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Determining optimal fallout shelter times following a nuclear detonation

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In the event of a single, low-yield nuclear detonation in a major urban area, rapidly providing adequate shelter to affected populations could save 10 000–100 000 individuals from a fatal exposure to fallout radiation. However, poorly sheltered individuals may remain at risk. Current guidance and prior studies are not consistent as to the timing and conditions under which poorly sheltered individuals should leave their shelters to evacuate or obtain better shelter. This study proposes methods to determine the optimal shelter time based on information potentially available following a nuclear detonation. For the case in which individuals move to an adequate shelter that can be reached within 15 min, individuals should stay in a poor-quality shelter for at most 30 min after the detonation. If adequate shelter is available nearby (within 5 min), then poorly sheltered individuals should immediately proceed to the better shelter.

1. Introduction

In the event of a single, low-yield nuclear detonation (0.1–10 kT) in a major urban area, response strategies implemented in the first hour have the potential to save 10 000–100 000 individuals from a fatal exposure to fallout radiation [1–5]. In the studies and guidance documents that have examined the appropriate response to this scenario, sheltering within existing buildings has been widely accepted as a critical initial action.[1] For example, US federal guidance states that 'the best initial action immediately following a nuclear explosion is to take shelter in the nearest and most protective

[1]Shelter was also considered a key emergency response action during the cold war in which analysts considered how to mitigate the impacts of multiple, high-yield (megaton class) detonations on urban populations. Owing to differences in number and yield, the cold war guidance, such as [6], is not directly applicable to the current problem.

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building' [4]. In addition, 'individuals in the poorest shelters ... can [further] reduce their dose by early transit to an adequate shelter'. The latter guidance is particularly important for individuals in buildings that are constructed from lightweight materials and that lack basements (this category includes more than 20% of US households[2]). These buildings will not provide adequate protection against fallout radiation, particularly in the most contaminated regions, and so individuals sheltered within them can be exposed to hazardous radiation [1,2,4,5,8].

While sheltering is widely accepted, the prior guidance and study recommendations are less consistent with respect to the timing and conditions under which individuals should leave their shelters either to evacuate from fallout-contaminated areas entirely or to transit to a higher quality shelter (table 1). The methods developed here estimate the optimal shelter exit time that minimizes the total radiation exposure. These methods are intended to assist emergency planning officials in the development of an optimal low-yield nuclear detonation response strategy that considers not only the minimization of radiation dose, but also other key goals such as the minimization of physiological stress and the efficient allocation of resources to minimize the total loss of life. The latter goal also needs to consider other injury mechanisms, such as burns and blast injuries, caused by other nuclear detonation effects and secondary hazards such as fires.

2. Response strategy overview

Individuals following a *shelter–evacuate* response strategy initially shelter from hazardous fallout radiation and then evacuate fallout-contaminated regions. Prior to evacuation, individuals can minimize their fallout exposure by remaining within highly protective shelters. When no highly protective shelters are immediately available, individuals must decide if and when to travel to a highly protective shelter: either immediately (*transit first*) or after initially sheltering in the best immediately available shelter (*shelter first*). These response strategies are illustrated in figure 1 and discussed in this study. The *evacuate* strategy, in which individuals leave the impacted regions before fallout arrives, theoretically allows some individuals to completely avoid any radiation exposure. However, this strategy is not discussed in this study as it requires (i) rapid and accurate assessment of the fallout plume and (ii) timely communication of this assessment (and appropriate evacuation instructions) to individuals in potentially hazardous zones.

3. Shelter–evacuate strategy

For a given individual, shelter and spatial pattern of fallout radiation, the optimal *shelter–evacuate* shelter time occurs when the first derivative (with respect to time spent in the shelter) of the total dose equals zero,

$$\frac{\partial}{\partial t_{\text{shelter}}}[\text{total\_dose}](t_{\text{fallout}}, t_{\text{shelter}}, t_{\text{evacuation}}) = 0$$
$$= \begin{bmatrix} \dfrac{\partial}{\partial t_{\text{shelter}}}[\text{sheltered\_dose}](t_{\text{fallout}}, t_{\text{shelter}}) \\ \quad + \dfrac{\partial}{\partial t_{\text{shelter}}}[\text{evacuation\_dose}](t_{\text{shelter}}, t_{\text{evacuation}}) \end{bmatrix}, \tag{3.1}$$

[2]The US Energy Information Administration performs a national survey that is representative of 113.6 million US housing units [7]. The 2009 survey results (microdata) were filtered to include only those buildings without basements and whose external walls are constructed of wood; aluminium, vinyl or steel siding; or composite (survey codes: walltype = 2, 3 or 5; cellar = 0). The sum of the final sample weight (N_{weight}) indicates that 26 million (23%) of US households live in such buildings.

