

Nuclear Terrorism: A Global Threat

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Presented at the U.S.-Chinese Dialogue
on Nuclear Energy and Nuclear Security

Session I: Nuclear Security: Threat Perceptions and Actions Needed

Harvard-Tsinghua Workshop on Nuclear Policies

Beijing, China

March 14, 2010

Nuclear terrorism includes:

1. the use or threat of use of radioactive dispersal devices—RDD—sometimes called a “dirty bomb,”
2. the detonation of a nuclear weapon or improvised nuclear device—“IND”, and
3. terrorist attack on a nuclear reactor, spent-fuel pond, reprocessing facility.

As we will show, in summary and by reference, the RDD is not so much a weapon of mass destruction as a weapon of mass disruption. The effect of an RDD is not so much illness and death, but denial of economic use of space and buildings. This main effect of nuclear terrorism can be mitigated by a more rational choice of criteria for continued occupancy and use of contaminated buildings after a nuclear attack.

The detonation in a city of a nuclear explosive (whether one that has been stolen or an IND, is a major threat. There is no reason why the stolen explosive would not detonate at full yield from 1 kiloton (1 kt) to 200 kt, and an IND could perfectly well have the explosive power of the Hiroshima bomb—13 kt or so. Widespread death and destruction would accompany the nuclear explosion, as was the case of Hiroshima. In addition, there might be an equal number of deaths due to intensely radioactive fallout in the vicinity of the detonation and also to the deposition of fallout perhaps 10 or 20 km away, carried by

the wind prevailing at altitude, as heavy particles of rock and soil from the surface detonation fall back to earth. I will provide some estimates of casualties and consequences of a single such detonation.

Terrorist attack on a nuclear reactor might take place through external attack with aircraft or explosives. Alternatively, it could be an internal attack in which guards, operators, and physical barriers are overwhelmed by a terrorist group that had as its objective to disable the safety and control systems and to provoke a meltdown of the reactor, with rupture of the containment and the emission to the atmosphere of much of the radioactive inventory of the reactor core.

The radiological consequences of the Chernobyl disaster in April, 1986, have been the subject of such misinformation and even disinformation. My own best estimates are that some 24,000 people worldwide have now died or will die from radiation exposure¹, in contrast to the “32 deaths” among the firefighters often attributed to Chernobyl.

¹ “Expanding Nuclear Power While Managing the Risks of Accident and Proliferation,,” by Richard L. Garwin, March 29, 2006, <http://www.fas.org/rlg/060329-brussels.pdf>

Less remarked is that the earlier accident and meltdown in 1979 at Three-Mile Island (TMI) in the state of Pennsylvania, USA, would have had comparable transfer of radioactive material to the environment had the containment dome been breached either accidentally by the hydrogen explosion within the containment or intentionally by terrorist attack.

Similar consequences might follow from a dedicated attack on the fuel-element storage pool at reactors. Although far more radioactive material can be released from a major reactor accident than from a nuclear explosion, the rate of delivery of the radiation dose is much slower, and with the exception of internal irradiation of the thyroid, there is typically much more time to adopt protective measures.

Radiological Dispersal Devices—RDD

An RDD consists of some radioactive material and the means for attempting to disperse it on command. Although one approach to an RDD is the so-called “dirty bomb” with dispersal by high explosive, that term does not capture several of the more effective means of dispersal—a manned or unmanned aircraft in “crop duster” mode, or a nebulizer mounted in an automobile or truck that is driven upwind of the target, across the direction of the prevailing wind.

I show here equal-dose contour lines of the very large plume of contamination resulting from an assumed explosive dispersal of Co-60, one of several examples of radioactive materials and dispersal means, as testified² by Henry Kelly, then President of the Federation of American Scientists—FAS.

If the populace would remain in place for 40 years, the result would be:

