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Inaccurate Prediction of Nuclear Weapons Effects and Possible Adverse Influences on Nuclear Terrorism Preparedness

Robert C. Harney

The unthinkable is probably inevitable. At some time in the future a terrorist group will detonate a nuclear explosive in a major metropolitan area. Nuclear non-proliferation regimes are not working. The earliest U.S. policies failed to prevent the U.S.S.R., United Kingdom, France, and China from developing nuclear weapons. Later policies failed to deter Israel, South Africa, Pakistan, and India. They have not proven successful with North Korea or Iran and did not work in Iraq (unless you count invasion as an element of our non-proliferation policy). The few apparent successes (South Africa, Libya, etc.) can be attributed to internal factors as much as to the effects of non-proliferation activities. Once nuclear weapons are in the hands of unstable states or states that support terrorism, there is little doubt that one or more will ultimately wind up in the hands of non-state or state-supported terrorist organizations. Terrorist possession of a nuclear weapon will result in its use against a “highest-value” target – most likely a large city with major economic value, cultural and/or religious significance, and a dense population in which high casualties will result.

The likelihood of an attack has prompted considerable public debate about what are the best steps to prevent such an attack. In many of these discussions estimates of the number of casualties or the size of the area that would be damaged by an attack are used to reinforce the importance of action.¹ Ironically, as discussed later, these estimates may evoke inaction in some critical areas. Paraphrasing many examples, they typically state: a Hiroshima-sized weapon detonated in a major metropolitan area will kill a million people or will vaporize everything within a half-mile of ground zero or some other equally dramatic claim (although some scenarios are less cataclysmic). To this author, the estimates do not ring true – they sound excessive. The estimates are often quoted or repeated by individuals who clearly lack technical expertise in nuclear weapons effects and original sources for the estimates are seldom cited. Although it is possible that some are the product of hyperbole used in political oratory to reinforce a point, the frequency is too high for this to always be the case. It is more likely that valid estimates made for a military attack scenario have been improperly extrapolated to the terrorist scenario. However, if the policymakers making such statements actually believe these estimates, then inaccurate information is being used to set policy, and something should be done to rectify the situation. Such “excessive” estimates have been used to establish emergency response planning guidance.² It remains to be seen whether this will result in over-preparation or under-preparation. Neither is desirable. The primary purpose of this paper is to discuss the accuracy of common effects estimates and describe how more realistic estimates might affect nuclear terrorism preparedness.

STANDARD EFFECTS ANALYSIS

The standard weapons effects prediction process occurs as follows. The desired type of nuclear explosive, its yield, and its height of burst are selected. The distances at which specific effects levels are expected to be achieved are estimated using relations derived from comparison of theory to measurements obtained during nuclear testing. Using these distances, areas are calculated that are associated with each effects level. The effects levels are then correlated with percentages of casualties. This correlation is somewhat subjective, but in the best cases is based on modeling that has been validated by the results from Hiroshima and Nagasaki. Once a target has been selected, population density data, the calculated effects areas, and the casualty correlations are multiplied to estimate the total numbers of casualties expected.

For purposes of example, we will assume that a Hiroshima-sized fission weapon (nominal 10 kT) is the most probable terrorist weapon. Slightly smaller or larger yields will not dramatically alter the results. Doubling the yield results in 22% larger blast damage distances and less than 49% larger areas (or casualties). Manhattan (New York City) is assumed to be the hypothetical target as it is arguably the highest probability target in the United States. It has the highest workday population density, it is the economic capital of the country, and it is a symbol of freedom and American might and prosperity.

The “standard” analysis is an outgrowth of military effects analysis. Most experienced weapons-effects predictors learned their skills while addressing either global thermonuclear war or the tactical employment of nuclear weapons. Thus, virtually all examples used to guide novice or inexperienced effects predictors will be based on military analyses. With the exception of nuclear attacks on missile silos, deeply buried command centers, naval targets, and similar targets, an optimum altitude airburst is assumed in military nuclear-effects analyses. The optimum altitude airburst is far and away the most common analytical assumption in nuclear effects analysis. As we shall see, this may be the source of the putative overestimates.

The range at which each effect level occurs can be estimated from simple relations that scale with the nuclear explosive yield W (in kilotons, abbreviated kT). Scaling relations allow the experimentally verified ranges at which specific effects are produced for a reference explosion of known yield (typically 1 kT) to be extrapolated to the ranges at which those same effects would be produced by an explosion with a different yield. Hundreds of atmospheric nuclear tests at Nevada Test Site, Enewetak Atoll, and elsewhere have contributed to the verification of these scaling relations. The scaling relation for the distance (in meters) at which a specific overpressure (i.e., the pressure in excess of atmospheric pressure) is produced by air blast from the explosion is given by³

$$R_{Xpsi}(W) = R_{Xpsi}(1kT) W^{1/3}$$

where the scaling distance $R_{Xpsi}(1 kT)$ for a 1 kT optimum altitude airburst can be shown to be

- = 2125 meters for 1 psi overpressure
- = 1290 meters for 2 psi overpressure
- = 700 meters for 5 psi overpressure
- = 405 meters for 12 psi overpressure.

These four overpressure levels are those used in the Office of Technology Assessment casualty correlation described later.⁴ The relation for distance (in meters) at which different levels of thermal radiation is produced by the explosion is given by

$$R_{2cal/cm^2}(W) = 1180 W^{1/2}$$

$$R_{8cal/cm^2}(W) = 590 W^{1/2}$$

$$R_{20cal/cm^2}(W) = 375 W^{1/2}$$

The thermal radiation ranges are strongly dependent on atmospheric transmission. The values shown assume a perfectly clear day (no atmospheric attenuation). Ranges for hazy days will be shorter; the hazier the day, the shorter the thermal range. The relation for the distance (in meters) at which specific doses of direct nuclear radiation can occur is given by

$$R_{70rad}(W) = 1200 + 500 \log W$$

$$R_{300rad}(W) = 950 + 500 \log W$$

$$R_{800rad}(W) = 800 + 500 \log W$$

Given a 10 kT airburst at the optimum altitude, the blast effects distances and their associated levels of damage are seen to be:

12 psi = 870 m for severe damage (steel-reinforced structures damaged)

5 psi = 1510m for moderate damage (wood/masonry structures destroyed)

2 psi = 2780 m for minor damage (wood/masonry structures damaged)

1 psi = 4580 m for light damage (windows shattered).