Table 1. Summary of prior studies and guidance.

study	method and assumptions	optimal shelter time depends on	optimal shelter time in poor shelters	optimal shelter time in good shelters
Davis *et al.* [9]	recommendations based on subject matter expertise and analysis of a simple, hypothetical fallout pattern	knowledge of overall fallout pattern	no dependence on shelter quality fallout pattern known: do not shelter (evacuate immediately) fallout pattern not known: wait for responder guidance (may be 1–2 days)	
Florig & Fischhoff [10]	analytic solution assuming a spatially homogeneous outdoor radiation field	shelter quality evacuation time (independent of outdoor dose rate)	remain only the first few hours	remain several days
Poeton *et al.* [11]	scoping estimate based on a simple, hypothetical fallout pattern and criteria to avoid exposure to 1+ Sv (threshold for acute health effects)	shelter quality distance from detonation (used as a surrogate for outdoor dose rate)	distance from detonation: $<$16 km: remain only shortly after fallout arrival (implicitly a few hours) $>$16 km: remain 1–2 days	remain 1–2 days
US federal guidance [4]	recommendations based on existing knowledge and techniques	knowledge of overall fallout pattern outdoor dose rate shelter quality impending hazards (e.g. fire) medical needs food and water operational and logistical considerations	no quantitative value or method provided (typical expected shelter time of 12–24 h) sheltering advised until basic fallout pattern is known and appropriate evacuation path determined (likely to be at least several hours) individuals in poor shelters should be prioritized for evacuation or transit to higher quality shelter self-evacuation strongly discouraged in first day	
Archibald & Buddemeier [12]	numerical analysis of evacuation for five complex, hypothetical fallout patterns along an 'optimal' or similar evacuation path	shelter quality indoor dose rate (outdoor dose rate = indoor dose rate × shelter quality)	outdoor dose rate (Sv h^{-1} at 1 h post detonation): $>$0.4: remain first few hours $<$0.4: remain up to 1 day	outdoor dose rate (Sv h^{-1} at 1 h post detonation): $>$0.4: remain several hours $<$0.4: remain at least 1 day

(*Continued*.)

Table 1. (*Continued*.)

study	method and assumptions	optimal shelter time depends on	optimal shelter time in poor shelters	optimal shelter time in good shelters
Buddemeier & Dillon [5]	numerical analysis of shelter and evacuation dose for several complex, hypothetical fallout patterns	shelter quality outdoor dose rate evacuation dose knowledge of overall fallout pattern (optional criterion)	shortly after fallout arrives (evacuation implied to occur after the first hour)	more than 12 h (recommends to err on side of late evacuation)
Wein *et al.* [3]	system analysis that considered nuclear effects (prompt and fallout), population distribution, responder actions, traffic flow patterns, evacuation, and health effects	shelter quality fraction of individuals evacuating evacuation method evacuation route evacuation starting location	pedestrian evacuation: 5 h vehicle evacuation: ideal: 5 h realistic: no optimal time within the first day	more than 12 h
Brandt & Yoshimura [1,2]	numerical analysis of shelter and evacuation dose for two complex, hypothetical fallout patterns for a variety of shelter and/or evacuation response strategies and evacuation routes using city-specific shelter quality estimates study examined minimization of (i) total casualties and (ii) dose at an exemplar, high outdoor dose rate location	shelter quality evacuation route specific response strategy knowledge of overall fallout pattern	early transit to a better quality shelter (within the first few hours) fallout pattern is: known: evacuate high outdoor dose rate regions after 1 h not known: shelter for 8+ h	shelter for an extended period (owing, in part, to uncertainty in identifying the optimal evacuation route)