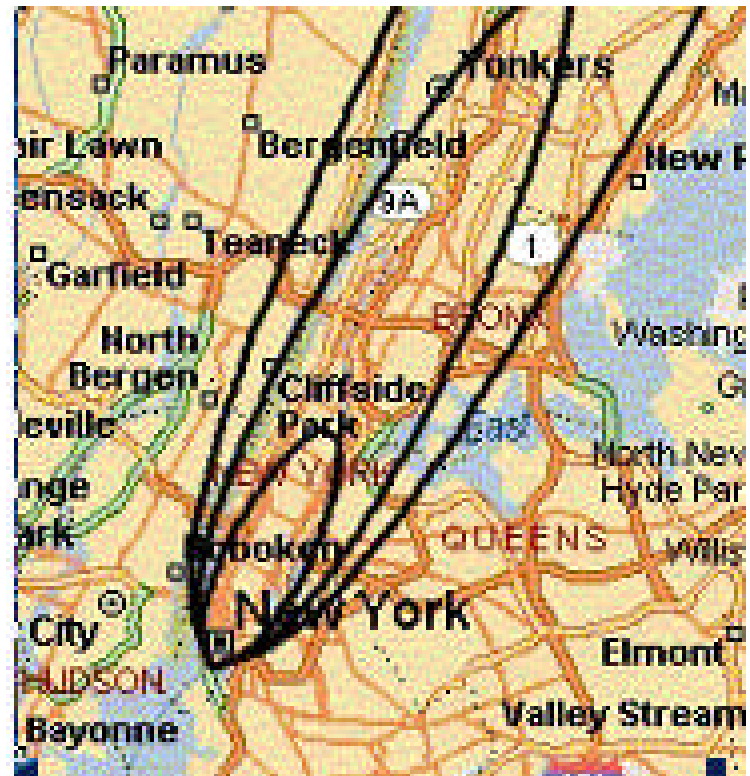
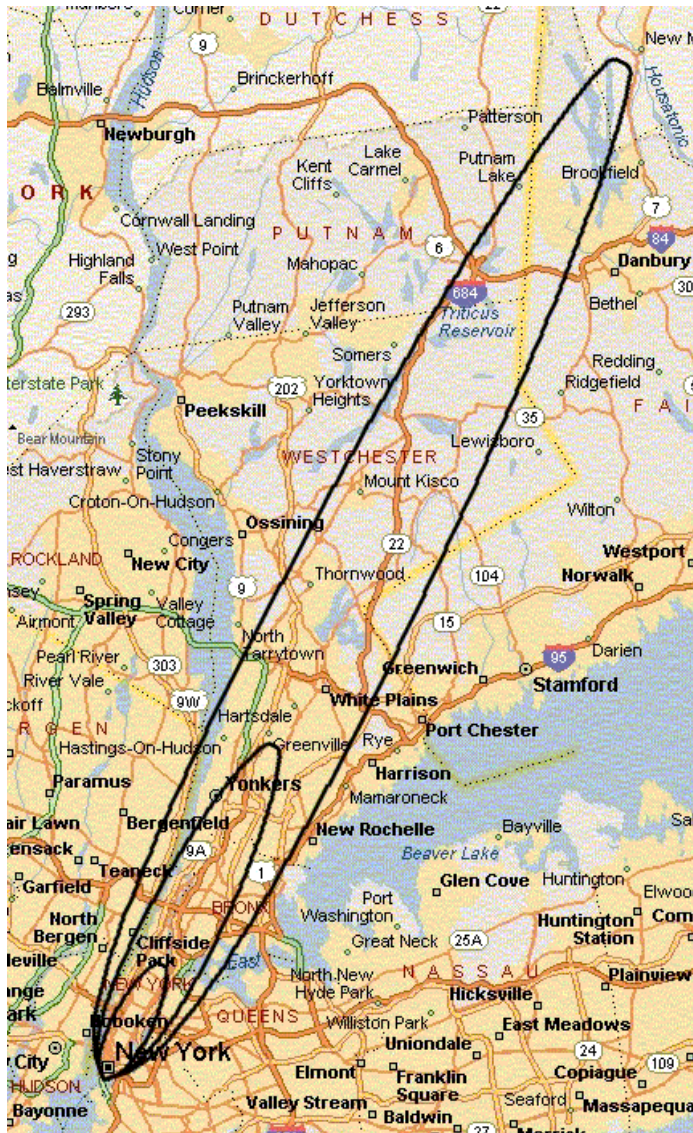
Inner Ring: One cancer death per 100 people due to remaining radiation

Middle Ring: One cancer death per 1,000 people due to remaining radiation

Outer Ring: One cancer death per 10,000 people due to remaining radiation EPA recommends decontamination or destruction

But if decision on evacuation was delayed a week, the radiation dose from that week of exposure would lead to a number of cancer deaths only 1/400 that large—e.g., 25 per million people in the inner ring.

² http://www.fas.org/ssp/docs/kelly_testimony_030602.pdf



Inner Ring: One cancer death per 100 people due to remaining radiation
Middle Ring: One cancer death per 1,000 people due to remaining radiation
Outer Ring: One cancer death per 10,000 people due to remaining radiation EPA recommends decontamination or destruction (From testimony of Henry Kelly, March 6, 2002)
 Figure 1. for Garwin Harvard-Tsinghua talk.

Ionizing radiation, from certain radioactive materials, may be in the form of alpha-particles emitters that are dangerous only when inhaled or ingested. The energy deposition within the body is so local, within a few thousandth of a centimeter, that cells are killed by the dense track of ionization, and some of the bone-seeking alpha emitters are potent causes of bone cancer, for instance. As a specific example, consider a hypothetical attack on Munich with one kilogram of plutonium dispersed by high explosives. Assuming a very pessimistic low wind speed so that the cloud remains over the city for 12 hours, the net result is that 120 people would die of cancer after 40 years or so.

In contrast to alpha particles, gamma rays penetrate on the order of 10 grams per square centimeters of material, with a largely exponential falloff, which in the case of water or animal tissue amounts to about 10 cm of depth. Since the density of air is 1.3 milligram/cc, 1 g/sq cm of air corresponds to about 8 meters and 10 g/cc attenuation length about 80 m. Normal urban housing gives little protection from gamma emitter on the surface of the building or on the surface of the ground outside.

The dose to human tissue can be measured in terms of the rad, or the gray--an SI unit that is equal to 100 rad. One gray is defined by the deposition of 1 J/kg of water, which with the normal specific heat of 4.2 kJ/kg-deg C would suffice to raise the temperature by 0.24 milli-deg C.

