INDIVIDUALS' DECISIONS AFFECTING RADIATION EXPOSURE AFTER A NUCLEAR EXPLOSION

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Abstract—**In the aftermath of a nuclear attack, shelters can offer potentially important protection. How well they fill that role depends on a set of interdependent decisions made by the individuals and organizations that must prepare and use them. We look at three such decisions. For each, we begin with formal analysis of the consequences expected from different possible actions. Those analyses are, then, reviewed in terms of how individuals facing these choices will perceive them, given the information that they are likely to have. The first example suggests that preparing a home shelter according to guidelines from the Department of Homeland Security may not pass a cost-benefit test. The second example explores the use of readily available information about a blast to infer how urgently shelter should be sought. The third example considers when shelters should be left, suggesting that individuals with the best shelters and slowest evacuation speeds should evacuate last, if they have the provisions needed to remain. In each case, helping people to protect themselves requires prior risk analyses and communication development.**
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INTRODUCTION

PERHAPS THE threat of greatest consequence in terrorists' arsenal is detonating a stolen or improvised nuclear device in an urban area. Various bodies have issued guidance on how citizens should respond to this threat, typically recommending that they take shelter in order to reduce radiation exposure from fallout (CDC 2005; NAE 2005). Although any shelter is better than none, it is not clear how fully this advice considers the options and consequences facing citizens. For example, sheltering in one's current location may provide less protection than sheltering in another one, even when considering the additional exposure while in transit between the two. Even when a shelter provides enough additional shielding to justify moving there, reduced radiation exposure will not be the only issue on many citizens' minds. For example, they might wonder about the risks that they would be taking, by forsaking the best personal shelter, in order to help others. Or, they might wonder whether the resources needed to provision a home shelter might be better invested in other protective actions or other things altogether.

Sound advice regarding sheltering (or any other behavior) should reflect analyses that systematically evaluate the expected utility of alternative actions. Absent such analyses, advice may mislead its recipients. When individuals' circumstances vary, then any single message will fit some of them better than others. As a result, such advice should reflect a deliberate weighting of those individuals' welfare—so that it fits best those whom it will bring the greatest benefit. That benefit will depend on recipients' willingness and ability to follow the advice.

Here, we develop advice regarding three interrelated sheltering decisions. For each, we accommodate the variability in people's circumstances, at a level of complexity suitable to the conditions under which the decisions will be made. In each case, we show how relatively simple analysis can capture important elements of the decision. The three decisions are:

1. Should one prepare a shelter space in one's home?
2. Should one risk traveling from one's location at the time of a blast?
3. How long should one remain in a shelter before evacuating the area?

HOME SHELTER PREPARATION

A number of government and non-government organizations with emergency-management functions recommend that people stock emergency supplies in their homes to sustain and protect them in the event of an emergency requiring people to stay sheltered for an

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extended period. The Department of Homeland Security (DHS), which the National Response Plan names as the primary government organization for mass care (DHS 2004), recommends stocking enough emergency supplies to sustain those in the shelter for three days. Their checklist of recommended emergency supplies (DHS 2006) includes over two dozen items, including water, food, clothing, utensils, medicines, first aid supplies, personal sanitation supplies, radio, flashlight, dust mask, duct tape and plastic sheeting, bedding, pet needs, and entertainment. Other organizations to which the public might turn for advice on radiological emergencies offer similar, but not identical, stockpile recommendations (CDC 2005; American Red Cross 2006). Given that the effort and expense of procuring and organizing these emergency supplies are non-negligible, a reasonable person might ask whether the benefits of securing them outweigh their costs. Tables 1 and 2 address this question.

Some cost estimates

Table 1 details the approximate costs of equipping a home shelter to supply four people for 3 days with the goods on the DHS Emergency Supply List (DHS 2006). Durable goods are assumed to last 10 years and non-durables are replaced as needed. The initial outlay for the median household is estimated to be about $465, with additional annual costs of roughly $250. Applying a 4% discount rate, the net present value of the 10-y costs of following DHS's recommendations comes to about $2,400. The initial outlay might be negligible for some families and impossible for others (equaling two weeks' income for minimum wage workers). Census data on disposable income could be used to assess its affordability across the population. Doing so would be a necessary first step toward estimating compliance rates. It would also allow targeting those for whom the message is meaningful (because they could, conceivably, comply), while avoiding those who might find it offensive (because it asks them to do the impossible if they want to protect their families).

