Dose Thresholds for Evacuation Following Explosion of an Improvised Nuclear Device or Radiological Dispersal Device

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Abstract

A November 2011 report from the U.S. Department of Homeland Security provides substantial advance in understanding of damage from the explosion of an improvised nuclear device, IND, in the urban environment—i.e., an improvised nuclear explosion, INE. Substantial reduction in fatalities and injuries would be achieved by the discipline of responding to the flash by immediately seeking cover under a desk or other protection against damage from wind-driven shattered windows. Furthermore, on the order of 100,000 lives might be saved by a rational response to taking shelter in existing buildings within minutes of the explosion, together with informed evacuation after some hours. For contamination and exposure to radioactivity from a radiological dispersal device, RDD, there is far less urgency to consider evacuation, since there is no early spike in dose rate. Rather than mandatory evacuation, an optional evacuation should be the primary response, with compensating damages paid to those who remain.

Far too little provision is made in implementing the preparation and dissemination of information to guide public response to an INE or an RDD, and that should continue to be a priority of our group. Over the ten years in which we have been considering these matters, the preferred option has evolved to be “push technology” that over the next months or years could result in highly specific information residing in the smart phones or other mobile IT devices of much of the populace.

Major effort worldwide is directed toward preventing terrorists from acquiring highly enriched uranium, HEU, or plutonium, Pu, for fabricating an improvised nuclear explosive device, but prudence demands also that attention be given to mitigating the consequences if such a device were actually exploded in an urban area. The more likely case of a radiological dispersal device, RDD, perhaps in the form of a "dirty bomb" in which conventional explosive is used to disperse an intense source of radioactive material normally used for cancer treatment in hospitals, industrial radiography, or irradiation of food or plastics, will also be addressed. It is quite different from a fission explosion because there is no early peak of dose rate, and far less radioactive material involved.

In addressing any question of public health, one must be concerned with different epochs. The most obvious is that which follows not only the analysis but consequent decisions, planning, and deployment; it might be characterized as the "steady state." What would be the consequences for various attacks, and how can they be mitigated?

But long before the steady state, there is the question as to what should be done immediately after the publication of the paper or the delivery of this talk, before societies can be fully prepared to do "the right thing" following an attack. Although the probability of such an event in the first month or year may not be very high, the question must be asked. And we will attempt to describe improvised capabilities for mitigation.

Concentrating first on the improvised nuclear explosion, we note that this has been addressed at the 2010 Planetary Emergencies seminar, in which I drew upon an article that I published that Spring and on a parallel piece by Brooke Buddemeier[1] of LLNL. In turn, this was supplemented by a publication[2] from the Department of Homeland Security (DHS), which, in particular, provided

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[1] "A Nuclear Explosion in a City, or an Attack on a Nuclear Reactor," by R.L. Garwin, and "Reducing the Consequences of a Nuclear Detonation: Recent Research," by Brooke Buddemeier, *The Bridge*, Summer 2010, pp. 28-38, Both to be found at http://www.nae.edu/File.aspx?id=19815.

[2] "Planning Guidance for Response to a Nuclear Detonation", Second Edition, June 2010, at http://www.epa.gov/rpdweb00/docs/er/planning-guidance-for-response-to-nuclear-detonation-2-edition-final.pdf

shielding factors for fallout radiation, for various types of buildings common in the United States.

We can now refer to a much more substantive 120-page DHS document[3] which refers to the National Capital Region (Washington, DC), but which provides methodology and data that could be used for almost any detonation point. Many of my illustrations are taken from that document.

As emphasized much earlier[4] an INE is likely to be of much lower yield than the strategic nuclear weapons now common in the military inventories—which have yields of 100 kt or 500 or even 2000 kt. Instead, an IND is likely to aim for a yield of 10 kt but might achieve only 1 kt or even 0.1 kt. This last is still the blast equivalent of 100 tons of TNT (50 two-ton truck bombs detonated simultaneously at the same point). But with the smaller explosions, and a burst on the surface rather than at altitude, the various damage phenomena differ in relative importance from the strategic weapons.

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[3] "Key Planning Factors: Response to an IND in the National Capital Region" November 2011, http://www.fas.org/irp/agency/dhs/fema/ncr.pdf

[4] “The Many Threats of Terror” and an Epilogue by R.L. Garwin in A New York Review Book “Striking Terror: America’s New War, edited by R.B. Silvers and B. Epstein, March 2002, pp. 235-256., http://www.fas.org/rlg/020300-strikingterror.pdf

Nuclear explosions cause *blast* damage by overpressure and high winds; from *burns and fire* from the large amount of the explosion energy that is radiated from the fireball as heat in a second or less from these low-yield explosions; and from *ionizing radiation*'s impact on people. All of these effects could in principle but not in practice be mitigated by appropriate measures, even if not totally eliminated. Underground buildings are largely immune except in a region of very high blast overpressures, but no one is going to rebuild or build cities of totally different configuration to avoid damage from an INE. The flash burns from the low-yield explosion happen so quickly that little can be done to avoid or reduce them after the fact. Much of the damage from blast comes from broken glass, and tough plastic film on windows can reduce that hazard, as can tough blast curtains that allow light to filter through, but will retain broken window glass.

Where mitigation can really help is in reducing the death toll from the radioactivity instantly produced by the nuclear explosion, but whose dose is delivered over minutes and hours.

The explosion is accompanied by an instantaneous flash of neutrons and gamma rays from the fission reaction itself, much of it absorbed by materials of the bomb and attenuated at long distances by air itself. Beyond that, there is the local deposition of radioactive fission products from the bomb, mixed with soil and debris from the ground and buildings vaporized by the explosion. Much of this (perhaps half) falls to earth in the immediate neighborhood of the explosion, even in the region devastated by blast.