The thermal effects distance from ground zero is:

2 cal/cm² = 3730 m for first-degree skin burns (equivalent to a sunburn).

8 cal/cm² = 1865 m for severe skin burns & ignition of easily flammable materials.

20 cal/cm² = 1180 m for ignition of most flammable materials.

The distance associated with direct nuclear radiation effects (assuming no shielding) is:

70 rads = 1700 m for the threshold of radiation sickness (mild symptoms).

300 rads = 1450 m for the radiation sickness lethal threshold (approx. 5% fatalities).

800 rads = 1300 m for 100% fatal radiation sickness.

The next step in the analysis is to correlate casualties with weapons-effects levels. Although nuclear radiation and thermal radiation produce casualties, overpressure appears to be the best single predictor of casualty levels.⁵ The correlation used by the Office of Technology Assessment (OTA) and summarized in Table I is often used.

Table I. Correlation of casualty levels with overpressure.

Peak Overpressure (psi)	<u>Fraction of Population Density</u>		
	<u>Dead</u>	<u>Injured</u>	<u>Uninjured</u>
>12	0.98	0.02	---
5-12	0.50	0.40	0.10
2-5	0.05	0.45	0.50
1-2	---	0.25	0.75
<1	---	---	1.00

Consider now a 10 kT airburst in Manhattan. The average daytime population density in the Central Business District (Manhattan south of 60th Street) is 83,000 per square kilometer.⁶ The maximum local daytime population density occurs in the half-mile (0.8km) area around Grand Central Terminal⁷ and is approximately 330,000 per km². Circular damage areas are calculated using the overpressure distances above. The areas are multiplied by the appropriate population densities and by the OTA correlation fractions to determine casualties. Details are summarized in Table II. Roughly 66 km² are damaged, over six million people are directly affected, and total casualties are estimated to be in excess of 2,700,000. The areas and the casualty estimates determined in this fashion are consistent with those mentioned in the public debates. The injury estimates may be too high as the 1-2 psi area includes large portions of the surrounding rivers.

Table II. Casualty analysis for a 10-kiloton airburst over Manhattan.

ZONE (psi)	<u>DAMAGE</u>		<u>POPULATION</u>		<u>ASSOCIATED CASUALTIES</u>	
	<u>RADII</u> (km)	<u>AREA</u> (km ²)	<u>DENS.</u> (km ⁻²)	<u>TOTAL</u> ---	<u>DEATHS</u>	<u>INJURIES</u>
>12	< 0.87	2.38	330,000	785,400	769,692	15,708
5-12	0.87 - 1.51	4.78	83,000	396,740	198,370	158,696
2-5	1.51 - 2.78	17.12	83,000	1,420,960	71,048	639,432
1-2	<u>2.78 - 4.58</u>	<u>41.62</u>	83,000	<u>3,454,460</u>	<u>0</u>	<u>863,615</u>
TOTALS	4.58	65.90	---	6,057,560	1,039,110	1,677,451

This traditional casualty analysis coupled with observations of Hiroshima and Nagasaki presents a nearly “hopeless” picture. That is, one would expect that the southernmost one-quarter of Manhattan would be devastated. Roads through damaged areas would be impassable. Evacuation to mitigate fallout effects would probably be impractical in some areas. Power, water, communications,

transportation, and sanitation disruptions would extend well beyond the damaged areas. The expected number of injuries would exceed the number of hospital beds in the entire nation (approximately 945,000 in 2007),⁸ despite the fact that many of the casualties in the 1-2 psi area would not require hospitalization. A significant fraction of the first responders would be among the casualties. Many of the “injuries” might become “fatalities” due to inadequate medical care, shortages of food, and lack of shelter. The expected economic damage is severe, almost beyond comprehension. Economic repercussions would continue for years.

If we assume the traditional analysis is what will always result, then a weak U.S. government might consider giving in to terrorist demands (if voiced ahead of time), rather than suffer the effects of such an attack. Since permitting such a catastrophic attack would be utterly unacceptable, actions likely to be taken to prevent anticipated attacks might further erode Constitutional rights. As the aftermath of such an attack is “hopeless,” planning for emergency response would probably be inadequately funded. Why prepare for something that is beyond accommodation, especially when there are always competing priorities for using available funds? Furthermore, since the Cold War has conditioned the public to view nuclear attack as the end of the world and the “hopeless” scenario does nothing to contradict this view, little or no personal preparation will be made for self-preservation and survival. Inadequate planning and preparation at all levels would greatly magnify the effects of an attack *when* it comes. This must be avoided.

