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Grim Prospect: Low-Yield Nuclear Weapons in the Middle East

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14. ABSTRACT

This study assesses what amount of plutonium and highly enriched uranium is needed to make a low-yield nuclear weapon that can inflict as many casualties as the Hiroshima and Nagasaki bombs did. This was accomplished by modeling how many casualties a 1-kiloton device detonated at ground level would inflict against populations living in five major Middle Eastern cities. The study finds that such weapons can be built with as little as 1 to 3 kilograms of plutonium and 2.5 to 8 kilograms of highly enriched uranium. The weapon in question would have a yield of 1 kiloton and would be detonated at ground level. This weapon would inflict far more harm from prompt radiation and fallout than either the Hiroshima or Nagasaki bombs did. Those bombs were detonated not at ground level, but at roughly 1,600 feet to maximize blast damage against buildings. The study's conclusions raise questions about the credibility of the International Atomic Energy Agency's (IAEA's) current estimates of how much plutonium and highly enriched uranium are needed to make a bomb (what the Agency refers to as a significant quantity or an SQ). The IAEA's SQs are 8 kilograms of plutonium and 25 kilograms of highly enriched uranium. These quantities determine how frequently the IAEA inspects nuclear activities and materials to prevent and deter their possible military diversion. The study's findings suggest that the frequency of inspections, which are driven by what significant quantity is assumed, needs to be increased substantially.

15. SUBJECT TERMS

International Atomic Energy Agency (IAEA), Nuclear Safeguards, Timeliness Detection Goals, Significant Quantity, Middle East, Nuclear Casualty Models, Tehran, Dubai, Riyadh, Cairo, Tel Aviv, Implosion Device, Hiroshima, Nagasaki, Nuclear Weapons Effects

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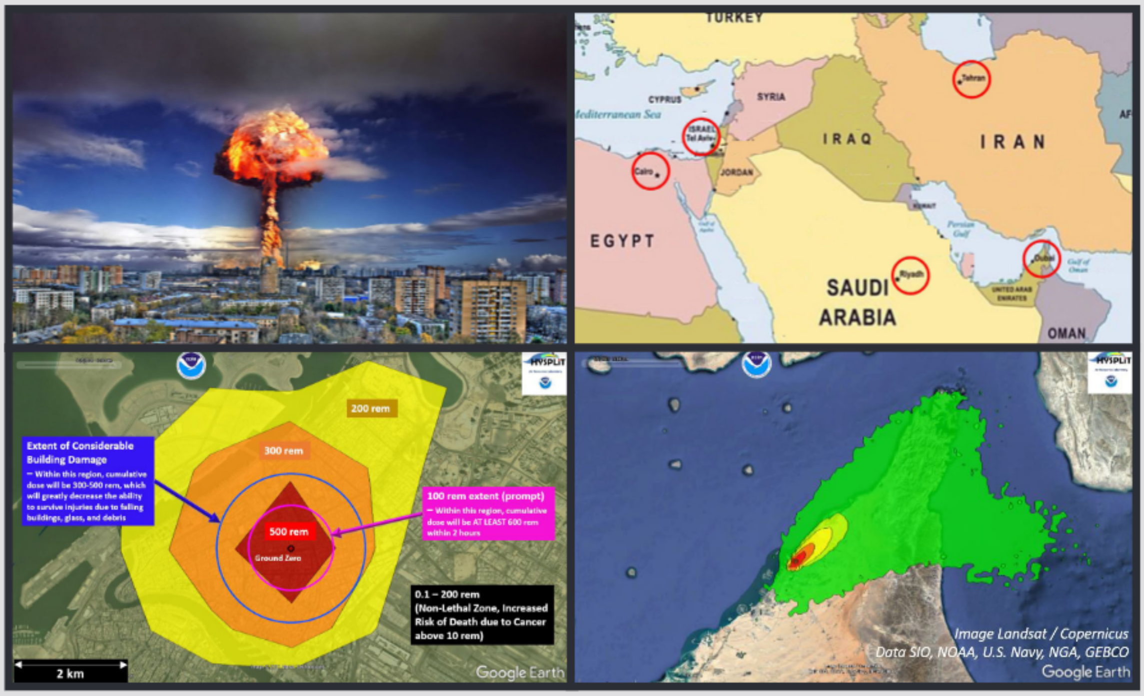

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Cover images, from top left clockwise: 1) artist's depiction of a nuclear explosion in a dense, urban city center (image by Mihan(AKA)Zed via Wikimedia Commons) ; 2) map of five major population centers in the Middle East; 3) 24-hr Total Effective Dose Equivalent (TEDE) map based on weather on June 1st, 2020, at 0800 GST; 4) map depicting overlap of prompt effects and nuclear fallout dose contributing to lethality.

Grim Prospect: Low-Yield Nuclear Weapons in the Middle East

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Acknowledgments

As noted in this paper's preface, the idea for this study came from previous research Thomas Cochran and Matthew McKinzie completed for the Nature Resource Defense Council. That work focused on a single American case and was not widely disseminated. This volume of research was financially supported by grants from the MacArthur Foundation, the Scaife Foundation, the Carnegie Corporation of New York, and the US Department of State's Bureau of Arms Control Verification and Compliance. Brooke Buskirk formatted and helped with the volume's editing. Finally, the paper would not have been possible without the extensive research work of the paper's author, Eva Lisowski.

Dark Future: Small Nuclear Weapons, Grotesque Effects

This study is part of a two-year project funded by the United States Department of State's Bureau of Arms Control, Verification and Compliance; The Scaife Foundation; the MacArthur Foundation; and the Carnegie Corporation of New York to determine what verifying and enforcing the Nuclear Nonproliferation Treaty (NPT) requires. It was prompted by recent public announcements by political leaders in Iran, Turkey, and Saudi Arabia that their nations might acquire nuclear weapons.[1] Such public statements are unprecedented and suggest nuclear weapons might not only spread in the Middle East, but might actually be used.

