place the neutron source as close as possible to the anthrax-contaminated area and to use the reflector to increase the energy deposition in the anthrax spores. Among all three reflecting materials tested in the MCNP simulation, we suggest that paraffin may be the best because it has the thinnest saturation thickness and is easy to machine. In a comparison of a ^{252}Cf neutron source and a 2.5 MeV D-D neutron generator in the sterilisation of anthrax contamination, simulation results show that the 2.5 MeV D-D neutron generator is a more effective neutron source because of its high neutron yield and easy operation.

The MCNP neutron radiation dose and fluence simulation calculations also show that the MCNP-simulated neutron fluence that is needed to kill anthrax spores agrees with previous analytical estimations very well. MCNP simulation results suggest that a 10 min neutron irradiation from a 0.5 g ^{252}Cf neutron source or a 1 min neutron irradiation from a 2.5 MeV D-D neutron generator can kill all the anthrax spores in the sample. This is a promising result because a 2.5 MeV D-D neutron generator with output $>10^{13} \text{ ns}^{-1}$ should be attainable in the near future; this indicates that a D-D neutron generator could be used to sterilise anthrax contamination within several seconds in the near future.

It should be emphasised that the calculation of the effect of a given exposure to neutron radiation is by its very nature a rough approximation. Biological effects are not absolute physical quantities that can be quantified with high precision. Further, the use of concepts of effective dose is only to provide guidance in approximating the potential effects of a given neutron exposure on anthrax spores. The MCNP simulation results need to be confirmed in further experiments. The anthrax spore lethal dose level, which we used in the radiation dose calculation, under other circumstances may be significantly lower than that of anthrax spores mixed with goat hair [8]. The associated γ -ray irradiation, which is created when neutrons interact with anthrax spores and the materials around them, is also lethal to anthrax spores and is ignored in the MCNP simulation for ease of

calculation. All these factors may reduce the required neutron irradiation time dramatically.

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