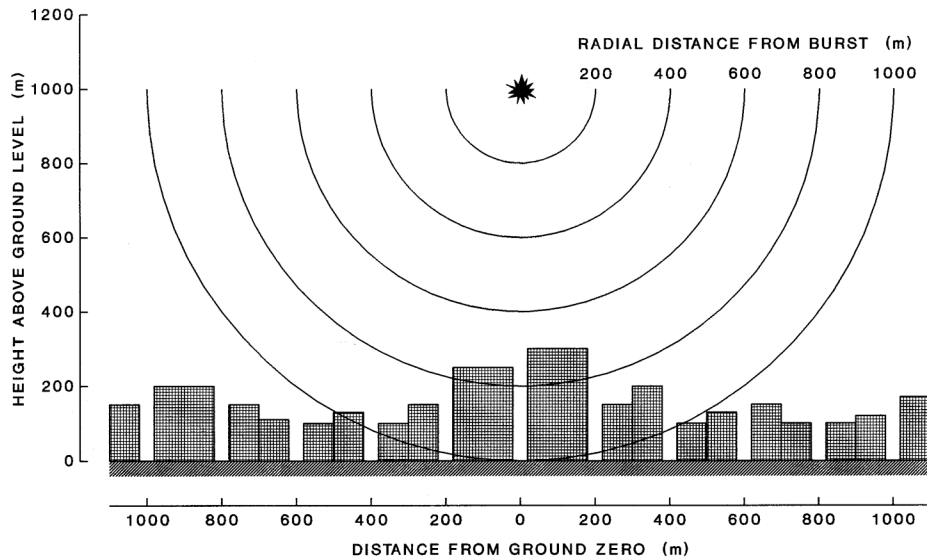
NONTRADITIONAL EFFECTS ANALYSIS

At this point it is worth injecting an additional dose of reality. That is, the heuristics for predicting airburst casualties presented in the preceding section (and used by the most vocal predictors) are applicable *only* to optimum altitude airbursts. Thus, the damage and casualty analysis is realistic only for an optimum altitude airburst. Although the underlying theory is valid for other types of bursts, the numbers are not. There are fundamental differences between an airburst and a surface burst (Figure 1). Airbursts affect every structure separately; surface bursts affect structures sequentially. Airburst blast waves reflect off the surface, increasing the damaging overpressure; surface bursts do not produce such reflections. The optimum altitude also scales as $W^{1/3}$, and for a 10 kT device is 670 meters (twice as tall as the highest buildings) if optimized for 5 psi overpressure. Thus, detonation at the top of a tall building will not produce the optimum airburst effects, although the effects produced will be larger than those for a surface burst. Only an aircraft-delivered bomb, cruise missile, or ballistic missile can produce an optimum altitude airburst. For a variety of reasons, we anticipate that terrorist attacks are more likely to use a surface burst than an airburst.

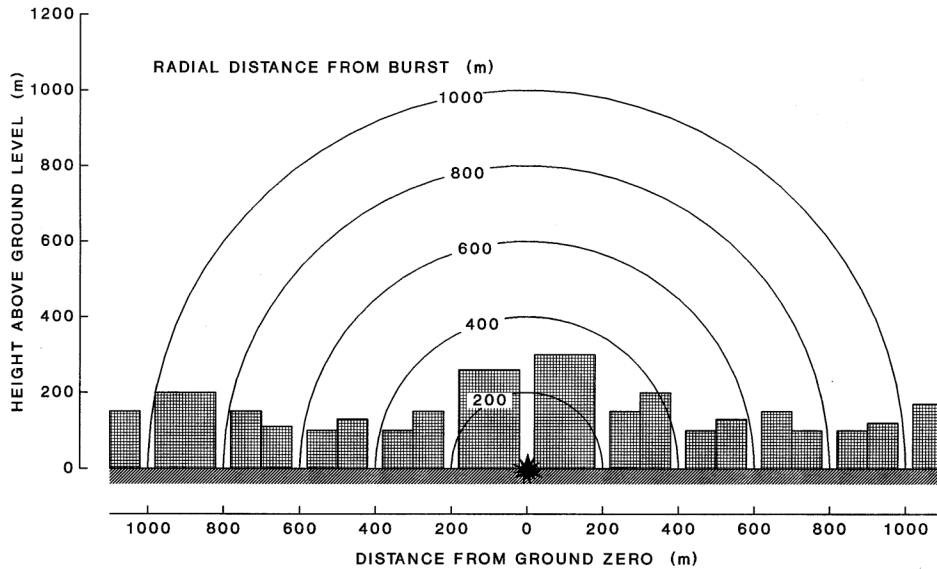
Terrorists are not state-operated military forces. A terrorist bomb is unlikely to be mounted on a missile. It is unlikely to be man-portable. It is likely to be large and heavy. Delivery by aircraft will probably require a multi-engine aircraft,

although aircraft of sufficient size are readily available in the general aviation community. If a policy of no overflight of downtown areas is established (or reestablished) and enforced, then an airburst can be made extremely difficult, if not prevented. Transport to the top floors of the tallest skyscrapers is difficult and likely to be detected. A policy of requiring access control and surveillance of elevators in all buildings taller than average, can further reduce this possibility. Given the severity of the threat and the utility of both aircraft overflight and tall buildings in potential delivery of chemical or biological weapons, consistent and effective controls of both should be implemented. Even if the bomb could be detonated on a tall building, the effects would be closer to surface burst levels than to airburst levels. Transport by truck, however, is relatively easy and difficult to prevent. Thus, it is more likely for a terrorist weapon to be detonated at street level than at the optimum airburst height.

Figure 1. Fundamental difference between an airburst over a downtown area & a surface burst.



Airburst – Buildings provide little mutual shielding from blast. Surface reflection enhances the overpressure.