Beyond the immediate, local fallout, there is the portion that was lofted into the atmosphere, condensed on fine particles of debris rather than on coarse, and that thus takes longer to deposit from the parcel of air in which the debris finds itself. It falls under the influence of gravity, more slowly the finer the particle.

From the days of atmospheric testing of nuclear weapons, much is known about the distribution of fallout, and modern atmospheric modeling with fast computer complexes allows the real-time prediction of distribution of fallout and dose to exposed personnel. In similar fashion can be calculated the shielded dose that would be received by a person within a building of nominal construction of one kind or another. The Figure shows nominal protective factors (PF) against fallout deposition on ground and roof. But first the extent of the fallout plume, for a particular wind structure and a 10 kt ground burst.

The boundaries of the

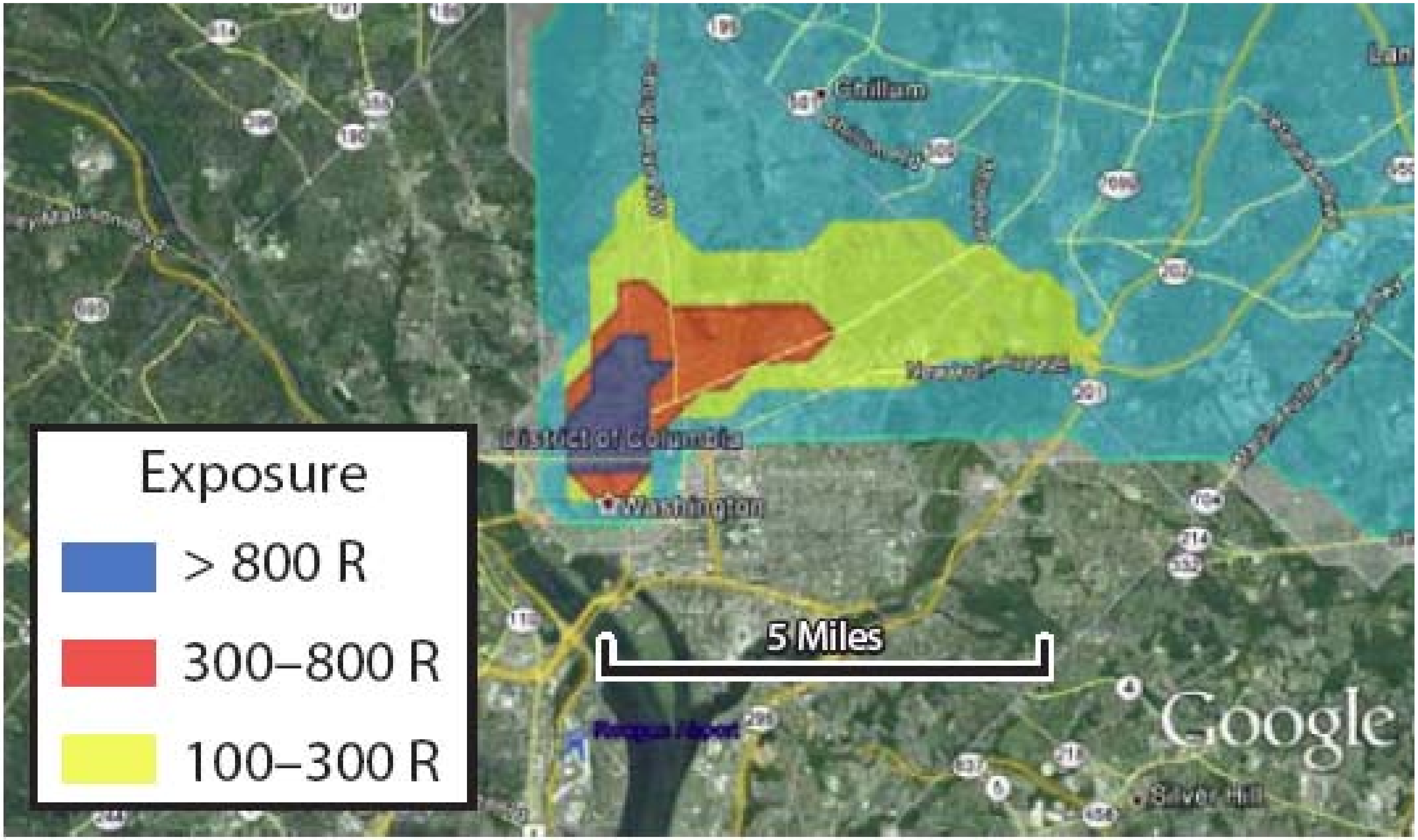
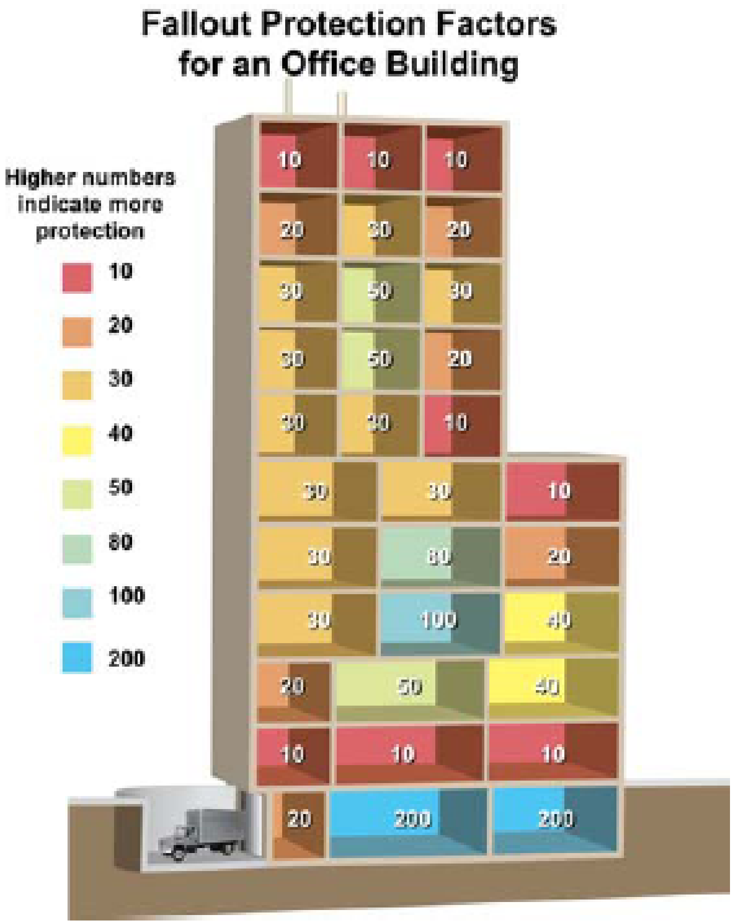