A dose of 4 Gy delivered to the entire human body corresponds to the LD-50—lethal dose 50—which means that about 50% of the people will die, typically in a few weeks. The lethal radiation would have raised the body temperature by only 0.001 deg C . On the other hand, doses less than

1 Gy is unlikely to cause death or even severe illness in the near term. One gray of whole-body exposure, on the other hand, is a significant cause of cancer and radiologists and public health specialists usually take an incidence of lethal cancer³ of about 0.05 per person-Gy.

To determine the health effect of an RDD in an urban environment is not a simple matter, since one needs to understand the dispersal of the material at a time of the order of seconds, minutes, or hours, the dose given to individuals under such dispersal, possibly over years, and the health consequences of such a dose.

³ In fact, the effective dose in causing cancer depends to a considerable extent on where the radiation is received. It is measured in sieverts (Sv) and depends on the relative exposure to different portions of the body and the nature of the ionizing radiation. For gamma rays, 1 Gy of whole body irradiation corresponds to 1 Sv, for a Relative Biological Effectiveness—RBE—of 1.0.

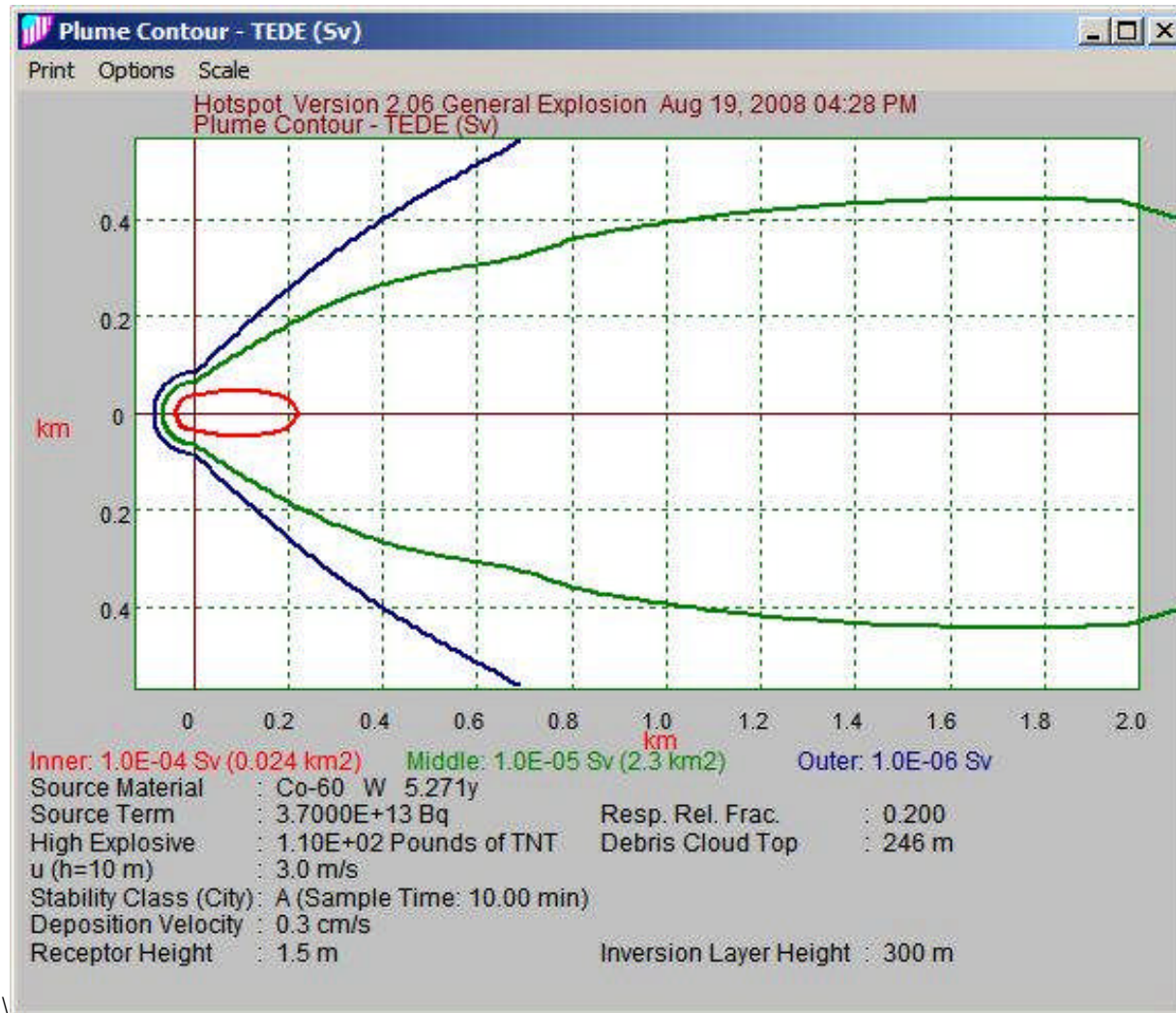


Figure 2: Cobalt (Co-60)-based dirty dust--total effective dose equivalent (TEDE)-contour plot in an urban environment (Co-60 activity: 37 TBq or 1000 Ci; explosives: about 50 kg TNT)⁴ (from Friedrich Steinhauesler).