To get an idea what modifications would be useful, NPEC sought the advice of Dr. Thomas B. Cochran, former director the Nuclear Program at the Natural Resource Defense Council (NRDC). Dr. Cochran said that his NRDC colleague, Matthew G. McKinzie, using a government model no longer publicly available, found that a 1-kiloton (kt) nuclear device, if detonated at ground-level in an area with a high population density, e.g., near the Brooklyn Bridge in New York, would produce causalities comparable to those inflicted in the nuclear bombings of Hiroshima and Nagasaki. Dr. Cochran also noted he and his NRDC colleague, Christopher E. Paine in earlier work had shown that a 1-kt nuclear device could be readily made with far less fissile material than the IAEA considers "significant," and as a consequence the IAEA's safeguard standards were woefully inadequate.

To validate these findings, NPEC commissioned Eva Lisowski of MIT to see what the numbers might be using publicly available models. Her case focused on what would occur if a relatively crude, small nuclear 1-kt bomb was set off in several major Middle Eastern cities. The device was detonated at ground level to maximize radiation casualties rather than at ~1,600 feet, as the Nagasaki bomb was to maximize blast damage to buildings. Using the best available models, Ms.Lisowski determined that a 1-kt device could cause just as many, if not more, casualties than the 20-kt bomb detonated over Nagasaki at ~1,600 feet.

This is worrisome. It suggests the United States and like-minded nations should recalibrate how much diverted nuclear material international inspectors should be trying to detect. This report's findings are also relevant, if not actually timed, to the renegotiation of the 2015 Iran nuclear deal. This agreement adopted what the IAEA believes are the amounts of plutonium and highly enriched uranium needed to make a nuclear device. Set back in 1977,[2] these "significant quantities" — eight kilograms of plutonium and 25 kilograms of highly enriched uranium — are enough to make a first-generation implosion weapon with a yield not of one kiloton, but of 10 to 20 kilotons — i.e., the range of explosive energy the Hiroshima and

1. See Norah O'Donnell, "Saudi Arabia's Heir to the Throne Talks to 60 Minutes," *CBS NEWS*, March 19, 2019, available at https://www.cbsnews.com/news/saudi-crown-prince-talks-to-60-minutes/.7 ; *Reuters* Staff, "Erdogan says it's unacceptable that Turkey can't have nuclear weapons," *Reuters*, September 2019, available at https://www.reuters.com/article/us-turkey-nuclear-erdogan/erdogan-says-its-unacceptable-that-turkey-cant-have-nuclear-weapons-idUSKCN1VP2QN ; and *Al Jazeera* Staff, "Iran to quit NPT if its nuclear programme referred to UN: Zarif," *Al Jazeera*, January 2020, available at https://www.aljazeera.com/news/2020/1/20/iran-to-quit-npt-if-its-nuclear-programme-referred-to-un-zarif .
2. See Marvin Miller, "Are IAEA Safeguards on Plutonium Bulk-Handling Facilities Effective?" (Washington DC, August 1990), available at https://www.nci.org/k-m/mmsgrds.htm.

Nagasaki bombs unleashed.

These figures, however, are not just old, they are dangerously obsolete. The reason why is simple. Set the significant quantity high and the frequency of inspections needed to reliably detect a diversion of that quantity declines. Set the number low and the inspection frequency needed increases.

Critics of the IAEA safeguards system (myself included) have long argued that the IAEA's significant quantities are at least twice as large as what they should be to build a 10-20 kt device. In fact, other than South Africa, states that planned to get or actually acquired nuclear weapons historically used much more modern and efficient designs than those employed in 1945. By tying its significant quantities to outdated, inefficient 1945 weapons designs, then, the IAEA has kept the frequency of its inspections (what it calls its "timeliness detection goals") far below what would otherwise be called for to detect smaller quantities of plutonium and uranium sufficient to build more modern and more likely (e.g., hollow core and levitated pit) designs.

This is an important point. It is not one, however, that this commissioned study focuses on. Instead, for purposes of this study, Ms. Lisowski was directed to use a first-generation, 1945 implosion design. But rather than build a 20-kt device and set it off at ~1,600 feet, as the United States did in Nagasaki, this study uses a 1-kt device set off at ground level — a contingency weapons states actually plan for.[3] Ms. Lisowski's conclusion: A 1-kt devise at ground-level can easily be as lethal as the 20-kt Nagasaki weapon that was set off at ~1,600 feet.

What difference should this make? Even if a 1-kt device used a crude, 1945 implosion design, it would only need three kilograms of plutonium or eight kilograms of highly enriched uranium. Yet, the IAEA has designed its timeliness detection goals to detect not three, but eight kilograms of plutonium and not eight, but 25 kilograms of highly enriched uranium. If one uses only slightly more modern designs than the IAEA uses (i.e., ones perfected in the late 1940s), the amount of plutonium needed to make a 1-kt device drops to 1.5 kilograms and the amount of highly enriched uranium down to four. These lower figures range between less than one half to less than one fifth of the IAEA's current significant quantities and suggests just how much the IAEA should lower their own figures.

This may seem to be a radical. It is not. Late in 2016, Olli Heinonen, the former deputy director general of the IAEA for safeguards, argued that the agency should lower its significant quantity for plutonium from eight kilograms down to between two to four kilograms.[4] This study makes similar recommendations. At a minimum, if the United States and other like-minded nations are eager to avoid the prospect of destructive strikes equivalent to Nagasaki and Hiroshima, they will want to recalibrate international inspections to account for much lower significant quantities.

Henry D. Sokolski

May 2021

3. On this point, see Samuel Glasstone and Philip J. Dolan, Eds., *The Effects of Nuclear Weapons* (Washington, DC: U.S. Departments of Defense and Energy, 1977), available at https://www.dtra.mil/Portals/61/Documents/NTPR/4-Rad_Exp_Rpts/36_The_Effects_of_Nuclear_Weapons.pdf.
4. See Ollie Heinonen, "North Korea's 5th Nuclear Test — What Now?" *FDD Policy Brief,* September 17, 2016, Available at https://www.fdd.org/analysis/2016/09/16/north-koreas-5th-nuclear-test-what-now/.

An Assessment on the Effects of Low-Yield Nuclear Weapons on Five Major Middle Eastern Cities

Eva M. Lisowski

- The current ***IAEA SQ values*** are **too high** – based on outdated WWII-era implosion design and air delivery (**25 kg** U-235 in HEU / **8 kg** Pu).
- The **20-kiloton (kt) Nagasaki "Fat Man" Implosion Device** was detonated as an airburst at ~1600 feet in order to ***maximize blast effects and infrastructure damage*** (***60k – 80k*** human fatalities).
- Given a highly dense, modern, urban city center, a ***low-yield 1-kt*** nuclear weapon ***set off at ground level to maximize prompt radiation effects and nuclear fallout*** may result in death tolls in excess of Nagasaki.
- A **1-kt** nuclear weapon requires ***much less*** nuclear material (**2.5–8 kilograms, kg** HEU / **1–3 kg** Pu) than a 10-20 kt nuclear device and far less than what the IAEA significant quantities assume (**25 kg** U-235 in HEU / **8 kg** Pu).