Figure 16. Integrated 2-hr outdoor exposure for the illustrative scenario.

The equi-dose boundaries of the plume mark unshielded doses of 800, 300, and 100 R.



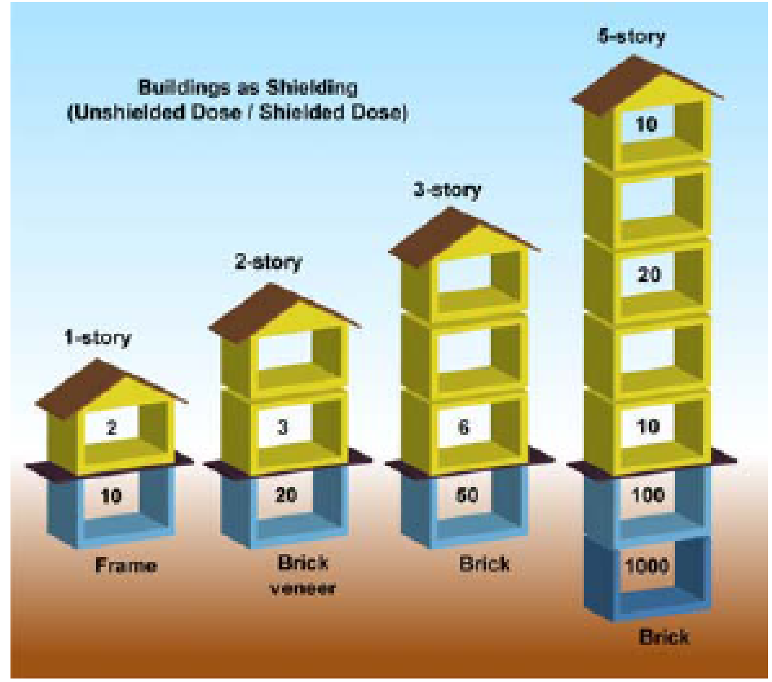


Figure 3.1 a: Building as shielding – numbers represent a dose reduction factor". A dose reduction factor of 10 indicates that a person in that area would receive 1/10th of the dose of a person in the open.

Figure 3.1 b: Building as shielding: numbers represent a dose reduction factor. A dose reduction factor of 200 indicates that a person in that area would receive 1/200th of the dose of a person out in the open.

It has always been recognized that the “open field” values for blast and especially burns and prompt radiation are in reality affected and reduced by the presence of many buildings and structures, and with the increased computing power and sophistication of analysis, the most recent DHS paper reflects these modifications, as shown in its Fig. 9.

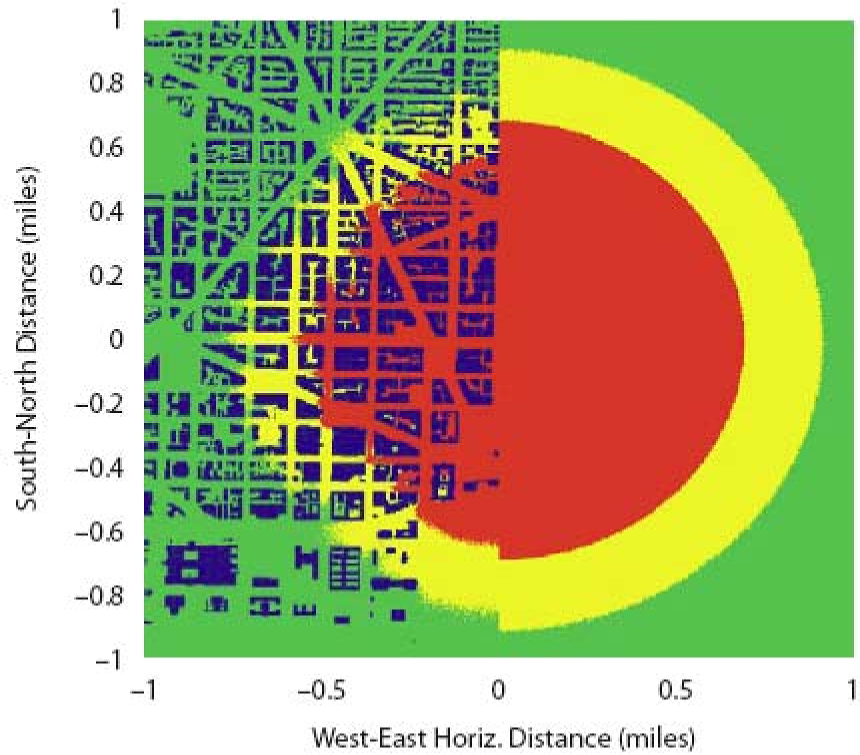


Figure 9. Outdoor casualty areas for the illustrative scenario (left) and for an open field (right) from a 10-kT Hiroshima type device; red >800, yellow 100-800, green < 100 rad..