The recurring annual cost of maintaining provisions, which includes rent on the space needed to store them, is roughly half the initial cost. Psychologically, it may seem to be even less for people who substantially discount future costs. Conversely, the initial costs may seem disproportionately large for people who expect to move

Table 1. Estimated 10-y costs of provisioning a home shelter to sustain 4 people with 3 d of supplies, as recommended by the DHS Emergency Supply List. Ranges represent central 95% of households. Costs for items used by only some households (e.g., pet food) are weighted averages across all households.

Component	Initial stocking cost, $	Annual replacement cost, $
Potable water in safe container, 1 gallon/person/day	1–30	0–30
Food with long shelf life	25–70	5–70
Radio (AM/FM and NOAA weather) with extra batteries	10–20	2–4
Flashlights and batteries	5–10	2–5
First aid kit and first aid book	30–50	2
Whistle	5	0
Dust mask (one per person)	3	0
Duct tape and plastic sheeting	10–20	0
Personal sanitation/hygiene supplies	6	1
Tools (wrench, pliers)	5	0
Can opener	4	0
Road maps	3	0
Medicines including prescriptions	1–20	1–10
Eyeglasses or contact lenses and cleaning supplies[a]	3	2
Infant formula and diapers	1	1
Pet food	5	0
Copies of important documents	1	1
Cash ($500)[b]	35	35
Bedding	10–50	0
One change of clothes and shoes per person	10–40	5
Chlorine bleach and medicine dropper	3	2
Fire extinguisher	10–30	0
Paper plates, paper towels, and plastic utensils	5	0
Books, games, and entertainment	5–30	0
Space to store materials—1 m^2 @ $8–15 m^{-2} mo^{-1}	100–180	100–180
Time valued at $6–20 h^{-1}	18–60	9–30
Estimated median across all households	465	252
Net present value over 10-y lifetime, 4% discounting, $	2,400	

[a] Assumes existing eyeglasses/contacts are used. Costs are for cleaning supplies only.
[b] Assumes opportunity cost of cash stashed away is 7% per year.

Table 2. Event string required for home shelter preparation to be useful. Plausible probabilities have been assigned for illustration.

Event	Plausible probability
1. The probability of a nuclear attack anywhere in the U.S. over the physical lifetime of the shelter	0.05
2. If attack happens in U.S., it will be in their city	0.1
3. If attack happens in their city, the wind will blow fallout toward their house	0.2
4. If wind is blowing toward their house, $n = 1, 2, 3$, or 4 people will be at home	0.26, 0.13, 0.07, 0.34
5. If n people are at home, a timely alert indicating the need to take shelter will be issued	0.5
6. If timely alert is issued, they will hear it in time to take shelter	0.5
7. If a timely alert is issued, they will decide to take shelter rather than to flee	0.5
8. If they decide to shelter, their shelter will provide sufficient protection to save them	0.5
Joint probability that shelter will save the lives of 1, 2, 3, or 4 people	1.6×10^{-5}, 0.8×10^{-5}, 0.4×10^{-5}, 2.1×10^{-5}
Expected number of lives saved, $p_1 + 2p_2 + 3p_3 + 4p_4$	1.3×10^{-4}

soon, given the hassles of arranging for storage space and moving supplies to a new home. Those people might defer action until after they have moved, hoping that nothing happens in the interim. Determining the prevalence of such tendencies would allow further refining estimates of compliance rates.

Each item on the DHS list could be evaluated in terms of its impacts on individuals' choices. For example, the largest single cost in Table 1 is rent for the floor space needed to store the supplies. Some households will have room to spare and not consider this a cost; others will have no way of securing the space. Shelter preparation would be easier for individuals in the former category, impossible for those in the latter. The prevalence of these "market sectors" might be estimated from census data on housing size or dedicated surveys.

The time needed for stockpiling is another large cost in Table 1. The number of hours is a rough estimate of how long it would take a person to translate DHS's general list into specific terms, purchase them, prepare the space, and stow them. The value of that time covers a range of wages. Although one might argue that people should not consider the value of the time spent in protecting themselves, economists commonly use time expenditures when placing a value on other human activities. For instance, the "travel cost method" is a standard way for monetizing the value of resources like national parks (Parsons 2003).