⁴ Friedrich Steinhauesler, presentation XXXX August, 2009??, at a meeting of the World Federation of Scientists, Erice, Sicily. One of many examples
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The middle contour of 10 microSv TEDE corresponds to about one additional death by cancer⁵ for each two-million people exposed at that level, and is the limit sometimes recommended by the IAEA (for an unavoidable exposure deemed “negligible”).⁶ Many cities have peak population density regions of some 40,000 people per square kilometer⁷, so that the 2.3 km² area of the middle contour would contain some 90,000 people. Without knowing the dose at each point within this 2.4 km² 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 $0.05 \times 9 = 0.45$ 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 m² 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. Note that Steinhäusler took a source of 1000 curies while Kelly used 10,000 curies in his example; in this range the 10,000-curie source would have caused 10 times as many deaths.

Nuclear radiation is readily detected by inexpensive, specialized “counters” that can detect much smaller rates of ionizing radiation than the background radiation received from the environment by the average human—about 2 mGy per year, which itself is judged to be responsible for lethal cancer in 0.01% of the people exposed. From the point of view of public health and the regulation of radioactive sources under normal circumstances, and embodied in regulations of the

⁵ Using the ICRP coefficient of 0.05 cancer deaths per person-Sv.

⁶ “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.”

⁷ <http://www.demographia.com/db-citydenshist.htm> (Selected Current and Historic City, Ward & Neighborhood Densities, P. 4 of 24)

Environmental Protection Agency in the United States—EPA-- is to hold additional exposure from any one source to less than 250 microSv (the equivalent of 25 mR of gamma-ray dose) per year, corresponding to an incidence of lethal cancer of 12 per million people exposed.

Deaths by cancer correspond to about 20% of the deaths in a normal population. Only a small fraction of these are caused by background radiation—the rest either from cancer spontaneously arising or perhaps from chemical and biological induction. So at the dose-response coefficient of 0.05 lethal cancers per Gy one could consider restrictions on occupancy following an RDD attack that would limit the increased cancer death risk to a relative 1% (i.e., 0.20% of the exposed population would then suffer a lethal cancer due to this irradiation). And that means limiting the actionable dose to 40 milliGy.

OPPORTUNITIES FOR COUNTERING RDDS. Of course, protection at the source is highly desirable, and that includes not only food irradiators and the like the world over, but medical radiotherapy devices such as that which in 1987, taken from scrap metal, contaminated much of the town of Goiania, Brazil with Cs-137. The villagers used their fingers to spread the glowing powder on their skin and some ingested it with their food. Fifty-four people were hospitalized; four died; and the cleanup of the town by the International Atomic Energy Authority (IAEA) required the disposition of 4000 tons of contaminated buildings and soil.

There is also the opportunity of interdiction of the material on the way to its dispersal target. Co-60 is widely used also as a high-energy x-ray source for radiographic industrial castings, structures, and the like. The penetrating radiation can be shielded in increasing amounts by increasing thickness of shield, but highly sensitive detectors can detect the specific gamma-ray lines of Co-60

or the other common industrial and medical sources. Such detectors are being deployed in various areas, and are increasingly linked in a network, so that a moving source that does not spend enough time near a single detector can still be reliably detected and identified as it moves through the system. But an effective system of this kind depends upon larger and more widely deployed detectors that are commonly present.

Improved security over intense sources of radioactivity in the health and industrial sector is evidently necessary to counter the threat of terrorism, since the existing measures were directed largely towards safety and not security. Increased costs associated with such protection will in some cases drive the process to replace the radioactive source with a compact electron accelerator, which can pose no threat of use as a radioactive dispersal device.

A Nuclear Explosion in a City

The term “improvised nuclear explosive” or “improvised nuclear device—INE or IND—refers to a nuclear explosive that is not one from the inventory of a nuclear state but is made by a sub-national group. This would employ weapon-usable material such as highly enriched uranium metal or plutonium combined with a means to assemble the fissionable material so that it exceeds a critical mass and is subject to a nuclear explosion.

While it is a difficult task to handle the plutonium and assemble it symmetrically with explosives, the problem is simple in principle. Far simpler, though, is the gun-type assembly usable only with U-235, which requires almost 60 kg of U-235 as 80% or 90% enrichment. Much has been published about the Hiroshima weapon which destroyed that city on August 5, 1945. Here is a photograph of the devastation.



Hiroshima in October 1945

The Hiroshima bomb was delivered by parachute in order to provide time for the aircraft to escape the blast. It was detonated by a radar fuze at about 500-m altitude in order to maximize the area destroyed by blast to an overpressure of about 0.3 bar (30 kilo-pascal—kPa). The blast knocked down buildings and the radiant heat from the explosion set fires and burned people. Prompt radiation from the explosion added a small amount to the death toll, but was a new and frightening phenomenon in warfare,

A terrorist explosion, despite a crude assembly system, could very well produce a comparable yield to the Hiroshima bomb—say, 10 kilotons of high explosive equivalent—10 kt. It would in all probability be detonated at ground level, so there would be an enormous crater as is demonstrated by similar detonations at the Nevada test site or in other countries. The proximity of the ground effectively doubles the explosive yield so far as blast is concerned, but a surface explosion lacks the

“Mach stem” that enhances the destruction for a detonation at optimum height. And the thermal pulse will be partially shielded by high buildings intervening between those who might survive the blast and radiation and those who would be killed by the blast in any case. In addition to the prompt radiation from the fission itself, and the near-term radiation from short-lived fission products in the rising fireball, a surface burst introduces a new phenomenon—radioactive fallout. The Hiroshima and Nagasaki bombs, detonated at altitude, were almost free of fallout, whereas a surface burst vaporizes some of the material from the crater and incorporates also in the rising stem of the mushroom cloud materials carried by the in-sweep of air following the pressure pulse. The intensely radioactive fission products from the nuclear explosion condense on the particles of rock and earth and debris drawn into the cloud and fall out with the larger particles.