Thus, as regards prompt radiation, a 10 kt explosion in a city might have the lethal radius of an 8 kt explosion in an open field.

The extent of structural damage to buildings is used to define the SDZ (Severe Damage Zone), the Moderate DZ, and the Light DZ. For a 10-kt ground burst at the intersection of K and 16^{th} Streets in Washington, the SDZ extends to about 0.5 mile radius, the MDZ to one miles radius, and the LDZ to about three miles.

Although the local explosion phenomena for a 10-kt burst happen within thousandths of a second, the blast *propagates* at the speed of sound and reaches the 2-3-mile radius in 10-15 seconds. This provides time for some people alerted by the flash from the explosion to take shelter under desks or behind cabinets so that they have less probability of being injured by windows that are likely to shatter under the blast load.

Fallout of bomb-produced radioactive material in the immediate area, and from the continued deposition as the radioactive material is moved out of the area by wind, leads to the definition of the Dangerous Fallout Zone (DFZ) and the Hot Zone (HZ). The DFZ is defined by radiation levels of 10 R[5]/hr or greater and is the region in which acute radiation injury or death is possible. In contrast, the HZ is defined by a dose rate of 0.1-10 R/hr and "could extend in numerous directions for hundreds of miles."

Little can be done to mitigate the radiation exposure from the prompt flash of gamma rays and neutrons from the explosion itself, which will give an effective dose to the body that decreases with distance, and in some azimuths is partially blocked by the mass of intervening buildings. But after a second or so, radiation will be dominated by that from bomb-produced fission products attached to coarse debris particles. People outside should get inside as soon as possible and crudely brush the debris from their clothing. Vehicles such as cars, trucks, and buses offer no protection against fallout[6], and they will all be

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[5] In this paper we use "R" for "roentgen," the unit of exposure to ionizing radiation. The health effect of radiation is better estimated from the Rem, but fortunately the R and the Rem aree equivalent for beta and for gamma rays. In more modern units, 1 R = 0.01 gray (Gy); 1 Rem = 0.01 sievert (Sv). One gy is 1 joule/kg of energy deposition.

[6] Not quite true, since they do protect against beta-emitting fission products such a Sr-90 that can cause severe destruction of human skin.

stopped in any case because of congestion and debris. Once inside, people continue to be exposed to radiation from the fallout on the ground or on ledges or roofs, with the protection factor offered by various types of building construction.

People should move to the regions of their building with higher PF, knowing that the dose rate will decline with time after the explosion. In fact, it has long been approximated that the fission product gamma-ray dose rate[7] decays as $T^{-1.2}$, with *T* the time since the fission explosion. The curve of Fig. 20 illustrates the gamma-ray dose rate.

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[7] See "Radioactive Fallout From Terrorist Nuclear Detonations," by R.E. Marrs (2009), UCRL-TR-230908, at https://e-reports-ext.llnl.gov/pdf/347266.pdf