The cost estimate for medicine covers routine over-the-counter remedies, which all households are assumed to need, and a weighted average of prescription medications, which some households need more of than do others. It underestimates costs for people who need special drugs, especially if their insurance plan will not cover such advance purchases or they must purchase additional refrigeration. These estimates, too, could be refined with dedicated studies (asking people about their circumstances) or with healthcare data regarding household drug needs and stores.

The analysis of the DHS list should begin by assuming wholly rational behavior, in the sense that citizens understand the options perfectly and choose the one with the greatest expected utility. The analysis should then be repeated, making more behaviorally realistic assumptions, such as recognizing that people sometimes forget that they need drugs or that they have extra doses already. The former would be less prepared than they think, while the latter overestimate the costs of stocking their shelter.

The estimates in Table 1 would represent an infeasible expense for some people, a trivial one for others. For the former, ignoring DHS's advice could reflect a reasoned response. For the latter, though, failure to stock up would require another explanation. The next section considers one possible other reason, seeing little chance of using the shelter—and getting a return on that investment.

Some benefit estimates

Let, $p_1, \ldots, p_4$ be the probabilities that using the shelter over its 10-y lifetime will save the lives of exactly $1, \ldots, 4$ household members, respectively. Using the cost estimates in Table 1, the expected cost per life saved for a household of four would be

$$\text{Cost per life saved} = \frac{\$2{,}400}{(p_1 + 2p_2 + 3p_3 + 4p_4)}. \quad (1)$$

Each p_n can be estimated as the product of the string of probabilities in Table 2. For illustrative purposes, plausible values have been assigned to each. For example, we assume that all household members are at home during sleeping hours (8 h d^{-1}), while during non-sleeping hours, each person spends the population average time at home (33%; Klepeis et al. 2001), distributed uniformly over the non-sleeping period. Under these assumptions, the probabilities of exactly one, two, three, and four household members being at home at a randomly selected time during any 24-h period are 26%, 13%, 7%, and 34%, respectively, for an expected occupancy of 2.1. An attack timed for maximum impact might be detonated during peak business hours, in a central business district. In that case, the expected occupancy of homes outside that area would be smaller.

Each probability in Table 2 could be similarly refined. After computing technically sound estimates of the chances of people benefiting from shelter preparations, one can examine the accuracy of the beliefs that will determine their actual choices. For example, optimism bias (Weinstein 1980) could lead people to underestimate the probability of a nuclear attack being in their city and to overestimate the probability of being near their shelter should it be needed. Lay estimates might be less than expert estimates because citizens believe that terrorist threats are being exaggerated for political purposes. Lay estimates might be greater than expert estimates because citizens do not appreciate just how many targets there are in the U.S. (and the world), relative to the limited number of nuclear weapons that terrorists might conceivably secure. Assessing the magnitude of these possible biases in lay beliefs requires direct empirical study, the results of which can focus risk communications on critical misunderstandings.

Given the values in Table 2, the joint probability of these events occurring (and a shelter saving lives) is very small. Psychological research has identified two processes that could lead people to exaggerate this probability and, with it, the value of a shelter. One such process is not seeing how a set of mostly possible events could add up to a nearly impossible conjunction (Cohen et al. 1956). The second is finding the scenario as a whole so compelling that its number of constituent events is neglected (Tversky and Kahneman 1973). Conversely, some people may view the probability of an attack occurring in their city as so small that they dismiss the entire prospect. Here, too, research is needed to assess the prevalence of such beliefs and the possibilities for changing them (Morgan et al. 2001; Fischhoff 2005).

Applying the probabilities in Table 2 in eqn (1) yields a cost per life saved of roughly \$15 million. This value is much greater than the cost-effectiveness of many other household life-saving interventions (e.g., smoke detectors, bicycle helmets) and well above the median \$4 million/life-saved guideline for government measures addressing health and safety risks (Morrall 2003). Individuals who see sheltering this way might rationally decide that provisioning one is a poor investment.

Like the estimates in Table 1, those in Table 2 could be refined. Perhaps the most uncertain is the first, the probability of a nuclear attack in the U.S. over the next decade. If shelter decisions are robust across the range of plausible values, then no greater precision is needed. If not, then more precise probability assessments are needed or the value of a shelter is indeterminate. Table 2's second entry (target city) might be taken from the analyses supporting the Department of Homeland Security's Urban Areas Safety Initiative, allocating money to cities according to threat levels and protection opportunities, or from external reviews (Willis et al. 2005; GAO 2006). Repeating this analysis at a finer geographic scale could accommodate statistics on the likelihood of living so near the blast that prompt effects are lethal or so far away that sheltering only modestly reduces cancer risk. The third value in Table 2 (wind direction) could be honed with meteorological data. The fourth value (being at home at the time of an attack) was discussed above. The fifth and sixth values depend on emergency authorities' operational readiness for issuing an alert and getting it heard. The seventh and eighth values partly depend on issues considered below concerning the risk reduction from getting to a shelter and staying there.