Coarse material will fall out at a distance of 5-20 km from the surface explosion and the intense radiation level of that fallout patch will typically provide a lethal dose to those who are there for more than 10 minutes or so. These matters are discussed in my 2002 paper⁸.

TERRORIST NUCLEAR EXPLOSIVES. A terrorist nuclear explosive would devastate a city, whether detonated in the hold of a ship in harbor, in a cargo container, in a cellar, or in an apartment. The essential ingredient for a nuclear explosive is fissile material-- highly enriched uranium (HEU) or plutonium. Although the yield of the uranium bomb that devastated Hiroshima was 13 kilotons (13,000 tons of TNT equivalent), and the plutonium bomb which destroyed Nagasaki yielded 20 kilotons, nominal U.S. and Russian strategic weapons now are in the range of

⁸[Nuclear and Biological Megaterrorism](http://fas.org/rlg/020821-terrorism.htm)," by R.L. Garwin, presented at the 27th Session of the International Seminars on Planetary Emergencies, Erice, Sicily, August 19-24, 2002, <http://fas.org/rlg/020821-terrorism.htm>.

(A shorter version was published in MIT's Sept. 2002 *Technology Review*, titled "The Technology of Megaterror" at <http://www.technologyreview.com/articles/garwin0902.asp>).

150 kt. A 2001 report⁹ details the damage of what we expected from explosions of 1, 10, and 100 kt at ground level in a city. The Table taken from NCRP shows the approximate radii to which the quality or destruction extends, for the 1 kt and 10 kt yields.

Consider a 1-kt explosion. This might occur from a gun-type device with less material than was used at Hiroshima, or a plutonium implosion-type device made from reactor-grade plutonium and yielding only a "fizzle" because of a large neutron background from the reactor-grade plutonium. On the other hand, the plutonium device might yield 10 kt, as might a uranium gun, so both are shown in the Table.

Table-- Summary of ranges for significant effects (in meters).

Yield (kt)	(a)*	(b)*	(c)*	(d)*
1	275	610	790	5500
10	590	1800	1200	9600

a* Range for 50% mortality from air blast (m)

b* Range for 50% mortality from thermal burns (m)

c* Range for 4 Gy initial nuclear radiation (m)

d* Range for 4 Gy fallout in first hour after blast (m) . But this is the distance to the fallout spot—not the radius of effect.

Considering the numbers in the 1-kt row, we see that people out to 275 m are likely to die from the blast. We can transform the first three columns into the number of Manhattan city blocks which

⁹ Table 3.7 on p. 23 of NCRP Report no. 138 of 10/24/01, Recommendations of the National Council on Radiation Protection and Measurements, 7910 Woodmont Avenue, Bethesda, MD 20814-3095.

would be destroyed, simply by equating the area within the circle of 50% effect to a number of city blocks.

The conversion was made by noting that Central Park is 836 acres, and there are 247 acres in a sq km. Thus Central Park is 3.38 sq km. Extending from 59th St. to 110th St., it is 51 blocks north-south and three large blocks east-west. Thus it has 153 large Manhattan blocks. There are thus 45 Manhattan blocks per sq km.

The city blocks destroyed by air blast (50% mortality in the "cookie cutter" approximation-- 100% lethality out to the 50% line, and 0% mortality beyond that): *11*

City blocks in which almost everyone would die from thermal burns: *53*

City blocks in which people would get a lethal dose of prompt nuclear radiation: *88*

For the 10 kt explosive, the results are *49, 457, and 203* city blocks.

To convert these areal measures into fatalities, we might take a particularly high¹⁰ local daytime Manhattan population density of 125,000 per sq km or an average of about 2360 people per Manhattan block. So for the 1-kt explosion, some 210,000 people would die-- mostly from prompt radiation within a week or so. Of these, 30,000 would have died from blast earlier, and about 100,000 from burns.

For the 10-kt explosion, about a million people will die from burns. Less than half of these would have died from radiation exposure.

¹⁰ Manhattan residents average about 28,000/km², but the commuter population almost doubles that. Because workers are concentrated in a small fraction of the area, I take a local density twice the overall daytime average.

As for fallout, the Table is to some extent misleading, since this provides the distance at which lethal fallout within one hour might be deposited, but it is not a circle of that radius. From the 1977 "Effects of Nuclear Weapons," Table 9.93 (p. 4.30) we see that for a reference dose rate (i.e., for a 1 kiloton explosion) of 3 Sv per hour (300 rads/hr), the downwind distance would be 4.5 miles, and the width about 0.15 miles, for a region affected on the order of 0.7 square miles or 1.5 square kilometers, or 80 Manhattan blocks. So the fallout, although lethal, would not totally dominate the casualties from a nuclear explosion.