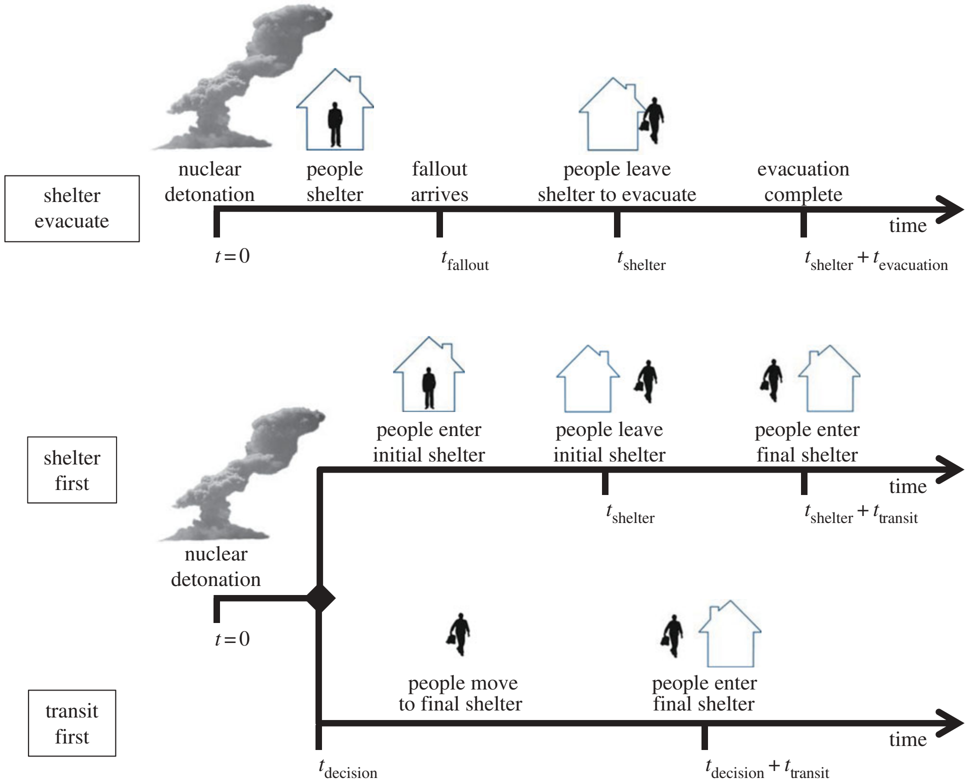

Figure 1. Schematic of response strategies. (Online version in colour.)

where [total_dose](t_{fallout}, t_{shelter}, $t_{\text{evacuation}}$) is the total dose experienced by a person who first shelters and then evacuates, [sheltered_dose](t_{fallout}, t_{shelter}) is the dose experienced by a person while sheltering from t_{fallout} to t_{shelter}, [evacuation_dose](t_{shelter}, $t_{\text{evacuation}}$) is the dose experienced by a person who starts evacuating at t_{shelter}, t_{fallout} is the time since detonation that fallout arrives, t_{shelter} is the time since detonation that a person leaves the shelter to evacuate, and $t_{\text{evacuation}}$ is the time that a person spends evacuating.

Assuming fallout radiation decays in proportion to time^{-n} [8], the first derivative of the sheltered dose is

$$\begin{aligned}\frac{\partial}{\partial t_{\text{shelter}}}&[\text{sheltered\_dose}](t_{\text{fallout}}, t_{\text{shelter}})\\ &= \frac{\partial}{\partial t_{\text{shelter}}}\int_{t_{\text{fallout}}}^{t_{\text{shelter}}} \frac{\text{DR}(t', x_{\text{evacuation}}(0))}{[\text{shelter\_protection\_factor}]}\,\text{d}t'\\ &= \frac{\text{DR}(t_{\text{r}}, x_{\text{evacuation}}(0))}{[\text{shelter\_protection\_factor}]}\left(\frac{t_{\text{shelter}}}{t_{\text{r}}}\right)^{-n},\end{aligned} \tag{3.2}$$

where $\text{DR}(t,x) = \text{DR}(t_{\text{r}}, x)(t/t_{\text{r}})^{-n}$ is the outdoor fallout radiation dose rate at time t and location x, t_{r} is an arbitrary reference time, $x_{\text{evacuation}}(t)$ is the location along the evacuation path at time t into the evacuation ($x_{\text{evacuation}}(0)$ is the shelter location), n is the fallout radiation decay constant (typically 1.2), and [shelter_protection_factor] is the ratio of outdoor to indoor radiation exposure.

Similarly, the first derivative of the evaluation dose is

$$\frac{\partial}{\partial t_{\text{shelter}}}[\text{evacuation\_dose}](t_{\text{shelter}}, t_{\text{evacuation}})$$
$$= \frac{\partial}{\partial t_{\text{shelter}}}\int_0^{t_{\text{evacuation}}} \frac{\text{DR}(t_{\text{shelter}}+t', x_{\text{evacuation}}(t'))}{[\text{evacuation\_protection\_factor}]}\,\text{d}t'$$
$$= \int_0^{t_{\text{evacuation}}} \frac{\text{DR}(t_{\text{r}}, x_{\text{evacuation}}(t'))}{[\text{evacuation\_protection\_factor}]}\left(\frac{-n}{t_{\text{r}}}\left(\frac{t_{\text{shelter}}+t'}{t_{\text{r}}}\right)^{-(n+1)}\right)\text{d}t', \tag{3.3}$$