The benefits of incurring the costs documented in Table 1 will be greater if the same preparations serve other ends, such as helping households to get through extreme weather events or extended electrical outages. Assessing these benefits requires additional analyses (e.g., preparations that help in an ice storm might be useless in a flood), incorporating factors like those in Fig. 1.

DHS has also issued recommendations for stockpiling emergency supplies at places of work (DHS 2005). Those, too, could be subjected to cost-benefit analyses similar to those presented here.

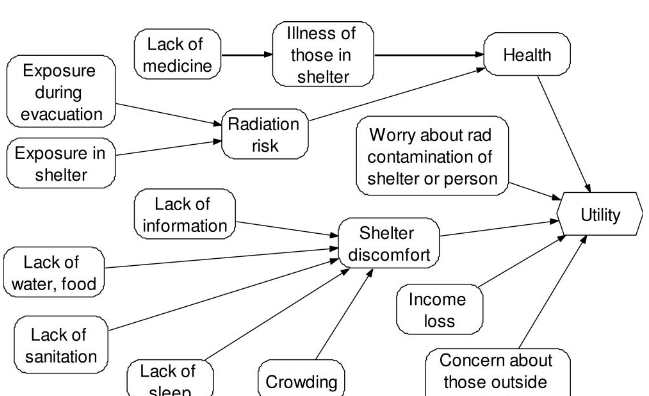

Fig. 1. Factors affecting the utility of sheltering.

TRAVELING IMMEDIATELY AFTER THE BLAST

Blast effects, immediate thermal/ionizing radiation, and fire would be lethal to most people within some radius (~2 km for a 10 kT ground burst) of ground zero. Beyond that, the main health concern is radiation exposure from fallout. As noted, unless a blast occurs at night, most people will be away from home. People who have prepared a home shelter will want to know what radiation risk they face in traveling home in order to gain its benefit. They may also want to know the risk from other travel, such as getting to loved ones at day care or a nursing home—or getting provisions that they neglected before (or consumed for routine purposes).

It is not known how quickly official public announcements relevant to travel decisions could be issued after an event as disruptive as a nuclear blast. If experience with Hurricane Katrina is any guide, it may take many hours. News media outside the blast zone, however, will likely continue to operate. As a result, people in fallout-vulnerable zones should be able to learn the blast's location quickly if their electricity is still working or they have battery-powered radios. If official recommendations were pre-positioned with media sources, along with simple criteria for using them (e.g., bright flash and mushroom cloud), they could be broadcast without post-blast authorization. Such preparation of news outlets could provide life-saving information to many people. However, survivors closest to the blast zone, who must secure shelter within minutes, could not wait even that long. They need to receive sound, comprehensible instruction before an emergency, as do people without access to communications. Not everyone needs that information, as long as someone around them has it and shares it. Understanding those advice distribution channels is an essential part of disaster preparation.

Regardless of the information channel (pre-blast education, pre-positioned media messages, or post-blast official announcements), the intense conditions after an attack mean that any advice will have to make minimal cognitive demands on those receiving it. Table 3 shows one possible form of such guidance, calibrated for a 10 kT ground burst. It offers simple recommendations, based on the time until fallout arrives or, if that estimate cannot be computed and conveyed, distance from the blast. Its simple decision rule compares risk from radioactive fallout with possible benefits of travel. For those closest to the blast, it gives orders, not options.

Table 3 advises taking shelter immediately for anyone whom fallout will reach within 15 min. The distance version of this advice applies it to the several-kilometer wide zone subject to local fallout (large particles of radioactive material either impelled directly by the blast or falling soon after being swept aloft by the "upwind" of the blast). Given the very high dose rates within this zone, it is hard to imagine circumstances that would override this advice.