→ ***The IAEA significant quantity values, which drive the agency's timeliness detection goals should be reevaluated and lowered significantly.***

Overview

The International Atomic Energy Agency (IAEA) was formed in 1957 to promote the peaceful use of nuclear energy and to inspect civilian nuclear materials and activities to deter military diversions. To decide the frequency of inspections and inspection criteria, the IAEA set its safeguard standards with the objective of assuring "timely detection of diversion of significant quantities of nuclear material from peaceful nuclear activities to the manufacture of nuclear weapons."[5]

The two nuclear weapon designs developed and detonated during World War II were the "gun-type" and "implosion" designs. Because implosion device technology requires much less fissile material than gun-type technology, the IAEA significant quantity[6] (SQ) values were determined based on the fissile material requirements of nuclear implosion devices like the plutonium-based "Fat Man" detonated over Nagasaki in 1945. Utilizing implosion designs perfected in the late 1940s, however, the explosive yields achieved in 1945 can be produced with much less fissile material. Table 1 lists the fissile material requirements of contemporary nuclear weapon technology. "Low Technical Capability" in Table 1 refers to the Mark III implosion device set off at Nagasaki. "Medium Technical Capability" refers to implosion designs per-

5. *Introduction to International Safeguards,* 2017, Office of Nonproliferation and Arms Control, National Nuclear Security Administration, https://www.energy.gov/sites/prod/files/2020/07/f76/Introduction%20to%20International%20Safeguards-2017.pdf.
6. Significant Quantity: The approximate amount of nuclear material for which the **possibility of manufacturing a nuclear explosive device** cannot be excluded.

fected in the late 1940s and "High Technical Capability" in Table 1 refers to the implosion technologies the United States perfected in the 1950s.

Table 1: NRDC Estimate of the Approximate Fissile Material Requirements for Pure Fission Nuclear Weapons[7]

WEAPON-GRADE PLUTONIUM (kg)				HIGHLY-ENRICHED URANIUM (kg)		
Yield	Technical Capability			Technical Capability		
(kt)	Low	Medium	High	Low	Medium	High
1	3	1.5	1	8	4	2.5
5	4	2.5	1.5	11	6	3.5
10	5	3	2	13	7	4
20	6	3.5	3	16	9	5
Values rounded to the nearest 0.5 kilogram.						

Despite advancements in nuclear weapons technology, the IAEA SQ values remain the same to this day: *8 kg of Plutonium* and *25 kg of Uranium-235 in highly-enriched uranium (HEU)*. Depending on the technical capability of the adversary, a low-yield 1-kt weapon could be produced with 1-3 kg of plutonium or 2.5-8 kg of HEU – mere fractions of the IAEA SQ values.

More important, and the focus of this paper, is how America's nuclear weapons were employed in 1945. Both the weapons dropped on Hiroshima (a 15-kt device) and Nagasaki (a 20-kt device) were set off at roughly ~1,600 feet to maximize blast effects to destroy buildings. If they had been set off at ground level, the blast effects would be far less but the prompt radiation and fallout effects would have been far greater. In fact, as this study shows, the number of casualties from a 1-kt device set off at ground level can be equal or even greater than those following the detonation of a 20-kt device at ~1,600 feet.

The table below highlights the simulated deaths resulting from 1-kt explosions in several cities in the Middle East. These figures will be further explained in the balance of the paper.

7. Cochran, Thomas B. "Adequacy of IAEA's Safeguards for Achieving Timely Detection." In *Falling Behind: International Scrutiny of the Peaceful Atom*, edited by Henry Sokolski, 121-57. N.p.: The Strategic Studies Institute Publications Office, United States Army War College.

Location	# of Deaths (high-estimate / low-estimate)
Tehran, Iran	137,000 / 55,000
Riyadh, Saudi Arabia	82,000 / 32,000
Tel Aviv, Israel	92,000 / 42,000
Cairo, Egypt	353,000 / 146,000
Dubai, United Arab Emirates	153,000 / 61,000

How might a nuclear yield of just 1 kt cause the same number of deaths as the 20-kt Nagasaki device? The nuclear attacks on Hiroshima (90k-166k deaths) and Nagasaki (60k-80k deaths) were airbursts detonated at around 1600 feet above ground level in order to maximize blast overpressure effects and infrastructure damage. However, by detonating a 1-kt weapon *at surface-level,* the prompt radiation dose and nuclear fallout effects will be maximized, resulting in higher fatalities due to radiation dose.

By simulating the detonation of a contemporary 1-kt implosion device at surface-level, this report will show that, in a highly-dense urban environment, a 1-kt weapon could produce the same or greater casualty count than the 20-kt implosion device detonated over Nagasaki. As a result, it may be desirable to recalibrate current IAEA SQ values downward.

1. Major Middle Eastern Population Centers

The effects and human casualties of a 1-kt uranium nuclear implosion device detonated at surface-level were simulated and estimated using programs and tools currently available to the general public. This analysis was performed for ground zero locations in five major Middle Eastern population centers that might be targeted in a future war. Figure 1 shows the locations of each potentially-targeted population center.