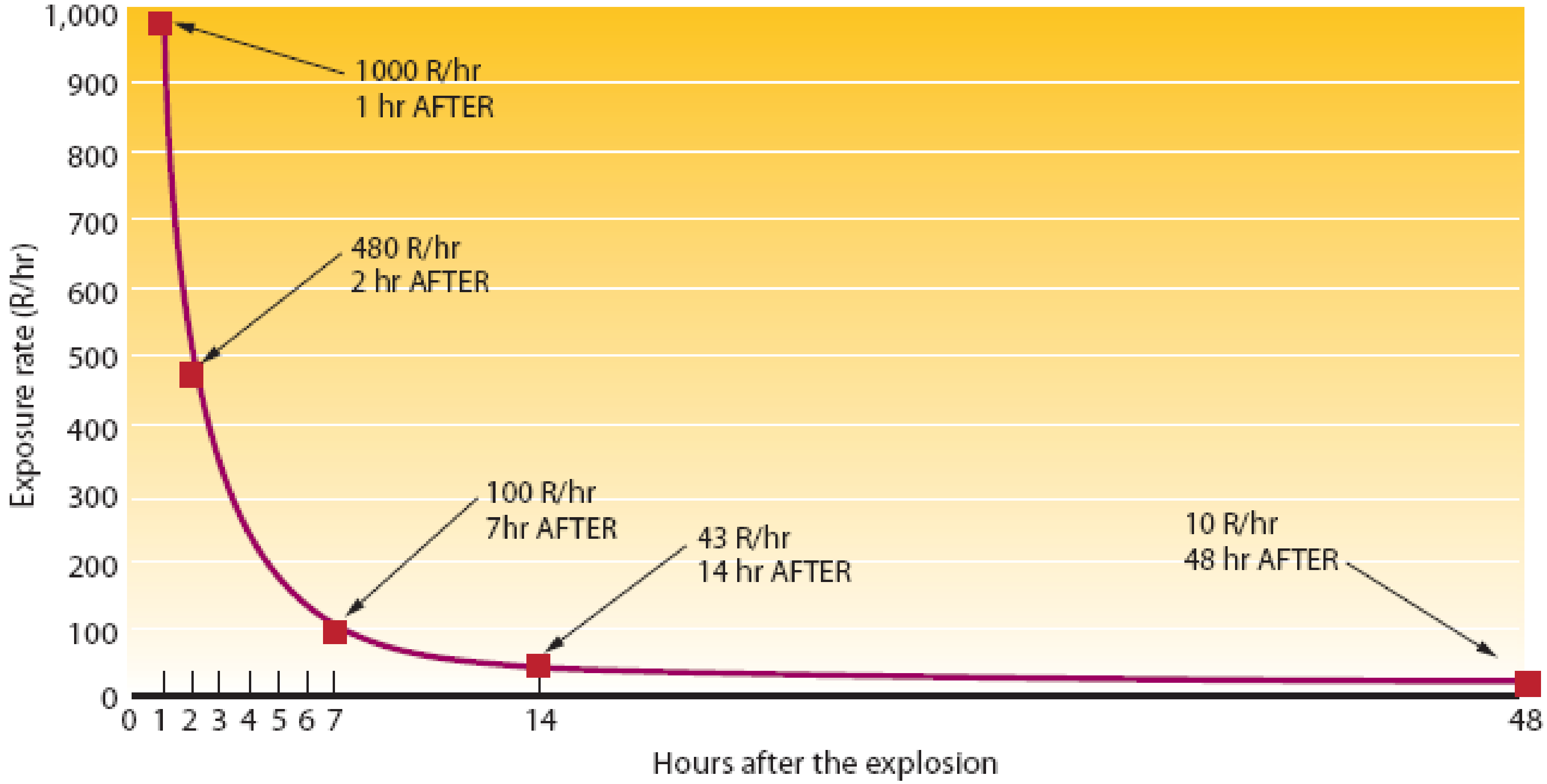

Fig. 20 of ncr.pdf "*Radiation levels from fallout decrease rapidly over time, emitting more than half of their radiation in the first hour.*"

The whole-body dose for which about 50% of those exposed will die within a couple of weeks is about 400 R, and Table 2 shows the life-saving importance of proper shielding from the fallout for the substantial portion of people who without shelter would receive a lethal dose.

Table 2. Modeled dose rates for the illustrative scenario at the point specified in Figure 21.

Time after detonation (hr:min)	Exposure rate (R/hr)
00:15	1,444
00:30	686
01:00	299
02:00	130
04:00	57
08:00	35
12:00	15
24:00	7
48:00	3
96:00	1

Evacuation after a couple of days, to reduce the additional dose to zero would be a good thing, and it is eminently feasible where that dose would have been significant

It is important, however, that evacuation routes do not inadvertently expose evacuees to very high dose rates because of pockets of initial fallout or accumulations due to rain. Figs. 37-39 illustrate the importance of *delaying* evacuation to minimize the contribution of evacuation to the total dose.

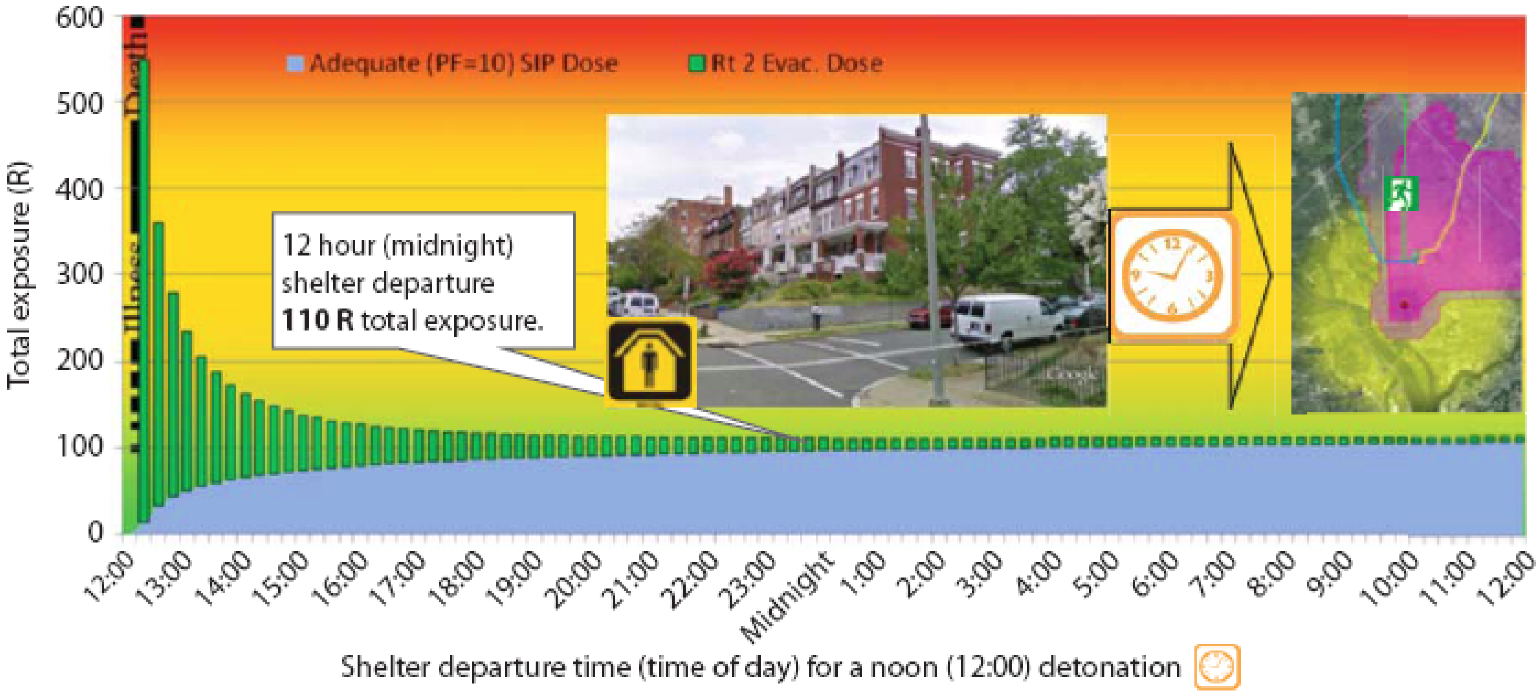

Figure 38. Comparison of total exposure from various shelter departure times from Adequate Shelters (PF=10) like the row homes pictured using the default city evacuation route (green) is selected for evacuation.