Beyond this zone, the best possible advice would depend on wind speed and direction. The debris cloud from a 10 kT blast would rise to an altitude of perhaps 8 km, where winds might differ substantially from those at ground level. Officials who know these conditions might be able to derive more precise advice and communicate it clearly. Unless they can, distance might be the best basis for decision making. In order to rely on it, people

Table 3. Travel recommendations for the period immediately after detonation of a 10-kiloton fission bomb, before the arrival of fallout. Cancer risks are based on dose estimates from Hotspot 2.05 (Homann 2003) and are expressed as the fractional increase in lifetime cancer risk from non-radiation causes. Distance ranges, risks, and recommendations would differ for a blast of significantly lower or higher yield.

Fallout arrival	Distance from blast	Risk from unsheltered exposure during first hour of fallout	Risk from 90% effective shelter during first hour of fallout	Recommendation
$<$ 15 min	$<$ 4 km	Acutely fatal for all	Acutely fatal for most	Shelter in deepest space reachable within minutes
15–60 min	4–10 km	Acutely fatal for most. Quadruple cancer risk for the few survivors.	Acutely fatal for some. Doubling of cancer risk for survivors.	Travel only if certain that better shelter can be reached before fallout arrives. Use extra time to fortify shelter space.
30–90 min	10–20 km	Acutely fatal for some. Doubling of cancer risk for survivors.	20% additional cancer risk	Travel if risk of exposure to fallout seems worth the benefit. Use extra time to fortify shelter space.
1–3 h	20–50 km	20% additional cancer risk	2% additional cancer risk	Travel if risk of exposure to fallout seems worth the benefit. Failure to reach shelter before fallout arrives has health consequences that are significant, but not acutely fatal.
$>$ 2 h	50–100 km	5% additional cancer risk	$<$ 1% additional cancer risk	Sufficient time exists for travel to get home, collect family members, and/or flee

might need to be dissuaded from relying on surface winds to predict the fallout plume.

Although officials should quickly know the blast's location, they may be uncertain about its magnitude. For an improvised nuclear device, 1–10 kT is the range of most likely yield (Mark et al. 1987; Ferguson and Potter 2006). Smaller yields, including a fizzle, are also possible, as are higher yields, with nuclear weapons diverted from a national arsenal. Because total radioactivity in the debris cloud is roughly proportional to yield, quick estimates of yield would allow refining advice on travel and sheltering. The most expedient method may be relating yield to the altitude and diameter of the debris cloud, several minutes after the blast. Night or overcast skies would require another method. Any method should be simple and robust to variations in conditions after a blast, with predetermined and pretested translation to advice for the public.

People further from the blast will have more opportunities to prepare for fallout. The second category of advice in Table 3 is for those whom fallout will reach in 30–90 min. They might be able to take reasonable gambles to improve their conditions (e.g., reach a home shelter, collect nearby family members, or shore up shielding in an existing space). To that end, they need to know which actions are most worth doing. Prior analysis can inform these choices by assessing the effectiveness of measures and the probability of accomplishing them, given the disruptions likely after a blast (e.g., will traffic lights work? will TV/radio be on the air?). Where the advice is counter-intuitive, messages should include brief explanations, previously tested for effectiveness (e.g., don't evacuate immediately because outdoor radiation levels are lethal; the water is safe for a while, because the reservoir is covered; don't drive, because roads are clogged with abandoned vehicles).

When personal radiation exposure is the only consequence that matters, it pays to change shelter locations only if doing so reduces exposure by improving one's shielding or one's ability to hold out. That calculation is straightforward and better done by radiation specialists than average citizens. More difficult tradeoffs arise when people decide whether to expose themselves in order to help others. Such valor is the natural tendency in disasters (Wessely 2005). Those who suppress the instinct to help will have to live with the knowledge that they put themselves first. In the unprecedented circumstances of a nuclear attack, people will be unusually attentive to expert advice. It must be formulated in a way that does not leave survivors feeling that they were induced to act against their own moral judgment. Here, as elsewhere, messages must be pretested, so that they are understood as intended.

Compared to the first row of Table 3, the second covers many more people, with more varied circumstances. Analysis is needed to assess how sensitive the advice is to that variation. For example, a sustained wind aloft could mean that some individuals are better served by advice in the third row or even the fourth. Taking advantage of that reality requires determining wind conditions and disseminating clear advice before people have committed to a course of action. It is a sad reality of communication that complicating any message will confuse some individuals. Thus, allowing some people to take advantage of lower fallout in their area will mean exposing others to more fallout—because they are confused about which advice applies to them. Whether that risk is justified requires explicit analysis after research creates the best possible messages.