Compared with an air burst of a large nuclear weapon at an altitude designed to maximize the blast damage, the prompt radiation and the fallout are far worse with a terrorist explosion. This comes about because the bomb detonated at or near surface of the Earth throws up an enormous amount of earth and vaporized structure, which descends in the immediate neighborhood, providing lethal fallout, which is essentially absent when the fireball does not touch the ground.

If it were known that a nuclear explosion was to take place, evacuation would be highly desirable. And as in the case of potential reactor accidents (with or without terrorist involvement) it would be very useful to have distributed and ready for use potassium iodide (KI) tablets or capsules. A 130-mg dose would block the uptake of radioactive iodine to a young thyroid (or to a nursing mother), and avoid many thyroid cancers which would destroy the thyroid and might be lethal.

Of course, hospitals would be overwhelmed with the number of people actually injured by flying glass, suffering from radiation exposure, and the like. Furthermore, transit in the city would be disorganized in the regions affected. With buildings down over a square kilometer or so, as was already evident in the case of the World Trade Center collapse covering 1% of that area, severe damage to the communications and transportation infrastructure would be expected.

Organized medicine would be unable to cope. A volunteer emergency medical corps, with adequate planning and practice, could save some people who would otherwise die.

Nevertheless, a terrorist nuclear explosion would explode in one place, or a very few, compared with the nuclear attack which we feared for many years and decades from the Soviet Union, and which China probably feared from the Soviet Union or from the United States. So other localities could send personnel and supplies and be a destination for evacuation from contaminated areas.

Public safety personnel would need to use radiation detectors to characterize places which posed no continuing radiological problem; regions in which people could not stay for even an hour or five hours without a high likelihood of dying within weeks from radiation damage; and to identify regions in which radioactivity was clearly evident, but which would add perhaps only 1% to the 20% of American citizens who ultimately die of cancer instead of from some other disease. A large-scale survey by light aircraft or helicopter could be very useful in this regard and could be conducted by an unmanned vehicle such as Predator.

The management of radiation exposure is entirely different following a surface burst than an airburst such as Hiroshima and Nagasaki. In case of airburst, those who will not die from immediate (prompt) radiation from the nuclear explosion will have received a dose less than 4 gray (400 rad) and will, accordingly have an additional cancer risk less than 15% of total mortality. For a surface burst, as many might die of fallout radiation as of blast and fire, and management in the minutes and hours after the burst could avoid many deaths.

The effects of a nuclear detonation in a city are so horrendous that it is clear that most effort should be placed on preventing access by terrorists to nuclear materials or weapons; to interdicting the

transportation of weapons or the building of improvised nuclear devices; and to keeping them out of areas of large population density.

Unlike the case of large-scale nuclear war, a single terrorist nuclear explosion would not eliminate the resources of the rest of the country, so healthy survivors could be accommodated elsewhere. Those in the regions subject to substantial fallout could receive expedient medical care, but little can be done for those exposed above the levels shown in the Table. Unlike an attack with biological weapons (BW), a nuclear explosion is evidently far better prevented than treated.

Stolen or diverted military nuclear weapons are rugged, but many are provided with substantial protection against unauthorized detonation, so considerable skill might be required to employ one. On the other hand, an improvised nuclear device (IND) would not have this problem, but can be difficult to achieve. The fissile material is not an article of commerce and would have to be stolen or diverted. The first plutonium bomb incorporated 6 kg of weapon-grade plutonium, of which more than 250 tons has now been made worldwide-- enough for 40,000 such crude weapons. Almost all the "military plutonium" was produced by the United States and the Soviet Union.

In addition, every large nuclear power reactor produces annually on the order of 200 kg of plutonium, which is not and need not be weapon grade to make an improvised nuclear device. In January 1997 the U.S. Department of Energy stated of reactor-grade plutonium, "Proliferating states using designs of intermediate sophistication could produce weapons with assured yields substantially higher than the kiloton-range possible with a simple, first-generation nuclear device."

At the March 6, 2002 hearing of the Senate Foreign Relations Committee, Senator Joseph Biden quoted former Los Alamos National Laboratory Director Harold M. Agnew to the effect that "If somebody tells you that making a plutonium implosion weapon is easy, he is wrong. And if

somebody tells you that making an improvised nuclear device with highly enriched uranium is difficult, he is even more wrong." Plutonium metal can be accumulated in spherical form almost up to the so-called "critical mass" of 10 kg for weapon-grade plutonium or 13 kg for reactor-grade plutonium. The analogous critical mass for 94% U-235 is 52 kg, and these numbers set the scale for the amount of fissile material required for a nuclear weapon.

Instead of being assembled by high explosive as in the plutonium bomb (which can also be used for assembly of a uranium core) the Hiroshima bomb employed two solid masses of highly enriched uranium metal, one of which was propelled in a shortened, converted naval gun to form more than a critical mass with the stationary uranium metal. Although less efficient, this is far simpler than is the plutonium IND.