Much can be done by moving to better shelters, while awaiting evacuation.

A striking conclusion is that

> *"the existing Washington, DC structures offer better than adequate protection. If all residents adopted a shelter-in-place strategy, it would reduce the number of potential acute radiation casualties by 98% (there would be ~3,000 fallout casualties out of the ~130,000 potential casualties of an unsheltered population)."*

As your PMP-MTA (Permanent Monitoring Panel on Mitigating the effects of Terrorist Acts) has long emphasized, the DHS report recommends,

> *"Messages prepared and practiced in advance are fundamental to conveying clear, consistent information and instructions during an emergency incident. Planners should select individuals with the highest public trust and confidence to deliver messages. Such individuals should be prepared to deliver key information almost immediately to the public in affected areas about protection to maximize the number of lives saved."*

Thus far I have simply recounted the results of a major DHS study, but that has some value in itself, because few of you were probably aware of it. Now let's see what value we can add to that study.

First, to go back to basics, is there much sense on reducing exposure from 500 R to 200 R? How about the risk of cancer even at an exposure of 200 R? Indeed, there is great value in such a reduction. The probability of death at 500 R is on the order of 80%, whereas at 200 R, perhaps only 5% will succumb, although half will be sick. The probability of a lethal cancer is about 1/2000 R, so at the hypothecated 200-R exposure, it would be about 10%. Ten percent residual cancer mortality vs. 75% reduction in prompt lethality is a good payoff—65% of a human life saved—perhaps even more important if it is your own or the life of one of your family members. Furthermore, the death from cancer will not occur for years—perhaps 20 years on the average—a lot of life to be lived from the personal point of view, and invoking a discount rate from the economic or public planning approach.

How realistic is “informed evacuation” and sheltering?

First there is the question as to whether people can be made aware of the considerations of the 2011 “National Capital Region” paper and its summary here. That is involved with the “prepared communication” that gets only a single paragraph in the important DHS report but that has been treated at considerable length in the PMP-MTA papers. We propose not only the identification of people who deserve and indeed possess public trust (if any remain in the fractured American society) but also the dissemination of appropriate instructions and graphics that would reside on many, many home and office PCs and smart phones. Thus, even in the Moderate Damage Zone and heavy fallout areas a good fraction of the people could look up emergency summaries and graphics already resident on the smartphone to help guide their actions in the minutes following an INE.

How can we make this happen? In the United States, it will happen only if some contractor or consortium provides such a tool, either on speculation or in response to a solicitation and contract award from the federal government. This is not necessarily a long process, given fast-action elements of the U.S. government such as DARPA (Defense Advanced Research Projects Agency) and its younger sibling in the Department of Energy—ARPA-E.

But in the age of globalization, and in countries that have not yet been reached by the tsunami of privatization, this eminently governmental obligation and opportunity might be done within a government organization.

At this point one might have a short excursion as to why the contracting approach is faster than the in-house approach. Primarily it is because of the difficulty in diverting people from whatever they are doing to something that the management (occasionally leadership) of the organization decides they should do. It comes about because nobody is satisfied to appear to be doing nothing. It is bad for the soul and worse for the funding of the organization. You can write the rest of the story.

Even if there is a high probability of an urban INE somewhere, there is a low probability in any particular city. Therefore, whatever the merit of centrally-developed substance and communication, there is much less merit to its independent formulation in every potential target. Overall, if one assumes a 10% likelihood per year of an urban INE someplace, and considers that appropriate planning might save 100,000 people who would otherwise be killed by radiation from fallout, this would surely be an expenditure well justified on a world scale, even repeated several times in a competitive effort to produce a system that is considerably better than the uninformed response. Of course, many millions of people are at risk from disease and poverty, and that a few million dollars in rational thought and allocation of resources could save *them*, and that should be done, too. Here we are talking about people who have more or less functioning governments that are partially responsive to their demands and to rational thought.

Although the November 2011 DHS paper is a major advance over previous analyses, it does not do much in the way of sensitivity analysis. That is, how accurate are the projections in the paper? And to what extent would knowledge of the local meteorology (winds and rain) reflect reality in the projections? It is a great achievement that the excellent center at LLNL "NARAC" is able in real time to predict fallout, given only the magnitude and location of the IND detonation, but how accurate is that projection?

First, of course, it would be desirable to provide a proper input (explosive yield), and that is surely a government function that might be achieved from seismometers or from local barographs installed for the purpose. Location is readily and quickly determined seismically. Yield would then be determined by the low-frequency pressure pulse ("step") derived from the barograph. There is also a strong incentive to measure directly the fallout, in order to guide evacuation that might take place after a few hours or tens of hours. This could be done in a progressive manner, first with a low-resolution, less accurate fallout app or database, and later with increasing accuracy to guide evacuation routes and longer term planning.

As was recommended in my 2011 Erice paper[8], it would be feasible and desirable to have a small system of 10-kg drone aircraft, self-navigating via GPS, that would via data link provide a quantitative map of ground contamination of fission products. A single such vehicle flying at 50 km/hr could in 5 hours map a 15 km by 15 km square from an altitude of 0.5 km, with a resolution of about 0.3 km. Proportionally more quickly with more drones in operation. This would be enough to identify the broad patterns of ground contamination but not enough to provide a detailed map to help guide the sequence of evacuation.

That could be achieved sooner by a vehicle that would fly at an altitude of about 200 m, along potential evacuation routes, providing a ground

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[8] "Learning More from Fukushima Dai-ichi," by R.L. Garwin, at www.fas.org/rlg/2011%20Erice%20Fukushima1a.pdf

resolution on the order of 50 m, to determine the likely exposure and the regions where it is important not to loiter.