Analogous integration of risk analysis and risk communication research is needed to evaluate and refine the rest of Table 3's advice—or any other advice. Risk analyses could incorporate knowledge about traffic patterns, vehicles' shielding properties, clothing contamination, etc. The communication research would consider lay beliefs about radiation and shielding, citizens' priorities, etc. That research would also allow refining Table 2's estimates, by clarifying the chances of using a shelter.

SHELTERING DURATION

Those entering a shelter, or contemplating its use, must look ahead to when they will leave it. Fig. 1 shows some factors relevant to that choice. In addition to radiation risk, they include non-radiation health concerns, worry about contamination, physical discomfort, economic loss, and concern about loved ones elsewhere. In order to weigh these concerns, people need to know how evacuation timing affects their radiation risk. Fig. 2 offers a simple calculation of the sheltering period that minimizes the sum of the radiation doses received during sheltering and evacuation. Some people will want to stay longer (e.g., to allow injuries to heal); some will want to leave earlier (e.g., because of hunger). All will want to know what the dose-minimizing moment is—as will individuals wondering whether three days' provision will suffice.

Dose accumulates during (1) the *sheltering period*, as a function of the gamma ray shielding that the building provides as well as the building's air exchange rate, and (2) the *evacuation period*, as a function of conditions in the fallout-contaminated zone that would be crossed. The ground-level outdoor dose rate, $\dot{D}_o$, from fission-product fallout decreases with time since the blast as $t^{-1.2}$ (Glasstone and Dolan 1977):

$$\dot{D}_o \propto t^{-1.2}. \quad (2)$$

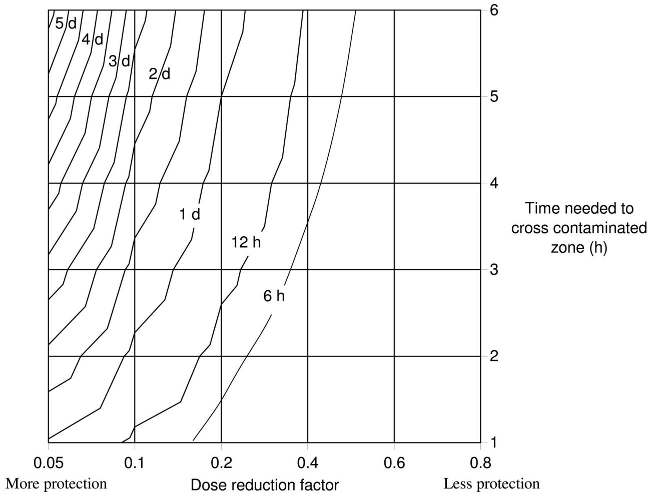

Fig. 2. Dose minimizing sheltering duration as a function of the dose-reduction factor of the sheltering structure and the time required to traverse the fallout-contaminated zone during evacuation.

The dose-reduction factor of a shelter (U.S. EPA 1992) is the ratio of the dose received within the shelter to that received on open ground. If f is the dose-reduction factor of a shelter, defined to include both gamma penetration and fallout particle infiltration, then the dose rate within the shelter is

$$\dot{D}_s \propto f\, t^{-1.2}. \quad (3)$$

We assume no shielding during the time, τ_e, spent traversing the contaminated zone when evacuating. Integrating dose rate over the shelter and evacuation periods, the dose-minimizing sheltering duration, τ_s, is found to be the solution to the transcendental equation:

$$-1.2 \ln(\tau_s) + \ln(1 - f) = -1.2 \ln(\tau_s + \tau_e). \quad (4)$$

Note that, under the assumptions leading to eqn (4), the sheltering duration that minimizes total dose is independent of dose rate. Thus, if radiation risk is the only concern, those closer to the blast point should evacuate no sooner (or later) than those far away—assuming that their evacuation takes equally long. Fig. 2 plots the relationships in eqn (4), showing the dose-minimizing sheltering period as a function of the shelter's dose-reduction factor and the time needed to cross the fallout-contaminated zone. Dose-reduction factors differ substantially for different prospective shelter locations. A person on the first floor of a wood frame house, in the basement of a brick house, or in the interior of a multistory building would receive roughly 90%, 20%, and 10%, respectively, of the gamma dose of an unshielded person outdoors (Glasstone and Dolan 1977; U.S. EPA 1992). According to Fig. 2, people in weakly protective shelters should evacuate within just a few hours of the arrival of fallout, even if it takes several hours to cross the fallout-contaminated zone. Those in highly protective shelters may be better off staying for several days, especially if the expected egress time is long. Actual dose-reduction factors will be larger than those used in these calculations, as a result of fallout particles infiltrating the shelter. The dose from infiltration is typically estimated to be much smaller than the gamma dose from outdoor particles (Ng et al. 1990). This may not be true for multistory buildings with air intakes that are not shut as the fallout cloud passes (Mead and Gressel 2002).