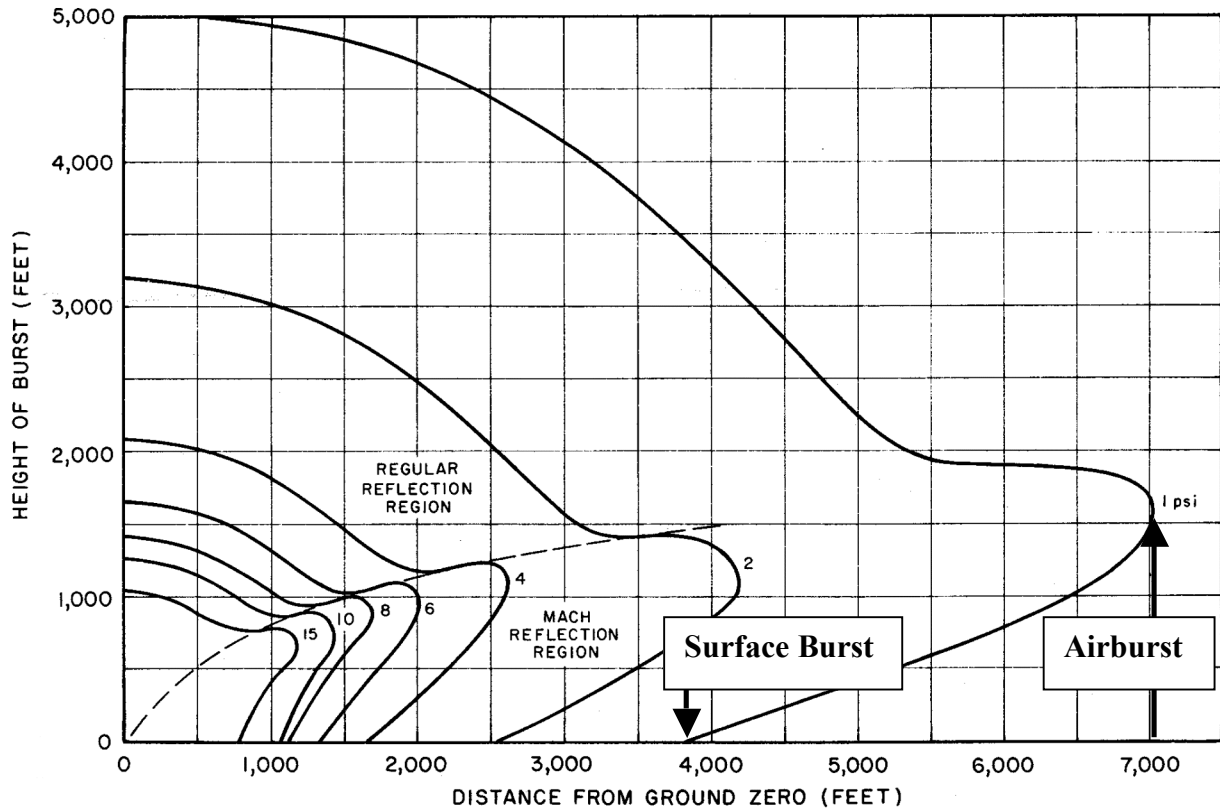


Surface burst – Buildings provide significant mutual shielding from blast. Lack of surface reflection reduces overpressure.

The same theory used to produce heuristics for airbursts can produce surface-burst heuristics. These have also been validated by experiments at Nevada Test Site and elsewhere.⁹ These surface-burst values are valid for flat surfaces without significant obstructions (such as the dry lakes where nuclear tests were conducted). Surface bursts do not have overpressure enhancement caused by reflections. Thus, the blast damage ranges for flat-surface bursts are considerably smaller than for optimum airbursts. These heuristics are almost certainly overestimates for built-up areas (high-rise downtowns or even suburban environments). Nagasaki proved that hills cast “shadows” that significantly reduce nuclear radiation, thermal radiation, *and* blast effects. Casualties at Nagasaki were one-half those at Hiroshima where no hills interfered with the explosion. The presence of multiple massive structures one behind another should cast similar shadows that must reduce predicted damage ranges. Nevertheless, before we consider the effects of buildings, it is instructive to analyze the flat-surface burst scenario as a worst case that is much more realistic than the airburst scenario.

Figure 2 shows the relation of burst height vs. range for different overpressures. The obviously larger ranges for airbursts are due to the fact that airburst shock waves are enhanced by reflections off the ground. Surface bursts over flat terrain are not similarly enhanced. Surface bursts over flat terrain will damage objects at considerably shorter distances than airbursts (e.g., 3800 feet vs. 7000 feet for a 1 psi overpressure).

Figure 2. The relationship between height of burst, distance from ground zero, and peak overpressure for a 1 kiloton nuclear explosion over flat terrain.¹⁰



Scaling relations for effects levels can be obtained for surface bursts. These relations have also been validated by atmospheric tests. The scaling distances $R_{Xpsi}(1\text{ kT})$ are:

- = 1170 meters for 1 psi overpressure
- = 715 meters for 2 psi overpressure
- = 450 meters for 5 psi overpressure
- = 275 meters for 12 psi overpressure

Given a 10 kT burst at a flat surface, the blast effects distances are seen to be:

- 12 psi = 590 m for severe damage (steel-reinforced structures damaged)*
- 5 psi = 970 m for moderate damage (wood/masonry structures destroyed)*
- 2 psi = 1540 m for minor damage (wood/masonry structures damaged)*
- 1 psi = 2520 m for light damage (windows shattered).*

Blast damage distances are considerably smaller for the flat-surface burst than for the airburst. The relation for distance (in meters) at which different levels of thermal radiation is produced by the surface burst is given by

$$R_{2cal/cm^2}(W) = 845 W^{1/2}$$

$$R_{8cal/cm^2}(W) = 425 W^{1/2}$$

$$R_{20cal/cm^2}(W) = 270 W^{1/2}$$

The thermal radiation ranges are strongly dependent on atmospheric transmission. The values shown assume an extremely clear day (no atmospheric attenuation). Ranges for hazy days will be shorter. The relation for the distance (in meters) at which specific doses of direct nuclear radiation can occur is given by

$$R_{70rad}(W) = 1200 + 500 \log W$$

$$R_{300rad}(W) = 950 + 500 \log W$$

$$R_{800rad}(W) = 800 + 500 \log W$$

The thermal effects distance from ground zero is:

2 cal/cm² = 2675 m for first-degree skin burns (equivalent to a sunburn).

8 cal/cm² = 1335 m for severe skin burns & ignition of easily flammable materials.

20 cal/cm² = 845 m for ignition of most flammable materials.

The distance associated with direct nuclear radiation effects is:

70 rads = 1700 m for the threshold of radiation sickness (mild symptoms).

300 rads = 1450 m for the radiation sickness lethal threshold (appx. 5% fatalities).

800 rads = 1300 m for 100% fatal radiation sickness.

Using the same analysis technique as for the airburst, flat surface burst casualty estimates were produced and are summarized in Table III. Fatalities are estimated at 510,640 compared to 1,039,110, and total casualties are estimated at 1,022,159 compared to 2,716,561. The reduction is significant (more than a factor of 2). However, the flat-surface burst ignores the fact that large structures attenuate blast effects.

Table III. Casualty analysis for a 10-kiloton flat-surface burst in Manhattan (without structures).