What is important, though, is to prevent such a disaster in a large city, which might kill 200,000 people, from resulting in the collapse of the entire society that might contain 60 million, or 300 million, or 1000 million people. This requires a greater evaluation of the short-time impact on all sectors of society—financial, medical, communications, and the like—with remedial measures to ensure that society could continue to function, even if considerably higher costs would be incurred. Investments must be made to make sure that this is so.

Critical skills and repositories of knowledge must be investigated as well, in order to be able to continue to build factories or to operate facilities.

Attack on a Nuclear Reactor, Spent-Fuel Storage Pool, or Reprocessing Facility

Two particularly severe accidents have occurred at civilian power reactors over the history of nuclear energy. The first at Three-Mile Island, March 28, 1979, injured no one and probably killed one person from exposure to the passing cloud of radioactive gas. The Chernobyl disaster in the Ukraine April 26, 1986, killed some 32 emergency workers and probably led to the death by cancer of some 24,000 people widely distributed across Europe and the Soviet Union.

The difference between the consequences of the two was not so much in the radioactivity content of the reactor core, nor was it the fact that the core in one case was little damaged. In fact, the TMI core was substantially melted and much of the radioactivity was transferred to emergency core cooling water in the containment dome. Fortunately, although there was a hydrogen explosion in the containment dome, it brought the overpressure only to some 40 psi, and did not damage the containment.

The Chernobyl graphite-moderated light-water reactor did not have a containment. Through mismanagement and poor design, it went “prompt critical” and the coolant water flashed to steam blowing off the 1000-ton concrete biological shielding lid of the reactor and exposing the hot metal fuel elements and the graphite moderator to the atmosphere. The radioactive plume rose to great heights and deposited radioactive core particles by fallout across much of Europe. There is no significant disagreement about the distribution of Chernobyl fallout and the resulting “collective dose” to the population; multiplying by the conventional factor of 0.04 cancer deaths per person-sievert gives this estimate of 24,000 cancer deaths.

In contrast, what destroyed the reactor core at TMI was simply the decay heat of the residual fission products after the reactor was shut down in an accident involving the cooling water pumps. The steel reactor pressure vessel of TMI remained largely intact, but the top of the reactor core was uncooled because hydrogen gas in the upper part of the pressure vessel prevented access to the core by cooling water.

Because a full-size one-million-kW power reactor fissions about one ton of U-235 per year, the accumulated fission products are almost exactly that same one ton. Because 1 kg of fission contributes 17 kilotons of yield in a nuclear explosive, the long-lived radioactivity accumulating in a reactor core corresponds to that from about 17 megatons per year of operation. On the average, the fuel elements in the reactor core are two years old, so the content of long-lived radioactivity is about that that would have been produced by 30 megatons of fission explosive or about 60 megatons of thermonuclear explosive. (In a so-called thermonuclear weapon, typically half of the energy comes from fission and half from fusion.)

Two particularly important and abundant fission products are strontium-90 (Sr-90) and cesium-137 (Cs-137), both happening to have a half-life of about 30 years. The spent fuel elements downloaded from the reactor into an at-reactor cooling pool after four years of exposure in the reactor core typically accumulate there. In the case of U.S. reactors, many have 20 years of spent fuel in the swimming pool, which is gradually transferred to dry-cask storage. Thus a cooling pond with 20 years of spent fuel has about 20 tons of fission products--the equivalent of more than 600 megatons of thermonuclear detonations.

The radioactivity of course diminishes with time, but that of Sr-90 and Cs-137 and isotopes of longer life not very much over the storage period. So a terrorist attack on a cooling pond (in which cooling is initially by passive convection in the swimming pool water) would not do much if it only cut off the active cooling that transfers the decay heat through a heat exchanger to the ambient air or to a river or sea; the cooling would be achieved automatically by slow evaporation of the water in the pool. If the cooling pond is above ground, however, placing an explosive in the pond next to the concrete wall could well breach the wall and allow the pool to empty, thus resulting in an overheating of the spent fuel and its eventual failure by melting. Proper design would keep this from being a serious hazard if the pool is below ground level. For existing pools, however, that is not an option. The pools might be attacked by aircraft, but the greater threat is probably a terrorist group that has access to the reactor through the use of overwhelming force and would thus be able to attack the cooling pool.

Similarly, such a group could in an intelligent fashion defeat the multiple protective systems that guard the reactor itself against accidents, inhibit the flow of emergency cooling water, and at the same time blow a hole in the containment. Both for attack on the cooling pool and on the integrity of the containment, there are measures that could be taken if one honestly admits the potential problem. These measures would be to have on site expandable plugs like those that are often used for a temporary fix of a hole in a domestic heating system. In the case of a cooling pool, the patch could be in the form of a metal plate stored vertically in the cooling pool, equipped with rubber gaskets around its edges. The plate could be transferred by a crane or by expedient means to cover the hole where water might be gushing out. A similar patch could be inserted through a hole in the containment dome of the reactor itself, in the form of a folded umbrella and expanded after it was

largely inside. Provisions should also be made for automatic spraying of the potentially exposed fuel rods by fire hose in the pool building, with emergency water supplied from the outside.