Given the sensitivity of the optimum sheltering period to shielding effectiveness and egress time, advice must be tailored to individuals' conditions. If people follow that advice, they will evacuate at different times, reducing congestion, so that everyone can leave more swiftly and, hence, sooner. Holding other things equal, the analysis shows that those with better shelters should wait longer. One possible complicating factor is discomfort from sheltering, for those who prepare only for the 3-d recommended period. For those with a moderately effective shelter and moderately long evacuation time, it would be better to stay longer.

Acting on this advice requires citizens to know the dose-reduction factor and egress speed relevant to their circumstances. That, too, is a matter for prior communication research. It should explore how to explain staged evacuation so that people feel that they are being treated equitably.

The analysis represented in Fig. 2 assumes that people are completely unshielded during evacuation, as would happen if they walked out of the contamination zone. Shielded evacuation vehicles could shorten the optimum sheltering period by getting people out faster and with greater protection during transit. A small number of shielded vehicles might be enough for a staged evacuation.

CONCLUSION

In principle, shelters can provide valuable protection after an event dispersing radioactive fallout. For that to happen, however, those shelters need to be properly prepared and used. We have adopted a behavioral decision research approach to examining three critical decisions: (a) whether to provision a shelter, according to Department of Homeland Security guidelines; (b) whether to travel immediately after an attack; and (c) how long to stay in a shelter. These choices are interdependent. The expected value of preparations depends on the chances of being able to use a shelter and of its provisions being sufficient. The acceptability of risks from traveling before fallout arrives depends on the benefits that such travel provides (e.g., getting one to a good shelter).

In keeping with behavioral decision research, each case study begins with a formal analysis of the decision, applying technical knowledge to identifying the action that best achieves individuals' goals. Each proceeds to ask how individuals perceive the options, given the information that is naturally available to them and that could be made available. These assessments seek behavioral realism in their expectations regarding the information that authorities can generate and disseminate, as well as that which individuals can absorb and apply. Each concludes by considering the opportunities to improve those choices.

Our goal has been to show how such citizen-centered research could proceed, rather than reach definitive recommendations. Nonetheless, these initial analyses suggest some tentative conclusions and directions for future work.

Preparations

The cost of the provisions on DHS's list (Table 1) would be trivial for many individuals, prohibitive for others. Those who cannot afford it need help if they are to comply (Bellagio Group 2006). Even those who can afford it may not comply if they see too little chance of recouping their investment, perhaps because they see probabilities like those in Table 2, perhaps because they expect to be trapped longer than three days (Fig. 2). If so, then authorities who count on citizen preparedness should reanalyze that expectation and see if they can make things better, with good communication and material support, for those who cannot act on their own.

Immediate response

After an attack, authorities will have limited ability to collect, analyze, and disseminate information. They may only be able to identify the blast location, then communicate simple advice for people in broad areas (Table 3). Investments in finer characterizations (e.g., plume models) may have little practical value, especially compared with investments in helping individuals to grasp and apply these simple rules (e.g., understanding the risks of traveling in fallout to be with loved ones).

Ultimate evacuation

Plausible ranges of shielding effectiveness and egress time lead to a wide range of optimal periods for staying in a shelter, in terms of minimizing radiation exposure. Other considerations (Fig. 1) might justify incurring the extra radiation exposure from evacuating earlier. Those pressures might be reduced by well-guided shelter preparations and plans for meeting the needs that impel people to travel (e.g., assured care for loved ones).

Such life-and-death decisions deserve formal analyses, both to provide citizens with sound advice and to provide authorities with realistic expectations for citizens' behavior (Dombroski et al. 2006; Fischhoff et al. 2006). Those analyses must reflect all the goals that individuals value—and not just those central to experts (e.g., radiation protection professionals, economists). Empirically evaluated messages are needed to ensure that individuals have the best possible chance of understanding what they are up against, so that they may make sound choices.

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REFERENCES

American Red Cross. Disaster supplies kit [online]. 2006. Available at: http://www.redcross.org/preparedness/cdc_english/dskit.asp. Accessed 21 February 2007.