EVACUATION IN RESPONSE TO AN RDD ATTACK?

Evacuation thresholds following use of a radiological dispersal device (RDD) as previous papers for and of the PMP-MTA have shown, the impact of contamination from an RDD can be large, even though the number of expected fatalities is small. That impact can be mitigated by appropriate analysis and communication strategy, including responsive monitoring of the environment following the RDD. Because industrial and commercial (including medical) sources of intense radiation all have lifetimes of years, there is far less urgency for evacuation or in fact any action following the dispersal of radioactivity than is the case with fallout from a nuclear explosion. For specificity, we take the illustration of Fig. 2.

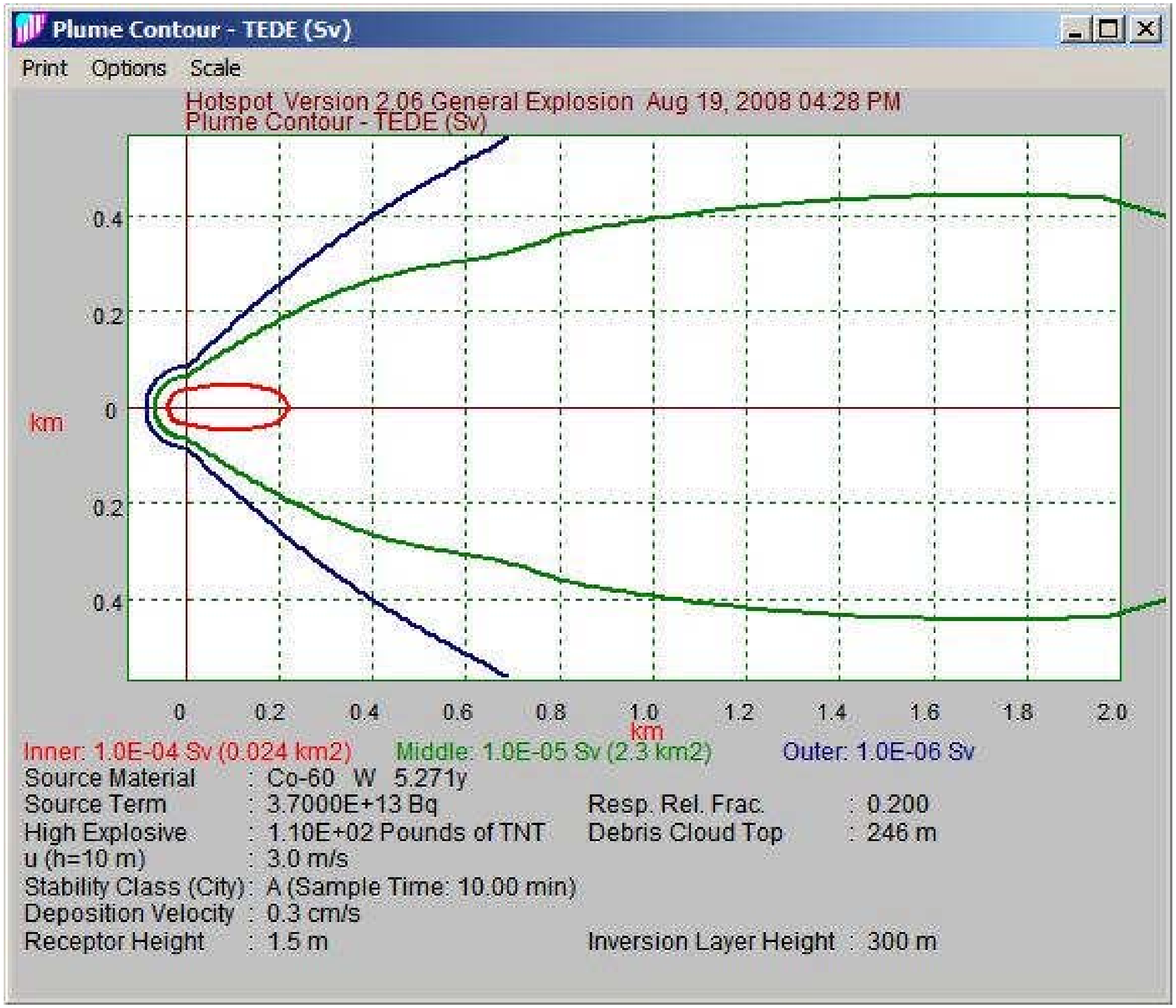

Figure 2: Cobalt (Co-60)-based dirty dust—total effective dose equivalent (TEDE)-contour plot in an urban environment (Co-60 activity: 37 TBq or 1000 Ci; explosives : about 50 kg TNT) (from Friedrich Steinhauesler).

in which 1000 Ci of Co-60 have been dispersed with 20% efficiency under certain atmospheric conditions. The contours shown are those without evacuation-- corresponding to 10 or more years of residence in the region.