where $\text{DR}(t_{\text{shelter}}+t', x_{\text{evacuation}}(t')) = \text{DR}(t_{\text{r}}, x_{\text{evacuation}}(t'))((t_{\text{shelter}}+t')/t_{\text{r}})^{-n}$ is the outdoor fallout radiation dose rate along the evacuation route at time t' into the evacuation assuming the evacuation starts at time t_{shelter}, $\text{DR}(t_{\text{r}}, x_{\text{evacuation}}(t'))$ is the outdoor fallout radiation dose rate along the evacuation route at time t' into the evacuation normalized to reference time t_{r}, and [evacuation_protection_factor] is the ratio of unmitigated to mitigated radiation exposure during evacuation. Mitigation may be due to shielding provided by numerous large nearby buildings or by active decontamination of the evacuation route.

The optimal shelter time can be determined by combining equations (3.1)–(3.3) and rearranging

$$1 = n\left(\frac{[\text{shelter\_protection\_factor}]}{[\text{evacuation\_protection\_factor}]}\right)\int_0^{t_{\text{evacuation}}} \frac{\text{DR}(t_{\text{r}}, x_{\text{evacuation}}(t'))}{\text{DR}(t_{\text{r}}, x_{\text{evacuation}}(0))}\left(\frac{t^n_{\text{shelter}}}{(t_{\text{shelter}}+t')^{(n+1)}}\right)\text{d}t'. \tag{3.4}$$

Given that $t_{\text{shelter}} \le t_{\text{shelter}} + t'$ (because $t' \ge 0$), equation (3.4) can be rewritten as

$$t_{\text{shelter}} \le n\left(\frac{[\text{normalized\_evacuation\_dose}](t_{\text{r}})}{[\text{normalized\_sheltered\_dose\_rate}](t_{\text{r}})}\right), \tag{3.5}$$

where [normalized_evacuation_dose](t_{r}) is the dose, normalized to reference time t_{r}, received while evacuating ($\int_0^{t_{\text{evacuation}}} \text{DR}(t_{\text{r}}, x_{\text{evacuation}}(t'))\,\text{d}t'/[\text{evacuation\_protection\_factor}]$), which is approximately equal to the actual evacuation dose starting at time t_{r} when $t_{\text{evacuation}} \ll t_{\text{r}}$, and [normalized_sheltered_dose rate](t_{r}) is the sheltered dose rate normalized to the reference time $t_{\text{r}}\,\text{DR}(t_{\text{r}}, x_{\text{evacuation}}(0))/[\text{shelter\_protection\_factor}]$).

Note that (i) the normalized sheltered dose rate and evacuation dose can be individually (and separately) measured and do *not* require knowledge of the overall fallout pattern and (ii) equations (3.4) and (3.5) do *not* depend upon the time at which the individual enters the shelter.

Previously published results can be used to demonstrate the use of, and provide a check on, equation (3.5). Buddemeier & Dillon [5], assuming a hypothetical fallout pattern, numerically calculated optimal shelter times for a location near the US Capitol Building for sheltered individuals when the 1 h outdoor dose rate was 350 cGy h^{-1}, and the corresponding evacuation dose, normalized to 1 h, was 60 cGy. The predicted optimal shelter times of (1.5–3 h) and (0.5–1 h) for individuals with a shelter protection factor of 10 and 3, respectively, agree well with the optimal shelter times calculated by equation (3.5) of 2.1 h and 0.62 h, respectively.

4. Shelter-first strategy

For the case in which an individual initially shelters in a poor shelter and later transits to a better shelter, the optimal time spent in the initial (poor quality) shelter is