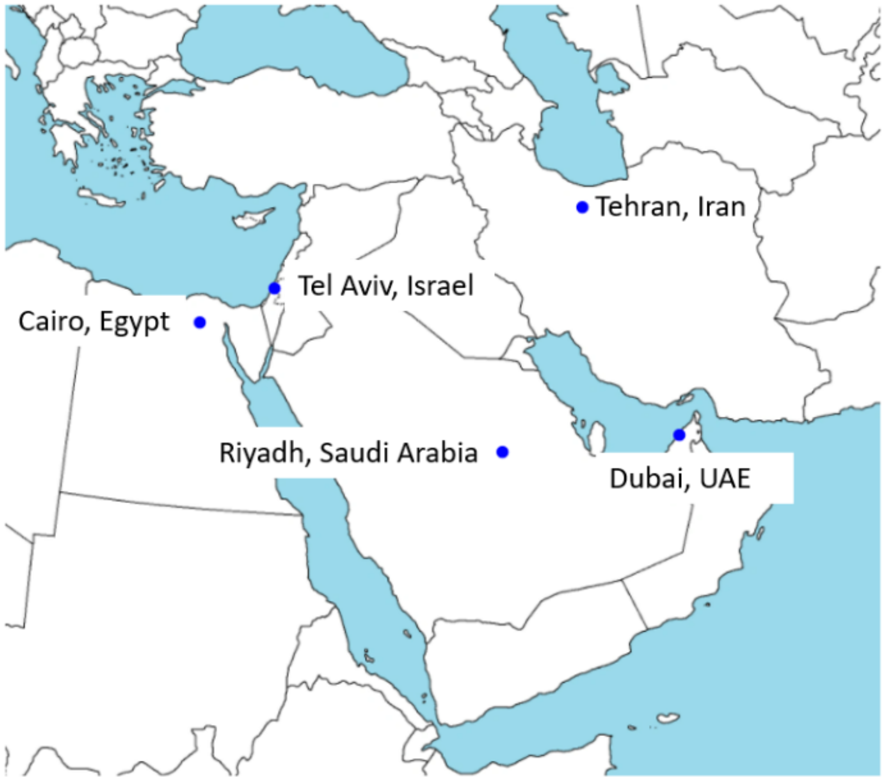


Figure 1: Five Major Population Centers in the Middle East

Each ground zero location selected is one of the most highly populated areas of the city at any given time on average.

In determining casualties, this study considered four primary effects resulting from the explosion of a nuclear weapon. Blast, thermal, and radiation injuries in combination will result in higher chance of death for victims than only sustaining one independent injury. The problem of estimating these combined effects is one of the primary difficulties when estimating nuclear weapon casualties.

2. Summary of Nuclear Weapon Effects

Blast

A publication on emergency planning and response to a nuclear detonation developed by a Federal inter-agency committee (led by National Security Staff and the Office of Science and Technology Policy) gives a detailed description of blast effects:

> Initially, blast causes the most casualties in a ground level urban nuclear explosion. Blast effects consist of overpressure and dynamic pressure waves … The human body is remarkably resistant to overpressure, particularly when compared with rigid structures such as buildings. Although many would survive the blast overpressure itself, they will not easily survive the high velocity winds, or the crushing injuries incurred during the collapse of buildings from the blast overpressure or

> the impact of high velocity shrapnel (e.g., flying debris and glass) … Blast injuries, such as lung and eardrum damage, will likely be overshadowed by injuries related to collapsing structures. Many of these will be fatal injuries [in the areas of moderate to severe building damage]. Further out, flying debris injuries will prevail … Large windows can break at blast wave pressures as low as 0.1 psi, and people will be subject to injury from the glass falling from damaged tall buildings.[8]

Peak Static Overpressure	Building Damage[9]
~0.1 – 1 psi	Buildings sustain minor damage, particularly broken windows in most residential structures.
1 – 5 psi	Most buildings sustain considerable damage, particularly on the side(s) facing the explosion.
5 – 8 psi	Buildings are severely damaged or destroyed.
>8 psi	Only heavily-reinforced buildings remain standing, but are significantly damaged and all other buildings are completed destroyed.

Thermal Radiation (Heat)

There are several features of the "thermal pulse" associated with a nuclear explosion. The portion covering the smallest physical area is the "fireball." Everything inside the fireball will be completely vaporized. Moving farther from ground zero, the thermal pulse results in a heat wave of high temperatures that will ignite flammable materials such as furniture, clothing, and skin. Other consequences of the thermal pulse include eye injuries that can occur out to many miles due to the bright flash of light.

The aforementioned Federal nuclear response publication provides further explanation:

> In general, the thermal hazard is greatest in the case of a low-altitude airburst. General thermal effects will be less for ground bursts resulting from less direct line-of-sight contact with the energy radiating from the detonation. Ground bursts result in a large part of the thermal energy being absorbed by the ground and any buildings around ground zero. Partial and sometimes complete shadowing of the thermal pulse and fireball may be provided to people inside or behind buildings and other structures. Terrain irregularities, moisture, and various aerosols (including pollution) in the air near the surface of the earth will tend to reduce the amount of thermal energy that is transported at distance … Thermalradiation emitted by a nuclear detonation causes burns in two ways; direct absorption of thermal energy through exposed surfaces (flash burns) or indirectly from fires ignited by the burst. Tall city buildings between people and the fireball provide substantial shadowing from the burst and reduce the overall flash burn impact. However, people within line of sight of the burst may be subject to burn injuries miles away.[4]

8. *Planning Guidance for Response to a Nuclear Detonation, 2nd Edition,* June 2010, Developed by the National Security Staff Interagency Policy Coordination Subcommittee for Preparedness & Response to Radiological and Nuclear Threats.
9. *Planning Guidance for Response to a Nuclear Detonation*, 2nd Edition, June 2010, Developed by the National Security Staff Interagency Policy Coordination Subcommittee for Preparedness & Response to Radiological and Nuclear Threats.

Prompt Radiation

Again, an explanation of this nuclear effect can be found in the Federal publication on guidance for response to a nuclear detonation:

> Prompt radiation … occurs nearly instantaneously with the flash. The intensity of initial nuclear radiation decreases with distance from ground zero. This decrease is a result of the radial dispersion of radiation as it travels away from the point of detonation and the absorption, scattering, and capture of radiation by the atmosphere and buildings. Buildings help to block the direct path of initial radiation; however, even if an individual is shielded behind buildings, reflected radiation off the atmosphere can still deliver a dose at levels that could make people sick or, if the shielding is not thick enough, possibly lead to death some weeks or months after the explosion. In an urban area, it is expected that those close enough to receive a lethal dose from initial radiation are likely to receive fatal injuries from other mechanisms of the blast. Moreover, sub-lethal doses of radiation also can induce acute health effects.[10]

Nuclear Fallout

Finally, the Federal interagency publication elaborates on nuclear fallout:

> Fallout is a major source of residual radiation hazard. During the fission process, radionuclides, called *fission products*, are created. Radionuclides emit dangerous gamma and beta radiation. After the explosion, these radionuclides attach to airborne particles of varying sizes to form fallout. If the detonation occurs near the earth's surface, fallout can be especially prevalent as the shock wave crushes and loosens thousands of tons of earth and urban infrastructure (e.g., buildings, roads, concrete) that can become caught in the fireball. Some of this material will be vaporized by the intense heat of the fireball, some will be partially melted, and some will remain essentially unchanged, but all of it becomes fallout.
>
> As the fallout cloud rises, winds transport radioactive particles from the cloud and carry fallout over significant distances downwind. The fallout pattern will be irregular; rarely does it form easily predictable deposition patterns. Winds of varying speed and direction at different levels of lower and upper atmosphere push the fireball and the descending fallout material in directions that may not be evident from ground-level observation.[11]

Biological Effects of Radiation Dose

Table 2 summarizes several biological effects of radiation dose to the human body. This table includes acute effects only, and does not detail increased cancer risk.