The middle contour of 10 microSv TEDE corresponds to about one additional death by cancer[1] *for each two-million people exposed at that level, and is the limit sometimes recommended by the IAEA (for an unavoidable exposure deemed "negligible").*[2] *Many cities have peak population density regions of some 40,000 people per square kilometer*[3]*' so that the 2.3 km^2 area of the middle contour would contain some 90,000 people. Without knowing the dose at each point within this 2.4 km^2 area, it is clear that it is less than the 100 microSv dose of the inner contour, so that the total collective dose cannot exceed 9 Sv; the expected cancer deaths without relocation are thus 0.05 x 9 = 0.45 total cancer deaths, compared with the 18,000 people expected to die of cancer of natural causes. Thus it is likely that there would be not a single cancer death outside the 0.024 m^2 contour, which itself might contain only 1000 people; it would be difficult to justify costly cleanup or restrictions on occupancy outside this 2.4 hectare (5.9 acre) boundary.*

1 Using the ICRP coefficient of 0.05 cancer deaths per person-Sv.
2 "Health and Environmental Impacts of Electricity Generation Systems: Procedures for Comparative Assessment," IAEA Technical Reports Series No. 394 treats as "negligible additional radiation" exposures comparable with the natural background of some 3 milliSv per year. But one finds in IAEA-TECDOC-1484 Regulatory and management approaches for the control of environmental residues containing naturally occurring radioactive material (NORM), (www-pub.iaea.org/MTCD/publications/PDF/te_1484_web.pdf). P. 20:
" The additional individual dose attributable to the exempted source should be of the order of 10 µSv per year or less;" and " Either the collective dose to be committed by one year of performance of the practice should not be more than about 1 man-Sievert or exemption should be the optimum option."
3 http://www.demographia.com/db-citydenshist.htm (Selected Current and Historic City, Ward & Neighborhood Densities, P. 4 of 24)

Unlike the case with an INE, outside the tiny region in which people are likely to be killed by the ordinary explosives used in the dispersal (if, indeed, explosives are used rather than a vaporizer of a solution of the radioisotope), the question is solely one of reducing the human damage due to cancer, for which we take, again, a probability of lethal cancer of 1/2000 R (0.05 per Sv).

The United States Environmental Protection Agency guidelines mandate long-term evacuation if the individual dose expected within two years exceeds 2 R. This was, for instance, the guiding principle in the Fukushima disaster.[9] For the most part, the energy deposition from release of radioactive materials from an operating reactor is intermediate in nature between the contamination from an RDD and the fallout from a nuclear explosion. After the first seconds, the gamma dose rate from reactor fallout (total core release) decreases as $T^{-0.2}$ rather than $T^{-1.2}$ from a nuclear explosion, as it should, being the integral over years of many fission events, each of which has the $T^{-1.2}$ behavior.

[9] In fact, in the confusion accompanying that disaster, some residents were evacuated from close-in regions to more distant locations that happened to have higher local fallout deposition.

Unlike Fukushima, an RDD will take place in a society undamaged by earthquake or tsunami, in which many resources can be brought to bear on this rare event, including the resource of analysis that we are attempting to provide here, well in advance of any such event. At a committed whole-body dose of 2 R, the probability of lethal cancer is 0.1%, and with the planning factor in use in the U.S. government of $5 million per life saved (except in the Nuclear Regulatory Commission), the value of 0.1% of a lethal cancer avoided is $5000. In general, the abandonment of housing and the cost of displacing people is probably more in the range of $20,000—a cost that will surely be incurred, in contrast with the expectation of $5000 loss some 20 years in the future. So the EPA evacuation threshold is probably set too low by a factor four to ten.

An additional element for the computation arises from the non-monetary costs of evacuation—even physical and psychological illness. On the other hand, many would worry about the validity of the estimate of harm if they remained in an area known to be contaminated with radioactive material at some level. For this, a personal dosimeter in the form of an easily read thermal luminescent detector (TLD) would be useful, together with a public system such that the TLD could be read by the individual at intervals of a few days or weeks, with the data going into a permanent database, and the TLD being reset. In the modern era, the ubiquitous smart phone camera can be used as a dosimeter[10] to monitor gamma ray exposure.

Incidentally, the phone display can provide a smart form of the "flash cards" now used by railway police in Europe, and mesh communication techniques being studied by the EU under its innovative crisis programs would be useful in the case of an RDD.

However, there is a major public policy question as to whether evacuation should be mandatory or whether it should be optional. My own preference is for optional evacuation, with a payment by the government (that is, by the rest of society) of $5000 per person who chooses not to be evacuated from a potential 2 R exposure.

[10] http://www.gammapix.com/sites/

Of course, for Cs-137, the exposure would go on well beyond two years, but probably for a period substantially less than the 30-year physical half-life of the isotope. We will have more information from Fukushima, but it appears from Chernobyl that the half-life in the environment is on the order of 5-15 years. I don't know the corresponding environmental half-life for Co-60 deposition.

Certainly a polluter who liberates to the environment radioisotopes that provide a dose to the public and thereby inflicts deaths from cancer at a cost of $2500 per person-R (on the assumption of $5 million per life lost) should pay a fine substantially higher than that, if the act is to be deterred and not simply assumed as a "cost of doing business." But once such dispersal occurs, whether intentional or not, mandatory evacuation is the wrong response.

Summary

In conclusion, I provide highlighted points from the Nov. 2011 paper in regard to a nuclear explosion in a city,

DUCK and COVER: After an unexplained dazzling flash of light, do not approach windows, and stay behind cover for at least a minute to prevent injuries from flying and falling debris, such as broken glass.

GO IN, TUNE IN: The best initial action immediately following a nuclear explosion is to take shelter in the nearest and most protective building or structure and listen for instructions from authorities. (EOP, 2010)

DON'T DRIVE: If in a car, try to find shelter immediately until given official information. A car does not offer protection.

STAY INDOORS: People should expect to remain sheltered for at least 12 to 24 hours. During that time, the intensity of fallout radiation will decrease greatly, allowing for less hazardous egress from dangerous fallout areas. (EOP, 2010)

GET CLEAN: Radioactive fallout particles can spread quickly and remain on the body and clothes until removed. Those in potentially fallout contaminated areas should take off the outer layer of clothing (including shoes) and wipe or wash exposed skin and hair upon leaving a contaminated area.

HELP OTHERS: Radiation injuries and fallout contamination on people do not represent a threat to others. People should allow others to enter their building, help decontaminate, render first aid, and share information.

But this is only the beginning of effective communication.