$$\left.\begin{aligned}
&\frac{\partial}{\partial t_{\mathrm{shelter}}}[\mathrm{total_dose}](t_{\mathrm{fallout}}, t_{\mathrm{shelter}}, t_{\mathrm{evacuation}}) = 0 \\
&= \left[\begin{aligned}
&\frac{\partial}{\partial t_{\mathrm{shelter}}}[\mathrm{initial_shelter_dose}](t_{\mathrm{fallout}}, t_{\mathrm{shelter}}) \\
&+ \frac{\partial}{\partial t_{\mathrm{shelter}}}[\mathrm{transit_dose}](t_{\mathrm{shelter}}, t_{\mathrm{transit}}) \\
&+ \frac{\partial}{\partial t_{\mathrm{shelter}}}[\mathrm{final_shelter_dose}](t_{\mathrm{shelter}}, t_{\mathrm{transit}}, t_{\infty})
\end{aligned}\right] \\
&= \left[\begin{aligned}
&\frac{\mathrm{DR}(t_{\mathrm{r}}, x_{\mathrm{transit}}(0))}{[\mathrm{shelter_protection_factor}]_{\mathrm{initial}}}\left(\frac{t_{\mathrm{shelter}}}{t_{\mathrm{r}}}\right)^{-n} \\
&+ \int_0^{t_{\mathrm{transit}}} \frac{\mathrm{DR}(t_{\mathrm{r}}, x_{\mathrm{transit}}(t'))}{[\mathrm{transit_protection_factor}]}\left(\frac{-n}{t_{\mathrm{r}}}\left(\frac{t_{\mathrm{shelter}}+t'}{t_{\mathrm{r}}}\right)^{-(n+1)}\right)\mathrm{d}t' \\
&- \frac{\mathrm{DR}(t_{\mathrm{r}}, x_{\mathrm{transit}}(t_{\mathrm{transit}}))}{[\mathrm{shelter_protection_factor}]_{\mathrm{final}}}\left(\frac{t_{\mathrm{shelter}}+t_{\mathrm{transit}}}{t_{\mathrm{r}}}\right)^{-n},
\end{aligned}\right]
\end{aligned}\right\} \tag{4.1}$$

where t_{transit} is the time that a person spends transiting from the initial to the final shelter, t_{∞} is the time at which there is negligible outdoor fallout exposure, $x_{\mathrm{transit}}(t)$ is the location along the transit path at time t ($x_{\mathrm{transit}}(0) =$ initial shelter location; $x_{\mathrm{transit}}(t_{\mathrm{transit}}) =$ final shelter location), $\mathrm{DR}(t_{\mathrm{r}}, x_{\mathrm{transit}}(t'))$ is the outdoor fallout radiation dose rate along the transit route at time t' into the transit normalized to reference time t_{r}, and [transit_protection_factor] is the ratio of unmitigated to mitigated (e.g. decontaminated) radiation exposure during the transit.

If the individual travels to a nearby shelter (or goes outside to improve the initial shelter quality), it is reasonable to assume that no outdoor mitigation has occurred (e.g. [transit_protection_factor] = 1), and the individual does not move to a location in which the reference dose rate is different from that outside the initial shelter. Equation (4.1) can then be rearranged in terms of the ratio of the shelter time (t_{shelter}) to the transit time (t_{transit}):

$$t_{\mathrm{shelter}} = K \times t_{\mathrm{transit}}, \tag{4.2}$$

where

$$K = \frac{M([\mathrm{shelter\_protection\_factor}]_{\mathrm{initial}}, n)}{M([\mathrm{shelter\_protection\_factor}]_{\mathrm{final}}, n) - M([\mathrm{shelter\_protection\_factor}]_{\mathrm{initial}}, n)}$$

and

$$M(y, n) = \left(\frac{y-1}{y}\right)^{(1/n)}.$$

M and y are used for computational convenience. Table 2 provides common values for K, the ratio of t_{shelter} (the optimal time to remain in the initial shelter after detonation) to t_{transit} (the time spent outdoors acquiring better shelter). Note that K is *not* dose rate dependent, which implies that no radiation measurements are required. For context, table 3 provides t_{shelter} assuming a better quality shelter is available in the same general region ($t_{\mathrm{transit}} = 15$ min). Note that equation (4.2) and tables 2 and 3 can also apply to the case in which an individual exits the initial shelter, actively improves the shelter quality (e.g. placing earth along the shelter walls and roof), and then re-enters the improved shelter.

Previously published results can be used to provide a check on equation (4.2). Brandt & Yoshimura [1,2], assuming two hypothetical fallout patterns, numerically calculated optimal shelter times prior to transiting to an adequate quality final shelter (shelter protection factor = 10) for an assumed transit time (t_{transit}) of 12 min and an initial shelter quality of 2 and 4. The corresponding optimal shelter times calculated using equation (4.2) (19 and 73 min, respectively)

Table 2. Values for K: the ratio of the optimal time after detonation to remain in the initial shelter to that spent outdoors acquiring better shelter.

initial shelter quality (shelter protection factor)	final shelter quality (shelter protection factor)			
	inadequate (4)	adequate (10)	good (40)	ideal (∞)
poor (2)	2.5	1.6	1.3	1.3
inadequate (4)	n.a.	6.1	4.1	3.7

Table 3. Values for t_{shelter}: the optimal time (in min) after detonation to remain in the initial shelter assuming 15 min are spent outdoors acquiring better shelter.

initial shelter quality (shelter protection factor)	final shelter quality (shelter protection factor)			
	inadequate (4)	adequate (10)	good (40)	ideal (∞)
poor (2)	37	24	20	19
inadequate (4)	n.a.	91	61	55

are consistent with the corresponding predictions provided in fig. 7 of Brandt & Yoshimura [1] and in fig. 8 of Brandt & Yoshimura [2].