10. Ibid.
11. Ibid.

Table 2: Summary of Clinical Effects of Acute Ionizing Radiation Doses[12]

Dose (rem)	0 – 100	100 – 200	200 – 600	600 – 1,000	> 1000
Characteristic Signs	None below 50 rem	Moderate leukopenia	Severe leukopenia; purpura; hemorrhage; infection. Epilation above 300 rem.		Diarrhea; fever; Electrolyte imbalance
Incidence of Death	None	None	0 – 90%	90 – 100%	100%
Death occurs within	–	–	2 to 12 weeks	1 to 6 weeks	2 to 14 days
Cause of Death	–	–	Hemorrhage; Infection		Circulatory collapse

Leukopenia: Reduction in white blood cell count; increases likelihood of infection, which can cause radiation doses of 200 – 600 rem to become lethal when paired with burns and physical injuries

Purpura: Hemorrhage beneath the skin

Hemorrhage: Bleeding, especially profuse blood loss

Epilation: Hair loss

Electrolyte Imbalance: Severe cases can cause coma, seizures, and cardiac arrest

For both prompt radiation dose and nuclear fallout dose, the greatest cause of death is not that the doses acquired will be instantaneously lethal, but that they will oftentimes be high enough to make recovery from mechanical (blast) injuries and burn injuries very unlikely due to infection and effects to the body's circulatory and immune systems.

Increased cancer risk (particularly leukemia) is a significant cause of death to individuals who have experienced at least 50 rem of acute radiation dose, and the U.S.NRC has recognized a definitive increased cancer risk for individuals who have acquired doses of at least 10 rem.

3. Effects of a 1-kt Surface-Burst in Five Middle Eastern Population Centers

3.1 Prompt Detonation Effects and Casualties

The geographical area around ground zero (Figure 2) was surveyed in *Google Earth* to acquire an understanding of the types and density of buildings in the area. The extent of structural damage due to a 1-kt weapon was mapped and analyzed in order to consider the consequences of mechanical damage to a population (blast injuries). Although the geographical survey and structural damage maps were analyzed for each city, for the sake of brevity, the results of such analyses are only included for Tehran, Iran to demonstrate how this analysis was performed. The results depicted are for a uranium implosion device, but the results would be nearly identical in the case of a plutonium implosion weapon.

12. Glasstone, S, and Dolan, P J. Sat. "The Effects of Nuclear Weapons. Third edition". United States. https://doi.org/10.2172/6852629. https://www.osti.gov/servlets/purl/6852629 (p. 580-581).

Structural Damage: Tehran, Iran

The city of Tehran is extremely dense and over-populated, especially during daytime work hours. Tehran's air pollution contributes to its unhealthy air quality, and the city has dense urban and residential structures, and is bordered to the northeast by a mountain range. The architecture in the local area consists largely of brick veneer and concrete two-floor and three-floor apartment and business buildings, including buildings with large glass fronts. There are several wide-area parks and parking lots as well.

Factors such as urban pollution, building density and material type, population density, and local geography are important in determining the effects of a nuclear weapon in an urban environment.

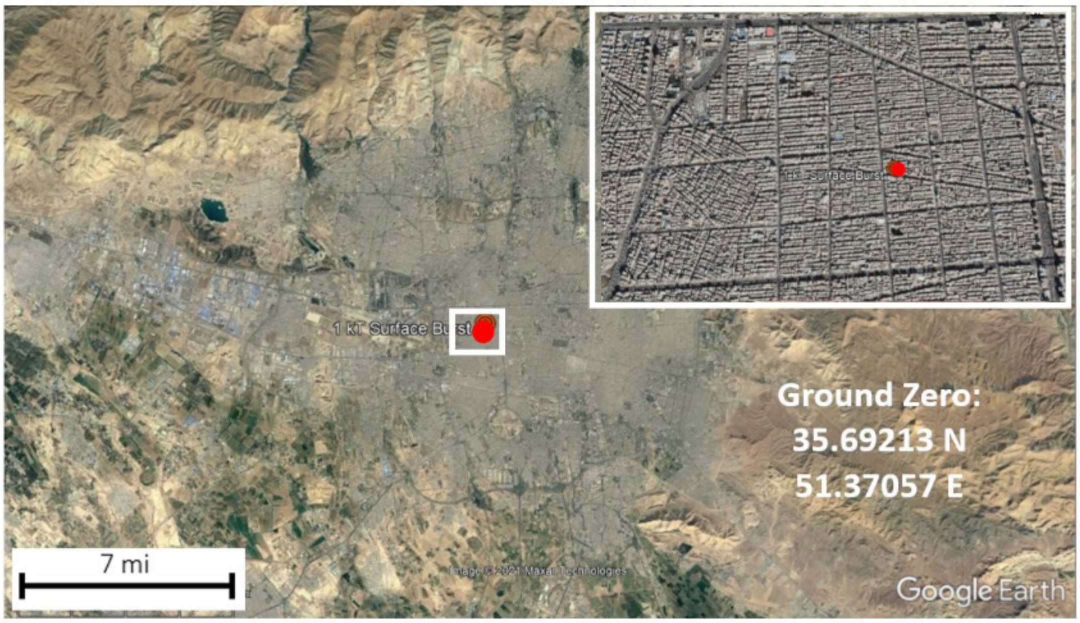


Figure 2: Google Earth Imagery of the Area around Ground Zero in Tehran, Iran

The rings overlaid on the satellite imagery of Tehran in Figure 3 depict the approximate extent to which structural damage would occur. Structural damage zones were determined by calculating blast overpressure at various distances using a weapons effects program published in 1984 by Horizons Technology, Inc.,[13] and a nuclear attack response pamphlet published by the U.S. government.[14]

13. "Weapon Effects," 1984, Horizons Technology, Inc.
14. *Planning Guidance for Response to a Nuclear Detonation,* June 2010.