ZONE (psi)	DAMAGE		POPULATION		ASSOCIATED CASUALTIES	
	RADII (km)	AREA (km ²)	DENS. (km ⁻²)	TOTAL ---	DEATHS	INJURIES
>12	< 0.59	1.09	330,000	359,700	352,506	7,194
5-12	0.59 – 0.97	1.86	150,000	279,000	139,500	111,600
2-5	0.97 – 1.54	4.49	83,000	372,670	18,634	133,350
1-2	<u>1.54 – 2.52</u>	<u>12.50</u>	<u>83,000</u>	<u>1,037,500</u>	<u>0</u>	<u>259,375</u>
TOTALS	2.52	19.95	---	2,048,870	510,640	511,519

NONTRADITIONAL ANALYSIS CONSIDERING STRUCTURES

Standardized and validated models for dealing with street-level explosions in built-up areas are not available. However, first-order models can yield considerable insight. The first model assumes that an explosion in the “canyons” of a city can be treated as a shallow buried explosion in rock that has a density equivalent to that of the average density of buildings, their contents, and the spaces in between. The buildings are the equivalent of the overlying rock. A nuclear explosion beneath but near the surface of the ground will produce a crater. Extensive test data exists for crater-forming explosions. The radius of a crater R_a in normal rock (e.g., granite, a standard material encountered in underground nuclear explosions) produced by an underground burst at the depth for producing maximum crater size is given by

$$R_a = 46W^{0.3} = 92 \text{ m (for 10 kT)}$$

The radius of the continuous ejecta layer surrounding the crater is given by

$$R_e = 2.15R_a = 198 \text{ m}$$

Crater dimensions will scale as the inverse cube root of the material density. The density (mass per unit volume) of a “city” is estimated to be 0.1-0.03 times the density of granite. The air between the various thicknesses of steel, wood, paper, and concrete produces the lower density. For this range of densities, the scaled radii are 2.15 to 3.22 larger than for granite. Thus, the scaled radii for a “city” are:

- Crater $R_a = 200\text{-}300 \text{ m}$
- Ejecta $R_e = 425\text{-}640 \text{ m}$

Buildings inside the crater radius will be shattered and toppled. Buildings inside the ejecta radius will be damaged and possibly destroyed by impact of flying debris. Buildings outside the ejecta radius will receive little serious damage.

A second model makes use of the fact that a blast wave cannot pass through a surface it cannot destroy. This is why a sturdy wall can protect one from a small conventional explosion on the other side of the wall. A wood frame wall can withstand overpressures of 1-2 psi. A masonry wall can withstand overpressures of 3-10 psi. A steel reinforced concrete wall can withstand overpressures of 7-15 psi. In the steel-and-concrete jungle of a downtown area, it is a virtual certainty that a steel reinforced concrete wall will be encountered every 100 m or so. Thus, as soon as the blast overpressure has dropped below 7 psi, blast effects will be no longer be important. For the flat-surface burst the 7-psi level occurs at about 400 m radius. Inside this radius this second model predicts damage will be severe; outside it will be light.

A third approach assumes blast wave propagation through buildings is equivalent to blast wave propagation through a layered medium producing many small reflections that add up to a significant attenuation. That is, each external

wall, internal wall, room partition, or large object (bookcase, file cabinet, desk, credenza, etc.) in a building will reflect a tiny fraction of the blast wave. This is analogous to a light wave passing through a window. Most of the light passes through the window, but a small fraction is reflected. In the remainder of this analysis, all such substantial objects will be considered “walls.” After passing through one “wall” with reflectivity r , the overpressure is reduced by

$$\Delta p = \Delta p_0(1-r)$$

After passing through N “walls” with reflectivity r , the overpressure is reduced by

$$\Delta p = \Delta p_0(1-r)^N \approx \Delta p_0(R) \exp[-rR/R_W]$$

with

$$N = R/R_W$$

where R_W is the average spacing between “walls.” The average spacing between reflecting surfaces may be assumed to be 3-6 m (10-20 ft). The reflectivity of a “wall” will depend on the strength of the “wall” and the overpressure incident upon it. If the overpressure cannot overcome the strength then the reflectivity will be close to 1. For very weak walls the reflectivity might be 0.001 or less. Since the reflectivity coefficient cannot be easily determined, we assume the average reflectivity is 0.005-0.02. Without substantiating experimental evidence, these assumed values for reflectivity may be suspect. However, assuming a relatively low value for this factor is likely to result in an underestimate of the attenuation effects of reflections, the occurrence of which is a virtual certainty. Table IV gives the overpressure vs. radius for several choices of wall spacing and reflectance per wall.

Table IV. Blast overpressure attenuation by multiple reflections.

RANGE (m)	NO WALLS (psi)	$r = 0.005$ $R_W = 3\text{m}$ (psi)	0.01 3m (psi)	0.02 3m (psi)	0.01 6m (psi)
380	30	15.9	8.4	2.3	15.9
470	20	9.1	4.1	0.8	9.1
590	12	4.5	1.7	0.2	4.5
660	10	3.3	1.1	0.1	3.3
970	5	1.0	0.2	0.007	1.0

All choices result in:

Severe damage radii (12 psi) \leq 420 meters

Moderate damage radii (5 psi) $<$ 600 meters

Minor damage radii (2 psi) $<$ 800 meters

Light damage radii (1 psi) $<$ 1000 meters.

The three unrelated models produce surprisingly similar results. Although this is not conclusive, it suggests that the results are reasonable approximations of

reality. Upon comparing the results of all three models it is reasonable to assume the following values:

Severe damage range is 400 m and produces 98% fatality rate and 2% injury rate

Moderate damage range is 500 m and produces 50% fatality rate and 40% injury rate

Minor damage range is 600 m and produces 5% fatality rate and 45% injury rate

Light damage range is 1000 m and produces 0% fatality rate and 25% injury rate.

A casualty analysis was performed using the ranges estimated for a building-modified surface burst. Figures are summarized in Table V. Fatalities are estimated to be 213,675 with total casualties of 381,285. About 1 km² will be significantly damaged. Note: street effects will increase these estimates slightly.

Table V. Casualty analysis for a 10-kiloton surface burst in Manhattan (with structures).