Bellagio Group. Statement of principles from the Bellagio Meeting on Social Justice and Influenza [online]. 2006. Available at: http://www.hopkinsmedicine.org/bioethics/bellagio/statement.html. Accessed 21 February 2007.

Centers for Disease Control and Prevention. Sheltering in place during a radiation emergency [online]. 2005. Available at: www.bt.cdc.gov/radiation/pdf/shelter.pdf. Accessed 21 February 2007.

Cohen J, Dearnaley E, Hansel C. The addition of subjective probabilities. Acta Psychologica 12:371–380; 1956.

Department of Homeland Security. National response plan [online]. 2004. Available at: http://www.dhs.gov/xlibrary/assets/NRP_FullText.pdf. Accessed 21 February 2007.

Department of Homeland Security. Every business should have a plan [online]. 2005. Available at: http://www.ready.gov/business/_downloads/ReadyBusinessBrochure.pdf. Accessed 21 February 2007.

Department of Homeland Security. Emergency supply list [online]. 2006. Available at: http://www.ready.gov/america/_downloads/checklist.pdf. Accessed 21 February 2007.

Dombroski M, Fischhoff B, Fischbeck P. Predicting emergency evacuation and sheltering behavior: a structured analytical approach. Risk Analysis 26:1539–1569; 2006.

Ferguson CD, Potter WC. Improvised nuclear devices and nuclear terrorism. Paper No. 2. Stockholm: Weapons of Mass Destruction Commission; 2006.

Fischhoff B. Decision research strategies. Health Psychol 21:9–16; 2005.

Fischhoff B, Bruine de Bruin W, Guvenc U, Caruso D, Brilliant L. Analyzing disaster risks and plans: an avian flu example. J Risk Uncertainty 33:133–151; 2006.

Glasstone S, Dolan PJ. The effects of nuclear weapons. Washington, DC: U.S. Government Printing Office; 1977.

Government Accountability Office. Terrorism insurance: Measuring and predicting losses from unconventional weapons is difficult, but some industry exposure exists. Washington, DC: United States Government Accountability Office; GAO-06-1081; 2006.

Homann SG. Hotspot health physics codes, version 2.05. Livermore, CA: Lawrence Livermore National Laboratory; 2003.

Klepeis NE, Nelson WC, Ott WR, Robinson JP, Tsang AM, Switzer P, Behar JV, Hern SC, Engelmann WH. The National Human Activity Pattern Survey (NHAPS): a resource for assessing exposure to environmental pollutants. J Exposure Analysis Environmental Epidemiol 11:231–252; 2001.

Mark JC, Taylor T, Eyster E, Maraman W, Wechsler J. Can terrorists build nuclear weapons? Washington, DC: Nuclear Control Institute, International Task Force on the Prevention of Nuclear Terrorism; 1987.

Mead KR, Gressel MG. Protecting building environments from airborne chemical, biological, or radiological attacks. Appl Occup Environ Hygiene 17:649–658; 2002.

Morgan MG, Fischhoff B, Bostrom A, Atman C. Risk communication: a mental models approach. New York: Cambridge University Press; 2001.

Morrall JF. Saving lives: a review of the record. J Risk Uncertainty 27:221–237; 2003.

National Academy of Engineering. Nuclear attack [online]. 2005. Available at: www.nae.edu/factsheets. Accessed 21 February 2007.

Ng YC, Anspaugh LR, Cederwall RT. ORERP (Off-Site Radiation Exposure Review Project) internal dose estimates for individuals. Health Phys 59:693–710; 1990.

Parsons GR. The travel cost model. In: A primer on nonmarket valuation. London: Kluwer Academic Publishing; 2003.

Tversky A, Kahneman D. Availability: a heuristic for judging frequency and probability. Cognitive Psychol 5:207–232; 1973.

U.S. Environmental Protection Agency. Manual of protective action guides and protective actions for nuclear incidents. Washington, DC: U.S. EPA Office of Radiation Programs; 400R92001; 1992.

Weinstein N. Unrealistic optimism about future life events. J Personality Social Psychol 39:806–820; 1980.

Wessely S. Don't panic! Short and long-term psychological reactions to the new terrorism. J Mental Health 14:1–6; 2005.

Willis HH, Morral AR, Kelly TK, Medby JJ. Estimating terrorism risk. Washington, DC: RAND Corporation; 2005.

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