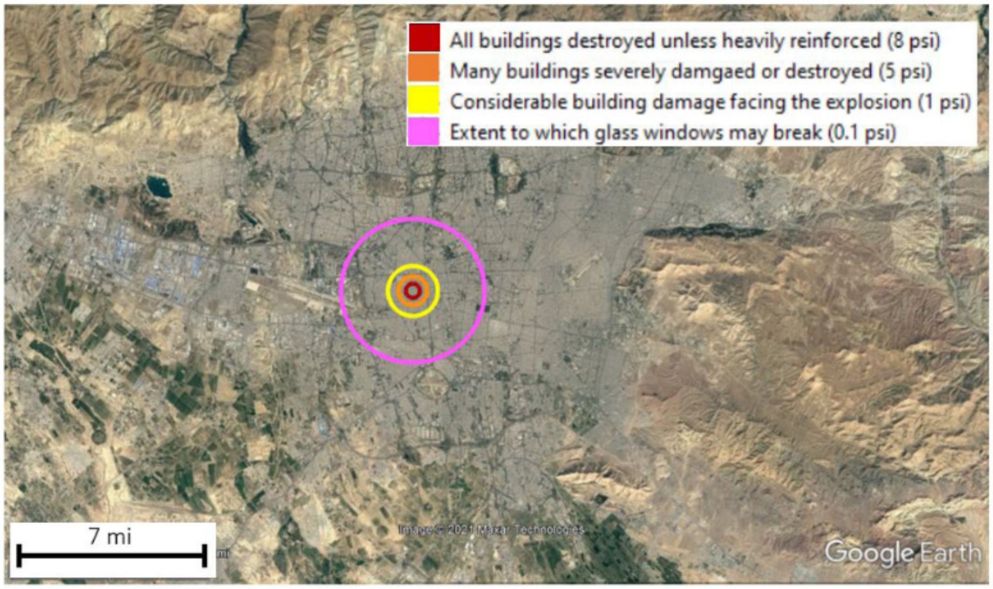


Figure 3: Structural Damage due to a 1-kt Surface-Burst in Tehran, Iran

Prompt Casualties

The numbers of dead and injured due to prompt nuclear weapons effects in high-end-estimate[8] and low-end-estimate[9] simulations are shown in Table 3 for each city. These numbers include those who will die of radiation dose and infection up to twelve weeks following the explosion.

It is important to note that the prompt casualty estimates listed below are the results of prompt effects only. This means the casualties are a result of blast overpressure (including building damage and glass injuries), thermal burns, and prompt radiation dose effects. Radiation dose effects due to nuclear fallout are neglected here and, as will be shown later, fallout dose effects can cause a dramatic increase in potential casualties depending on weather conditions.

Table 3: Casualty Estimation due to 1-kt Surface-Burst Prompt Effects Only

	Deaths	Injuries	Total
			Tehran, Iran
Outdoors or Unshielded[15]	137,000	49,000	186,000
Indoors or Shielded[16] **by Highly-Dense Urban Area**	55,000	58,000	113,000
			Riyadh, Saudi Arabia
Outdoors or Unshielded	82,000	31,000	112,000[17]
Indoors or Shielded by Highly-Dense Urban Area	32,000	35,000	67,000
			Tel Aviv, Israel
Outdoors or Unshielded	92,000	31,000	123,000
Indoors or Shielded by Highly-Dense Urban Area	42,000	36,000	79,000
			Cairo, Egypt
Outdoors or Unshielded	353,000	103,000	455,000
Indoors or Shielded by Highly-Dense Urban Area	146,000	147,000	293,000
			Dubai, UAE
Outdoors or Unshielded	153,000	51,000	205,000
Indoors or Shielded by Highly-Dense Urban Area	61,000	65,000	126,000

Two separate simulations were run for each city representing upper and lower bound estimates of the possible resulting casualties. The purpose of separately simulating (1) unshielded and (2) fully-shielded populations was to address the difficulty of estimating exactly how many people will be indoors or outdoors at any given time. Although it is unlikely that the entire population would ever be outdoors and unshielded, this case is accepted as an upper casualty limit since a realistic upper limit is impossible to determine with a high degree of accuracy. This practice is common in nuclear weapon casualty analyses. On the other hand, there will be some people shielded and some in the open driving, walking in open areas, sitting near

15. This simulation assumes the entire population was outdoors and unshielded, with a neutron RBE of 3.
16. This simulation assumes for the entire population that each individual was shielded by 24-in. concrete at his/her respective distance from ground zero, and with a neutron Relative Biological Effectiveness (RBE) of 1. This approximates a dense urban environment with many buildings in between the individual and ground zero.
17. Addition of rounded numbers may not equal the rounded total casualty count.

windows within direct line-of-sight of the detonation, etc. Thus, a lower limit is approximated as an absolute lower limit is impossible determine given hundreds of factors that affect lethality, such as weather, clothing, body orientation, reaction time, etc.

Potential Deaths Caused by Nuclear Fallout

For a 1-kt surface-level nuclear explosion, the radiation dose to the population due to nuclear fallout can be negligible or has the potential to *greatly increase* the casualty count, highly depending on the weather conditions immediately following the detonation. Nuclear fallout simulations are elaborated upon in Section 3.2. The goal of this section is to highlight the key conclusions that can be made from the simulations in Section 3.2.

Extreme Fallout Case: Dubai, UAE on December 1st, 2020 at 0800 GST

Two calculations were performed to acquire high and low estimates of the effects of cumulative radiation dose on death of the population. The results are shown in Table 4. Compare this Table to the results for Dubai in Table 3.