5. Shelter first versus transit first

Under specific circumstances, it can be advantageous to immediately transit to a higher quality shelter rather than remaining in an immediately available, poorer quality shelter until $t_{\text{shelter}} = K \times t_{\text{transit}}$. The decision on whether to pursue a *shelter-first* or *transit-first* strategy could be determined from dose minimization considerations and the results of equations (5.1*a*) and (5.1*b*).[3] The variables required are the fallout arrival time, transit time, decision time (i.e. $t_{\text{decision}} =$ the time since detonation that the response strategy is chosen) and shelter quality.

$$
\left.
\begin{aligned}
&[\text{shelter\_first\_dose}](t_{\text{fallout}}, t_{\text{transit}}, K)\\
&\quad = \frac{\text{DR}(t_{\text{r}}, x_{\text{transit}}(0))}{t_{\text{r}}^{-n}} \left[\int_{t_{\text{fallout}}}^{t_\infty} \frac{t^{-n}}{[\text{shelter\_protection\_factor}]_{\text{final}}}\,\text{d}t \right],\\
&\quad \text{where } t_{\text{fallout}} \geq t_{\text{shelter}} + t_{\text{transit}},\\
&\quad = \frac{\text{DR}(t_{\text{r}}, x_{\text{transit}}(0))}{t_{\text{r}}^{-n}} \left[\int_{t_{\text{fallout}}}^{(K+1)t_{\text{transit}}} t^{-n}\,\text{d}t + \int_{(K+1)t_{\text{transit}}}^{t_\infty} \frac{t^{-n}}{[\text{shelter\_protection\_factor}]_{\text{final}}}\,\text{d}t \right],\\
&\quad \text{where } t_{\text{shelter}} \leq t_{\text{fallout}} < t_{\text{shelter}} + t_{\text{transit}},\\
&\quad = \frac{\text{DR}(t_{\text{r}}, x_{\text{transit}}(0))}{t_{\text{r}}^{-n}} \left[\begin{aligned} &\int_{t_{\text{fallout}}}^{(K)t_{\text{transit}}} \frac{t^{-n}}{[\text{shelter\_protection\_factor}]_{\text{initial}}}\,\text{d}t \\ &+ \int_{(K)t_{\text{transit}}}^{(K+1)t_{\text{transit}}} t^{-n}\,\text{d}t \\ &+ \int_{(K+1)t_{\text{transit}}}^{t_\infty} \frac{t^{-n}}{[\text{shelter\_protection\_factor}]_{\text{final}}}\,\text{d}t \end{aligned} \right],\\
&\quad \text{where } t_{\text{fallout}} < t_{\text{shelter}},
\end{aligned}
\right\}
\tag{5.1a}
$$

[3]Equations (5.1*a*) and (5.1*b*) make the same assumptions as equation (4.2). Also note that other considerations, such as medical needs and shelter capacity, can influence the choice of response strategy.