ZONE	<u>DAMAGE</u>		<u>POPULATION</u>		<u>ASSOCIATED CASUALTIES</u>	
	<u>RADII</u> <u>(km)</u>	<u>AREA</u> <u>(km²)</u>	<u>DENS.</u> <u>(km⁻²)</u>	<u>TOTAL</u> <u>---</u>	<u>DEATHS</u>	<u>INJURIES</u>
Heavy	< 0.40	0.50	330,000	165,000	161,700	3,300
Moderate	0.40 – 0.50	0.28	330,000	92,400	46,200	36,960
Minor	0.50 – 0.60	0.35	330,000	115,500	5,775	51,975
Light	<u>0.60 – 1.00</u>	<u>2.01</u>	<u>150,000</u>	<u>301,500</u>	<u>0</u>	<u>75,375</u>
TOTALS	1.00	3.14	---	674,400	213,675	167,610

It is worth commenting that the OTA correlation of overpressure with casualties was based on airbursts over cities with limited high-rise construction. Given the nature of the elastic response of large structures (whipping motion) and the possibility of large overpressures occurring locally due to addition of many small, reflected contributions, the casualty correlations in modern urban settings are suspect. It is possible that casualty rates in the moderate damage and minor damage zones (nominally 2-12 psi overpressure) could be enhanced. This is another topic worthy of additional quantitative analysis and modeling. However, even if all of the population in the heavy, moderate, and minor damage zones were killed, the deaths would be a fraction of those predicted for the flat-surface burst (372,900 vs. 510,640). If that same pessimistic modified correlation (100% deaths for overpressure greater than 2 psi) were applied to the airburst and flat surface burst scenarios, their fatality levels would more than double (although injuries would be significantly reduced). Note: absent modeling yet to be done, there is no justification to assume the validity of this most pessimistic correlation.

The three effects that are the dominant contributors to the devastation of a nuclear explosion are blast (addressed above), nuclear radiation, and thermal radiation. Since this analysis has concentrated on blast effects, some discussion

of the other contributors is in order. Most nuclear radiation will be emitted before the fireball expands appreciably. Buildings provide significant shielding to nuclear radiation. As little as 22 cm (9 inches) of steel or 82 cm (33 inches) of concrete will stop more than 99% of the direct nuclear radiation. Nuclear radiation is not expected to penetrate beyond the first ring of buildings (roughly 100 m radius). The short range at which the nuclear radiation remains significant implies that nuclear radiation will not be a significant contributor to immediate casualties compared to the blast effects. Note: nuclear radiation is assumed to be a contributor to airburst casualties.

Thermal radiation is emitted from the fireball (whose maximum size is roughly the crater size in solid rock). It is a dominant contributor to airburst casualties and may even produce a firestorm. However, buildings provide significant shielding to thermal radiation. Only glass permits penetration beyond the first surface (and then only of the visible/near infrared component of the thermal radiation). As a result, thermal radiation is not expected to penetrate beyond the first ring of buildings outside the fireball (roughly 300 m radius). The short range to which significant thermal radiation can penetrate implies that thermal radiation will not be a significant contributor to casualties compared to the blast effects. Thermal radiation may start fires among the debris and produce a firestorm, although this is seriously debated.¹¹ Regardless, such firestorms will be confined to the areas of heavy damage in which we have already assumed the maximum fatality rates. Whether or not a firestorm occurs it will not significantly affect either the damage or the number of casualties produced by a surface burst affected by structures. This is not true in airbursts. A firestorm produced much of the damage and many of the casualties at Hiroshima. The area affected by the firestorm was almost identical to the area in which significant blast damage occurred.¹²

Fallout is a serious concern and could conceivably produce more casualties than blast, thermal, and initial radiation combined. Its effects are not included in the OTA correlation and do not appear in the analyses presented above, for the reason that they can be reduced to low numbers by timely evacuation of the fallout zone. Fallout production will not be strongly affected by the presence of structures. The fallout will spread downwind in an oval pattern from ground zero. For a 10 kT surface burst and 15 mph wind speed, the unit time (1 hour) dose rate contours are ellipses given in Table VI.¹³ Most people within the 1 rad/hr contour would receive a total dose (integrated over months) in excess of 5 rem if they were not continuously sheltered and did not evacuate. Workers in nuclear occupations are allowed to receive up to 5 rem in one year, and higher doses in emergencies. Thus, the 1 rad/hr contour represents the minimum area that would need to be evacuated. Since the permissible exposure limit for the general public is only 0.1 rem in one year, regulations might require much larger areas to be evacuated. However, in a disaster of the magnitude considered here, it might be necessary to decide that a level considered acceptable for radiation workers is also acceptable for the general public. It should be noted that any amount of sheltering reduces the exposure levels considerably and should be considered in disaster planning. The primary effect of low-level radiation exposure is the

production of cancers. The excess risk of dying from cancer over a lifetime is estimated to be 0.08% per rem for acute exposures.¹⁴ An individual exposed to 5 rem has an additional 0.4% chance of dying of cancer typically 20-30 years after exposure. This is statistically significant but small compared to the normal 18% chance of dying from cancer.

Table VI. Fallout analysis.

DOSE RATE (rad/hr)	CONTOUR		EFFECT AND EXPOSURE DURATION
	LENGTH (km)	WIDTH (km)	
1000	8.17	0.334	Median lethal dose in minutes
300	20.4	0.96	Median lethal dose in a few hours
100	40.3	2.43	Median lethal dose in a few days
30	72.7	4.43	Acute radiation syndrome in a few days (<120 rem)
10	109	7.6	Acute radiation syndrome unlikely (<50 rem)
1	182	16	No acute symptoms; increased cancer risk (<5 rem)

A surface nuclear explosion will also produce source-region electromagnetic pulse (SREMP). As with blast effects, models of SREMP generation by surface explosions in densely populated areas are not available. However, the source region for SREMP generation is the radiation deposition region. For a flat-surface explosion of 10 kT yield, the deposition region has a radius of about 1 km. The field strength falls off quickly with increasing distance from the source region. Significant SREMP field strengths extend to distances of several kilometers.¹⁵ Megaton yields are required to produce significant SREMP at ranges of 8-10 km. The area affected by the SREMP will scale as the size of the source region. We have already seen that for the 10 kT explosion in a downtown area, this will be limited to a radius of 100-200 m due to the surrounding buildings. Thus, the reduction in size of the source region is expected to reduce the distance at which significant field strengths are encountered to less than 1 km. It is nevertheless possible that SREMP may be strong enough to damage highly susceptible components (computers are among the electronic items most susceptible to damage) at distances out to several kilometers, but this is not a certainty. Much of the energy in SREMP is radiated at frequencies less than 100 MHz. At lower frequencies, the steel frames and steel reinforcing of most buildings will provide a shielding effect with some reduction of SREMP field strength at any electronic devices contained within. This is why cell phone and television reception using in-unit antennas is often poor in modern buildings. SREMP (and blast damage) effects on electrical power lines are likely to cause a local blackout, but new grid control systems (installed to prevent repeats of the great blackouts of recent memory) should prevent cascading failures, and power should be quickly restored to most areas. Integrated damage from SREMP will be negligible compared to that from blast. Contrary to common belief, SREMP will not destroy electronics throughout the whole city.