Table 4: Cumulative Radiation Dose Casualty Estimation – Extreme Case

Dubai, UAE	Deaths	Injuries	Total
Outdoors or Unshielded[1]	153,000	51,000	205,000
Indoors or Shielded by Highly-Dense Urban Area	61,000[1]	65,000	126,000
	200,000[2]	**104,000**	**304,000**
	371,000[3]	**176,000**	**546,000**

[1]Casualties due to Prompt Effects **only**
[2]**Low estimate** of Casualties due to **Prompt AND Fallout** Cumulative Radiation Dose
[3]**High estimate** of Casualties due to **Prompt AND Fallout** Cumulative Radiation Dose

In an extreme nuclear fallout case, such as when the wind speed is low or there is heavy precipitation, the dose to the local population can be quite high. In this simulation, the maximum possible radiation dose due to *nuclear fallout alone* was 735 rem. The danger of increased dose due to nuclear fallout is that injuries due to falling structures, glass, or burn injuries will be much more devastating to the human body, greatly decreasing chance of survival.

Figure 4 shows a 24-hr fallout radiation dose map of the area around Dubai, UAE that highlights the fallout doses that can cause a significant increase in the number of deaths resulting from the attack. Realistically, most of the dose acquired will be within the first two hours following the detonation, due to the nature of rapid radioactive decay.

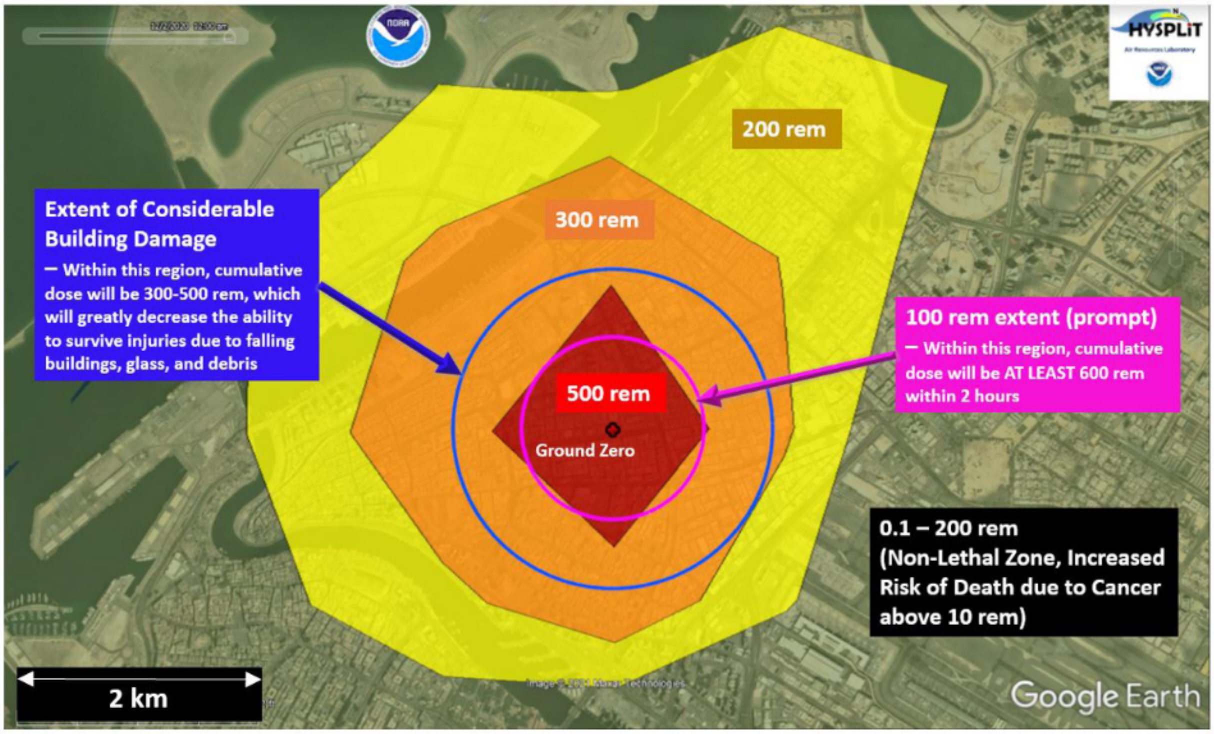


Figure 4: Overlap of Prompt Effects and Nuclear Fallout Dose Contributing to Lethality

Since weather patterns are highly variable, this "extreme case" simulation for Dubai should not be viewed as being the most probable case. It is an extreme example of what could be possible if there is little to no wind. Finding the most probable case would require many more simulations and a major additional research effort that would entail modeling and analysis beyond the scope of this study.

Negligible Fallout Case: Tel Aviv, Israel on March 1st, 2020 at 0800 IDT

Figure 5 depicts the fallout dose map of a case where the fallout is negligible to the death count (again neglecting risk of cancer). The effect of fallout is minimized when the wind speed is high and direction is consistent. In this simulation, the maximum possible radiation dose due to nuclear fallout alone was only 106 rem. Due to high wind speeds, the radioactive material is almost immediately scattered to the southeast. The greatest concentration of fallout material is actually deposited some distance away from ground zero.

In this situation, radiation dose due to nuclear fallout will have almost zero effect on the casualty count.