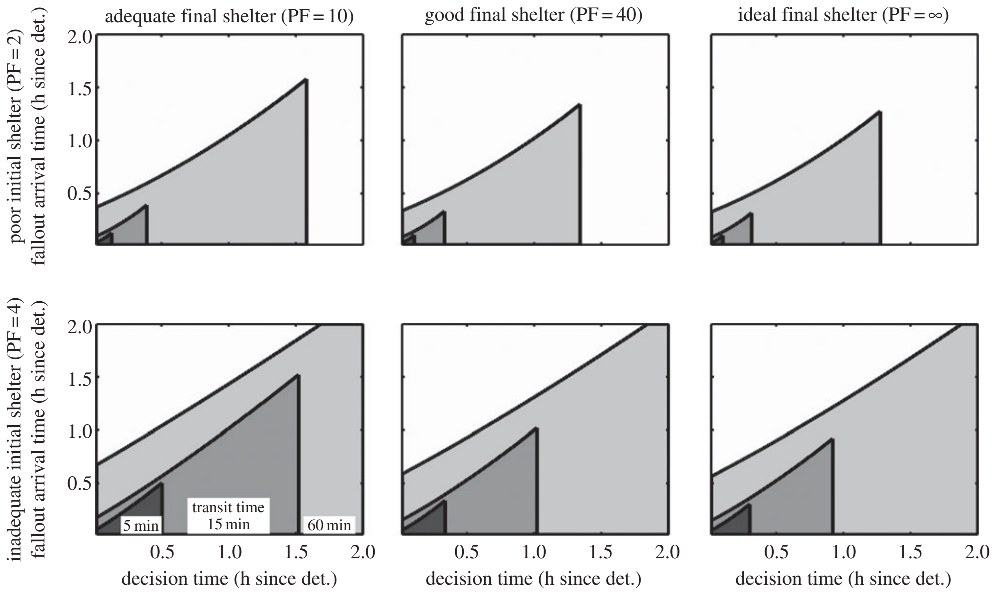

Figure 2. Model results for the *shelter-first* versus *transit-first* decision that yields the lowest radiation dose. Shaded areas in the graphs indicate that a *shelter-first* response strategy results in the lowest radiation dose. Areas outside a given shaded region in the graphs indicate that a *transit-first* response strategy results in the lowest radiation dose. Each identically formatted panel provides results for a different combination of initial and final shelter quality. The *x*-axis represents the decision time (t_{decision}—time since detonation at which the response strategy is selected). The *y*-axis represents the fallout arrival time (t_{fallout}—time since detonation at which the fallout arrives). The shading of the filled areas designates the assumed transit time (t_{transit}—time required to move from the initial to the final shelter): 5 min is black, 15 min is dark grey and 60 min is light grey.

$$\left.\begin{aligned}
&[\text{transit_first_dose}](t_{\text{fallout}}, t_{\text{decision}}, t_{\text{transit}}, K)\\
&\quad= \frac{\text{DR}(t_{\text{r}}, x_{\text{transit}}(0))}{t_{\text{r}}^{-n}}\left[\int_{t_{\text{fallout}}}^{t_\infty} \frac{t^{-n}}{[\text{shelter_protection_factor}]_{\text{final}}}\,\text{d}t\right],\\
&\quad\text{where } t_{\text{fallout}} \geq t_{\text{decision}} + t_{\text{transit}},\\
&\quad= \frac{\text{DR}(t_{\text{r}}, x_{\text{transit}}(0))}{t_{\text{r}}^{-n}}\left[\int_{t_{\text{fallout}}}^{t_{\text{decision}}+t_{\text{transit}}} t^{-n}\,\text{d}t + \int_{t_{\text{decision}}+t_{\text{transit}}}^{t_\infty} \frac{t^{-n}}{[\text{shelter_protection_factor}]_{\text{final}}}\,\text{d}t\right],\\
&\quad\text{where } t_{\text{decision}} \leq t_{\text{fallout}} < t_{\text{decision}} + t_{\text{transit}},\\
&\quad= [\text{shelter_first_dose}](t_{\text{fallout}}, t_{\text{transit}}, K),\\
&\quad\text{where } t_{\text{fallout}} < t_{\text{decision}}.
\end{aligned}\right\}\qquad(5.1b)$$

Figure 2 designates, by shaded areas, the combinations of t_{fallout}, t_{decision}, t_{transit} and shelter quality for which the *shelter-first* strategy minimizes the total radiation dose received. The shading colour indicates the assumed t_{transit} where a 5 min transit time is shaded black, a 15 min transit time is shaded dark grey and a 60 min transit time is shaded light grey. Areas outside a given shaded region indicate that a *transit-first* strategy will result in a lower dose for the corresponding transit time. Note that these predictions assume $n = 1.2$ but do not depend on the outdoor dose rate.

Figure 3, which recreates the lower left panel of figure 2 for $t_{\text{transit}} = 15$ min (dark grey shading), illustrates how to use figure 2. The black dot located in the shaded area indicates that, for a location in which fallout arrives 30 min after detonation ($t_{\text{fallout}} = 0.5$ h), an individual trying to decide what to do at fallout arrival ($t_{\text{decision}} = 0.5$ h) should enter an inadequate shelter (initial