If the nuclear explosive is detonated on a street (as opposed to inside a parking structure), then a line of sight will exist to the fireball for great distances along that street (or streets, if at an intersection) on which the detonation occurs. Because of funneling and waveguide effects, both blast and thermal radiation effects may extend along the streets to distances larger than the normal surface burst distances. Lack of shielding will expose objects on streets to the same levels of nuclear radiation expected in airbursts. The highest levels of damage will be to vehicles and pedestrians. Because dynamic pressure (blast wind) acts predominantly in the direction of shock wave propagation, only static overpressure can cause appreciable damage to the walls and windows of buildings fronting on the streets. Shock waves reflected at grazing incidence produce less than half of the overpressure produced by head-on reflections. The damage to the facing walls of these building will be much less than that experienced by those buildings directly impacted by the shock. Damage and casualties along streets should be minor compared to the damage near ground zero, but will not be negligible.

The shock wave propagating outward from ground zero will diffract around the edges of buildings. However, the diffracted shock wave will be significantly attenuated. Once the shock wave has turned the corner, it will act like the earlier shock wave along the first street, but with much less strength. Diffraction effects should result in significantly reduced overpressure in the shadows of large buildings. Diffraction effects will cause limited damage to the front corners of buildings at cross streets. It is likely that damage along cross streets will be determined more by whether or not the shadowing building is destroyed than by the diffracted shock. Damage and casualties along cross streets outside the direct blast damage radius should be negligible.

COMPARISON AND DISCUSSION

Table VI compares the results from the three analyses: airburst, flat-surface burst, and modified-surface burst. The differences in damaged areas and casualties are striking.

Table VI. Comparison of predicted airburst, flat surface, and modified surface burst effects.

<u>EFFECT</u>	<u>AIR</u>	<u>FLAT SURFACE</u>	<u>MODIFIED SURFACE</u>
Heavy damage	2.38 km ²	1.09 km ²	0.50 km ²
Moderate damage	4.78 km ²	1.86 km ²	0.28 km ²
Minor damage	17.12 km ²	4.49 km ²	0.35 km ²
Light damage	41.62 km ²	12.50 km ²	2.01 km ²
Fatalities	1,039,110	510,640	213,675
Injuries	1,677,451	511,519	167,610
Total Casualties	2,716,561	1,022,159	381,285

Contrary to the predictions of traditional analysis and experience of Hiroshima and Nagasaki, the more “realistic” analysis presents a picture that is much less dire. Fatalities are 20% of those predicted by the standard analysis, while injuries are 10% of those predicted and the damaged area is 5%. Much of the infrastructure will survive. Most evacuation routes will remain viable (permitting relocation for fallout mitigation). Food, water, sanitation, power, communications, and transportation will remain available to most of the city. Transportation to or from the rest of the country, especially air travel, is likely to be minimally affected. Airports are seldom located in the high population density areas that are attractive for casualty production. The first response system will remain intact. At most one or two police precincts and fire stations will be within damage zones. Only a small fraction of first responders will be among the casualties.

The majority of the health care system will remain intact. Few hospitals, clinics, or potential shelter areas may be located within the small damage zones and thus will remain intact and operational. Few health care professionals will become casualties. Regional health care facilities (an estimated 60,000-70,000 beds at three beds/1000 people) have the theoretical capacity to handle the most badly injured. However, most of the 60,000-70,000 beds are occupied during ordinary times and emergency rooms are almost always crowded. Diagnostics and elective procedures account for at least part of the occupation of beds and many emergency room visits occur in lieu of seeing primary care physicians. In a major emergency, many could be discharged by applying triage to those already at the facilities as well as to the victims of the explosion. Nevertheless, emergency treatment facilities will be stressed. This should be considered during planning for disaster preparedness, as well as in any discussions of generally improving national health care.

Although horrific and highly stressing of existing resources, this scenario is nearly ideal for disaster response and relief by local, state, and national entities. Because structures and roads will be undamaged outside the immediate blast area, the effects of fallout from a single nuclear event can be minimized through immediate and effective response including fallout prediction and a combination of evacuation, sheltering in place and/or decontamination. Sheltering for as little as one day can reduce the fallout exposure to less than 20% of the maximum possible accumulated exposure at any location, even if the individual then elects to remain in the contaminated area. It can reduce the total exposure to less than 1% of the maximum possible if the individual elects to walk out of the fallout zone (estimated to take a few hours at most). There is a place for renewed interest in civil defense.

Such civil defense must have a personal emphasis, not just a governmental emphasis. An unprepared population will suffer needlessly in any disaster, manmade or natural. In general, those people most likely to survive are those who are prepared to survive and who will not wait passively for the government to save them. Government has been willing to educate people what to do to prepare for earthquakes, hurricanes, and tornados, although it could be more

aggressive in this education. It should do the same for terrorist attacks, especially in likely target areas.

It is also important to realize that for any metropolitan area other than downtown Manhattan, the casualty estimates would be a small fraction of those calculated here. Hiroshima and Nagasaki both had downtown population densities of 10,000 per km². Initial U.S./Japanese casualty estimates for Hiroshima were 68,000 killed and 76,000 injured and for Nagasaki were 38,100 killed and 21,000 injured.¹⁶ Later Japanese estimates of casualties at Hiroshima are 114,000 killed and 78,000 injured.¹⁷ As there are reasons for the first set of estimates to be biased low and the later set to be biased high, some intermediate value is probably closer to the truth. Deaths occurring more than six months after the explosions (e.g., due to cancers) are not included. None of these estimates includes any military personnel or Korean “guest workers” that may have been in the cities and would have raised the numbers above those shown here.