There are fewer reprocessing plants than nuclear power reactors, but the plant may hold in much more accessible form the intense radioactivity not only for many decades of reactor operation but from multiple reactors. Thus the Sellafield plant in England reprocessed for more than 20 years fuel from Japan and Germany, in large part. Much of the fission products from most of those reactor years of operation is present in the HAST-- highly active storage tanks. These are above-ground, spherical steel tanks, equipped with triply redundant cooling coils within the liquid itself. I have spoken of the vulnerability of these tanks.¹¹ In brief, in 2002, 21 spherical tanks at Sellafield held a total of 1550 m³ of Highly Active Liquor, with each m³ of liquid containing 1.6 kg of Cs-137. The 1986 Chernobyl accident liberated 26 kg of Cs-137 and gave an overall population exposure of some 600,000 person-Sv, corresponding to about 30,000 deaths from cancer. From a single B215 150-m³ tank, 50% of the Cs-137 would be 120 kg—four times Chernobyl, or 120,000 cancer deaths according to the linear hypothesis (see “Megawatts & Megatons...” (2001), Ch. 4).

To counter attack on the nuclear reactor, a cooling pool, or a reprocessing plant, one would take advantage of the fact that these are relatively few locations, and relatively isolated from the urban environment. Therefore, one could use life-threatening means, in extremis, to protect against terrorist attacks. But one must reckon with terrorists obtaining GPS-guided bombs or simply resorting to extensive practice with a large aircraft loaded with explosives that could most simply be operated on a suicide mission. As was the case in the attack on the Twin Towers September 11, 2001, an experienced pilot would find it extremely difficult intentionally to fly her aircraft into an

¹¹ In my presentation, “Major Accident or Terrorism Risks From Sellafield,” to the 2002 conference of the Royal Irish Academy, “Making Sense of Sellafield.”
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obstacle. Much better would be a person with minimal flying skills and a commitment to a cause that would enable the novice pilot to undertake such a suicide mission.

COUNTERING NUCLEAR TERRORISM

Much effort has been expended in the United States and elsewhere to counter nuclear terrorism in the form of RDDs or stolen or improvised nuclear explosives. The Nunn-Lugar Cooperative Threat Reduction Program was begun in 1992 to reduce the threat of nuclear terrorism by making more secure Russia's stored nuclear weapons. The goals of Nunn-Lugar extend also to reducing the threat of biological or chemical terrorism from the former Soviet Union. Others here are far more expert about these activities and their results, so I won't discuss further this very important program.

Most recently the Obama Administration has put forth the goal of "securing the most vulnerable nuclear materials world-wide within four years," and the President's budget provides funds toward this goal.

MEASURES TO COUNTER NUCLEAR TERRORISM (1)

- **RDDs: establish better control of radioactive sources in hospitals and especially in industry**
- **Encourage the replacement of intense radioactive sources by electron accelerators**
- **Establish nuclear radiation detection networks to track sources**
- **Establish more sensible rules about use of buildings and areas contaminated in an RDD attack**
- **NUCLEAR EXPLOSIVE ATTACK ON A CITY:**
 - **PREVENT, by securing weapon-usable material worldwide, AND by massive reduction and improved security of nuclear weapons**
 - **Ready automatic systems of lethal force to protect nuclear weapons**
 - **ENSURE that the whole society is not vulnerable to the loss of hundreds of thousands of people in a single city**
 - **Mimimize availability of weapon-usable material by avoiding reprocessing of spent fuel, except where essential, as in a system of breeder reactors. And design and operate these with countering proliferation and terrorism as high-priority goals**

MEASURES TO COUNTER NUCLEAR TERRORISM (2)

- **ATTACK ON NUCLEAR REACTOR:**
 - **RECOGNIZE the threat, and deploy life-threatening systems to prevent terrorist action**
 - **Develop and deploy mitigation measures to cracked storage pool and breached containment**
 - **For the future, deploy nuclear reactors underground**
- **ATTACK ON REPROCESSING PLANT**
 - **RECOGNIZE the threat, and deploy life-threatening systems to prevent terrorist action**
 - **Build such plants only if necessary, taking into account cost of terrorism and cost of counter-terrorism**
 - **This will drive design to avoid wet processes or long-time storage of highly radioactive liquids (Sellafield!)**
 - **Design the reactors and fuel cycle so that fresh fuel is highly radioactive with long-lived fission products**
- **Do not reprocess LWR fuel and recycle into thermal reactors**

ON REPROCESSING AND RECYCLE IN THERMAL REACTORS

A misleading statement in the 2006 Report of the Commission on Weapons of Mass Destruction (“Blix Report”):

“The spent fuel that comes out of the power reactors contains plutonium as well as unused uranium and various actinides. Currently most spent fuel – highly radioactive – is simply kept in intermediate storage. However, it may be sent for reprocessing in another technically difficult process, which recovers plutonium and uranium that can be used as new fuel in reactors. If this is done, the amount of waste remaining is greatly reduced and the amount of energy that is extracted from the original uranium is increased about one hundredfold.” (From the 2006 WMD Report, p. 73.)

In reality, recycle from current power reactors into current power reactors increases the energy extraction from a ton of original uranium by no more than a factor 1.2, not “one hundredfold.” Dr. Blix and his colleagues agree.

I think the sentence should have read, “... that can be used as new fuel in *breeder* reactors...,” in which case it would have been correct.