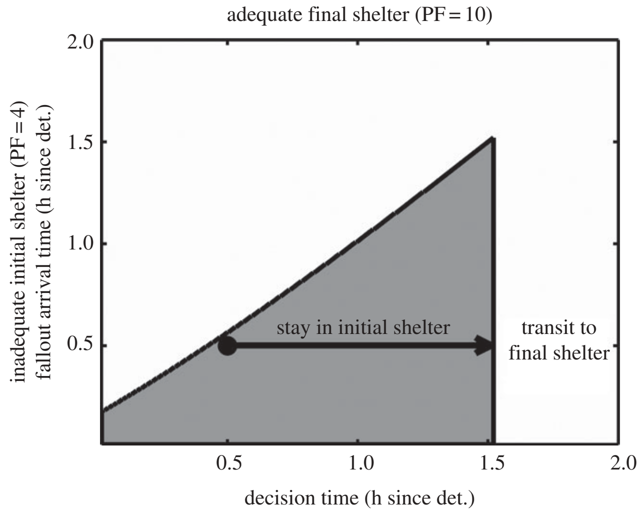

Figure 3. Example illustrating the use of the *shelter-first* versus *transit-first* decision graph.

shelter protection factor = 4) rather than travel 15 min ($t_{\text{transit}} = 15$ min corresponding to the dark grey shading) to a nearby adequate shelter (final shelter protection factor = 10). Furthermore, the arrow emanating from the black dot indicates that those in the inadequate shelter should remain there for about an hour, specifically until 91 min after the detonation ($t_{\text{shelter}} = 91$ min), after which the individual should then leave the inadequate shelter and travel the 15 min to the final shelter.

The values in figure 2 were determined by numerically evaluating equations (5.1*a*) and (5.1*b*) for a given set of values for t_{fallout}, t_{decision}, t_{transit} and K and then filling each location accordingly. The parameter ranges modelled were as follows:

— K: table 2 values;
— t_{fallout}: 1–120 min with 15 s resolution;
— t_{decision}: 1–120 min with 15 s resolution; and
— t_{transit}: 5, 15 and 60 min.

6. Discussion and conclusion

The models developed here provide quantitative methods that support emergency response decisions in the event of a low-yield nuclear detonation. The methods aim to minimize fallout radiation exposure using information that may be readily available after a nuclear detonation. Guidance and recommendations based on these methods are (a) the optimal shelter exit time prior to evacuating is approximately proportional to the ratio of: (i) the evacuation dose normalized to a single, arbitrary reference time and (ii) the sheltered (indoor) dose rate normalized to a single, arbitrary reference time; (b) if an adequate shelter is *nearby* (less than 5 min transit time), individuals should proceed to the adequate shelter and forgo sheltering in immediately available, poor-quality shelters; and (c) if an adequate shelter is available in the same *general region* (less than 15 min transit time), individuals in poor-quality shelters should leave the poor shelter to transit to the adequate quality shelter *no later than 30 min after the detonation*.

These methods provide two advantages. First, they demonstrate that the optimal shelter time minimizes both the avoidable and the total dose. Second, they do not assume any specific fallout pattern and therefore appear to be valid for all fallout patterns whose fallout radiation decays proportional to $t^{-1.2}$. An important consequence of this is that the derived optimal shelter exit time does not require knowledge of the overall spatial pattern of radioactive fallout.

There are several important practical considerations in the use of these methods. First, caution should be used in determining the appropriate evacuation dose since route congestion, e.g. traffic jams, can increase the evacuation time (and dose) above that originally assessed (see [3] for more details). Second, as noted in table 1, other factors, such as food, water, medical needs and impending hazards (e.g. fire), may also need to be considered. Inclusion of these factors is beyond the scope of this study. Third, knowledge of the fallout arrival time allows for improved decision-making. However, use of this information increases the decision-making complexity. Fourth, while many of these methods do not require knowledge of the absolute dose rate in determining the optimal shelter time, particular attention should be paid to ensuring that individuals most at risk, e.g. those located in high dose rate regions, act optimally. Finally, the implementation of these methods will require effective emergency communications and instructions which should be carefully scripted and tested. The interested reader is referred to [13] for examples of current US nuclear detonation response messages.

The results of this study appear to provide some important context to the results of prior studies and guidance (table 1). A number of studies have identified some combination of shelter quality and outdoor dose rate as important factors in determining an optimal shelter time, with a 10-fold difference in the optimal shelter time between poor- and good-quality shelters. This is consistent with this study's results that the sheltered dose rate (the outdoor dose rate × shelter quality) is a key predictive variable and, for a given evacuation dose, optimal shelter time is proportional to the shelter quality. However, this study also indicates that more nuanced guidance may be possible for individuals who initially shelter in poor shelters, particularly if better quality regional shelters are known to be available. Poorly sheltered individuals should be prioritized for transit to better quality regional shelters (if available) relatively soon after the detonation. The decision to transit does not require knowledge of the outdoor dose rate nor the overall fallout pattern. The prioritization of poorly sheltered individuals for evacuation should apply to a given region where outdoor dose rates are reasonably homogeneous spatially—not necessarily across an entire region impacted by fallout radiation.

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