For comparison, the 1980 OTA estimate¹⁸ of the workday population density in downtown Detroit was 8600 per km². If the modified surface burst casualty analysis of Table V were repeated for a population density of 10,000 per km², then fewer than 6500 deaths and 7850 injuries would be predicted. Placed in perspective, these figures are comparable to the roughly 6650 people that die of all causes on any average day in the United States¹⁹ and only twice the roughly 3000 dead and 6000+ injured in the 9/11 attacks. The United States has survived such disasters before and will again. Even if an airburst could be produced the estimated casualty levels would be 56,000 deaths and 200,000 injuries (and this is an overestimate because the 10,000 per km² peak density is unlikely to extend over the entire 40+ km² damage area of an airburst). Hiroshima had an average population density in the damage area of about 3300 per km² while Nagasaki had an average population density of only 2300 per km². An airburst in a city other than Manhattan is likely to be comparable to Hiroshima or Nagasaki.

Some critics might contend that an airburst is the likely form of attack and surface explosions are irrelevant. However, it is many orders of magnitude easier to secure the airspace over a few large cities (and thus deter attempts at producing airbursts) than it is to secure the surface areas of those cities. All the former requires is the government’s will to enforce “zero overflight” zones with deadly force. Such enforcement should be established. Similarly, uniform and effective security measures for controlling access to the tallest buildings are practical and should also be established. Securing the surface against terrorist attack is probably not possible except in a few specific locations at a few specific times, such as special events.

The promulgation of unrealistic estimates does the government and the general population a great disservice. People should not be persuaded to believe that a terrorist-initiated nuclear attack is the end of the world. We will probably experience such an attack at some point in the future and the world will not end. Millions will not be killed by a single event, although tens of thousands may. We will be forced to deal with the consequences. People tend to rise to the challenge in adverse situations, but they give up in situations perceived as hopeless.

Terrorist attacks, no matter how devastating, should not be made to appear hopeless.

The government must not be forced by public opinion to take short-sighted actions, such as appeasement, to avoid such attacks. Appeasement seldom works in the long term and even appeasement will not prevent every possible attack. This does not mean the government should not act vigorously to reduce the threat of nuclear terrorism, but it should be proactive not reactive, and certainly not over-reactive. The public and especially public servants and elected officials deserve better education concerning the facts about weapons effects. Disaster planning should consider realistic and stressing scenarios but not doomsday scenarios. Emergency response capabilities adequate to address the threat of limited nuclear attack should be developed, and the nature of those capabilities should be communicated to the public.

Although the models used above for surface bursts are first-order and do not take all possible phenomena into account, the author is confident that the effects for a real explosion will be much more limited than those predicted by the flat-surface burst, and the flat-surface burst is known to be much less damaging than an optimum altitude airburst. Better models for nuclear effects prediction in urban environments may produce somewhat different estimates. Such models should be developed and made available to emergency planning groups. The models should include not only the effects on structures, but also estimates of the injuries and fatalities that might result. With realistic effects estimates as inputs, planning processes should produce better policies and response plans.

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The views and opinions in this paper are those of the author. They do not necessarily represent those of the Naval Postgraduate School, the U.S. Navy, or the United States government.

¹ Graham Allison, *Nuclear Terrorism: The Ultimate Preventable Catastrophe* (New York NY: Henry Holt & Co., 2004). This is a widely-cited example, but even a quick search of the Internet reveals many others. See Bill Keller, “Nuclear Nightmares,” *The New York Times Magazine*, May 26 2002, <http://www.nytimes.com/2002/05/26/magazine/nuclear-nightmares.html> and Bruce Goldman, “Nuclear Nightmare in Manhattan,” *New Scientist*, March 18, 2006.

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- ² Interagency Policy Coordination Subcommittee for Preparedness & Response to Radiological and Nuclear Threats, “Planning Guidance for Response to a Nuclear Detonation”, Homeland Security Council, January 16, 2009.
- ³ Samuel Glasstone and Philip J. Dolan, *The Effects of Nuclear Weapons*, 3rd Ed. (Washington DC: U.S. Government Printing Office, 1977), 101. Most of the material on weapons effects can be found in this reference. If no reference is given for an effect, it is probably obtained from Glasstone and Dolan. Although long out of print, it can be found at <http://www.princeton.edu/~globsec/publications/effects/effects.shtml> among others.
- ⁴ U. S. Congress, Office of Technology Assessment, *The Effects of Nuclear War*, OTA-NS-89 (Washington DC: U. S. Government Printing Office, 1979), 19.
- ⁵ Ibid.
- ⁶ Sheldon Silver, “New York City Transit Needs”, Speaker of the Assembly, State of New York, February 2000, <http://assembly.state.ny.us/Reports/200002nyctransit.pdf>.
- ⁷ Federal Transit Administration, “Long Island Rail Road East Side Access,” Department of Transportation, November 2005, http://www.fta.dot.gov/documents/NY_New_York-LIRR_ESA.doc. 660,000 employees working within 0.5 miles of Grand Central Terminal corresponds to a density of approximately 330,000 per km² over a circle of radius 0.8km.
- ⁸ American Hospital Association, “Fast Facts on US Hospitals”, 2008, <http://www.aha.org/aha/resource-center/Statistics-andStudies/fast-facts.html>.
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- ¹⁰ Ibid., 115.
- ¹¹ Office of Technology Assessment, *Effects of Nuclear War*, 21-22.
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- ¹³ Glasstone and Dolan, *Effects of Nuclear Weapons*, 430.
- ¹⁴ National Research Council, Committee on the Biological Effects of Ionizing Radiations, *Health Effects of Exposure to Low Levels of Ionizing Radiation: BEIR V* (Washington, DC: National Academy Press, 1990).
- ¹⁵ Glasstone and Dolan, *Effects of Nuclear Weapons*, 535.
- ¹⁶ Ibid., 544.
- ¹⁷ Hiroshima International Council for Medical Care of the Radiation-exposed, *A-Bomb Radiation Effects Digest*.
- ¹⁸ Office of Technology Assessment, *Effects of Nuclear War*, 27-31.
- ¹⁹ Melanie Heron, Donna L. Hoyert, Sherry L. Murphy, Jiaquan Xu, Kenneth D. Kochanek, and Betzaida Tejada-Vera, *National Vital Statistics Report* 57, no. 14 (April 2009): 2. In 2006 there were 2,426,264 deaths in the United States for an average of 6647 per day.