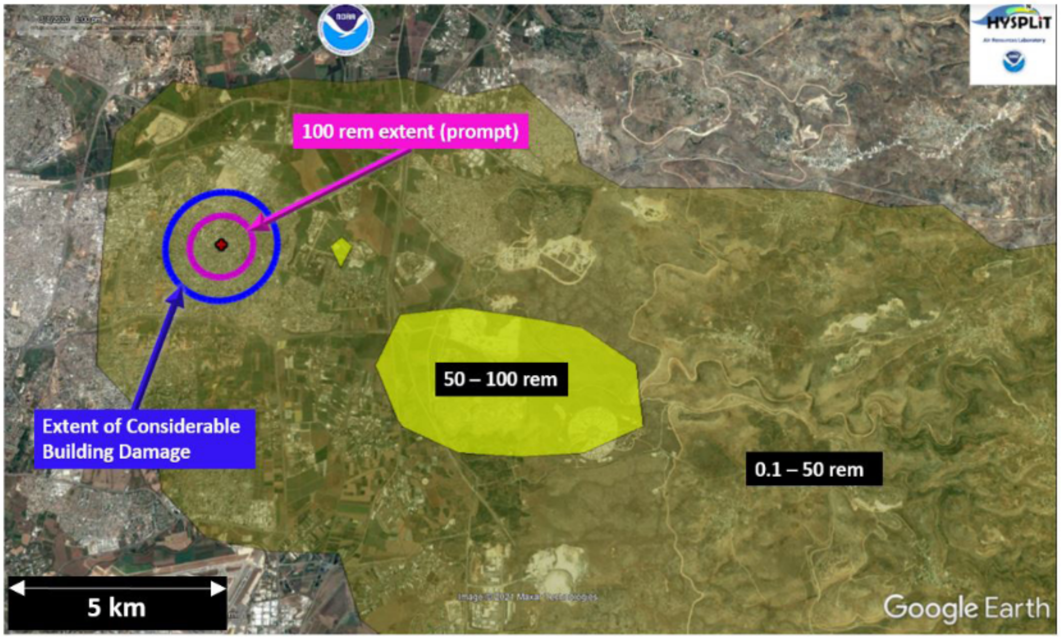


Figure 5: Example of a Negligible Nuclear Fallout Situation

Due to the highly-variable nature of weather effects, particularly precipitation, wind speed, and direction, the possibility of an unpredicted but devastatingly-high death toll due to the fallout caused by a low-yield, surface-level nuclear explosion is possible.

3.2 Nuclear Fallout Effects and Casualties

The resulting nuclear fallout and radiation dose to affected populations was simulated for each city to observe how fallout and dose can vary depending on season and time of day. Different combinations of these variables were selected for each city. Consistency between locations does not matter because the purpose of this study is to get a general sense of how weather variations can have drastically varying effects on fallout extent and radiation dose. For a more in-depth understanding of weather patterns and fallout effects in each location, many more simulations would need to be performed and analyzed. The following set of images, however, serve to show how wind speed and direction can affect a staggeringly high number of people in various ways, and either minimize or greatly increase the casualties caused by a nuclear attack.

Radiation Dose to Populations Due to Nuclear Fallout

The results of four scenarios are included for Dubai, UAE in the following section. The nuclear fallout simulations for the other four cities are included in an Appendix (available on request), for the sake of brevity. Each 24-hr Total Effective Dose Equivalent (TEDE) map shows the cumulative radiation dose acquired by a person remaining in the colored area for 24 hours following the detonation, based on real historical weather data, due to nuclear fallout only. Due to the rapid nature of radioactive decay, most of the 24-hr dose was actually acquired within the first two hours.

(1) The affected population table summarizes the results of the four simulations for each city, listing the minimum and maximum number of people affected by each dose, and the average over all simulations for that location.

(2) The first map (centered) for each location depicts the worst-case scenario out of the four simulations, zoomed-in to visualize the overlap of nuclear fallout with prompt detonation effects. As shown in Section 3.1, this overlap of prompt radiation dose with fallout dose may *greatly increase* the death toll of the attack.

(3) For each simulated detonation time, the first map (on the left) depicts a 24-hour TEDE map centering on the city, to show the extent of each radiation dose level throughout the densely-populated city center. The width of this map is roughly 50 miles.

(4) The second map for each simulation (on the right) depicts the same fallout extent but zoomed out to illustrate the overall extent of the fallout deposition within 24 hours following the detonation. The width of this map is roughly 250 miles.

Figure 6 shows a breakdown of the biological effects below 100 rem alongside the corresponding colors depicted on fallout dose maps.

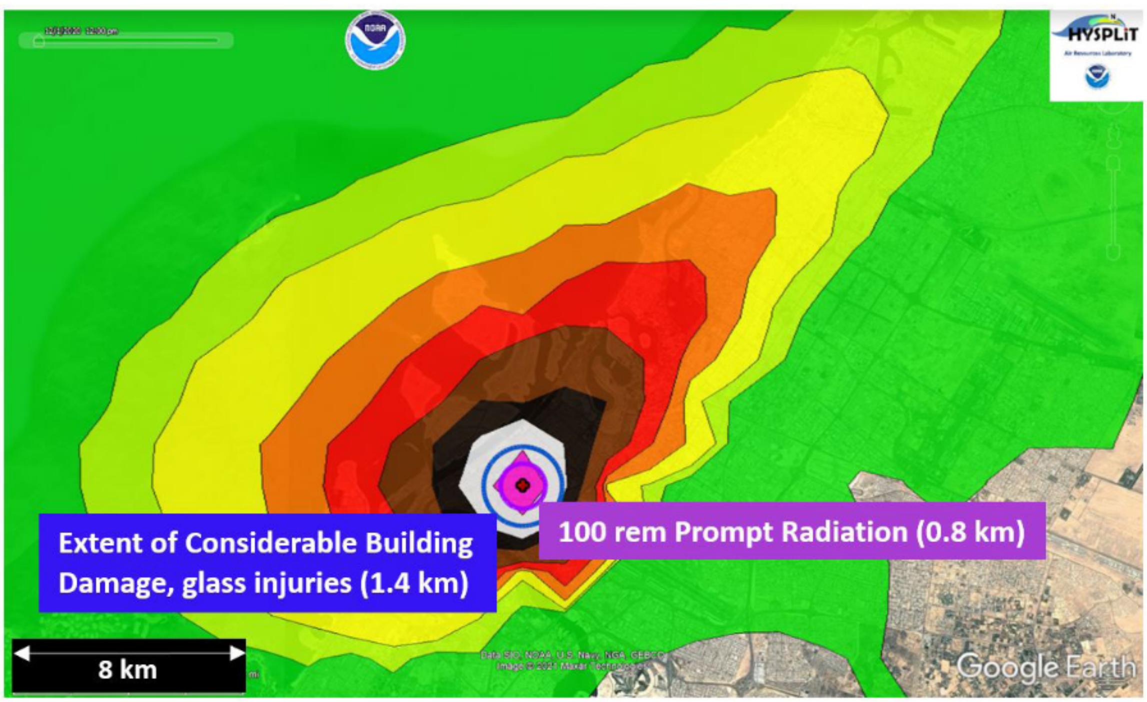
0.1	Annual Dose **Limit for Individual Members of the Public** due to USNRC-licensed operation of nuclear facilities
5	Annual Dose **Limit for Radiation Workers** (USNRC)
10	Definitive increased **risk of cancer** in lifetime
25	Temporary Sterility in Men
50	Considered a **large radiation dose** by the USNRC
100	Mild **radiation sickness**, Nausea, Reddening of skin

Figure 6: Biological Effects of Radiation Dose Below 100 rem

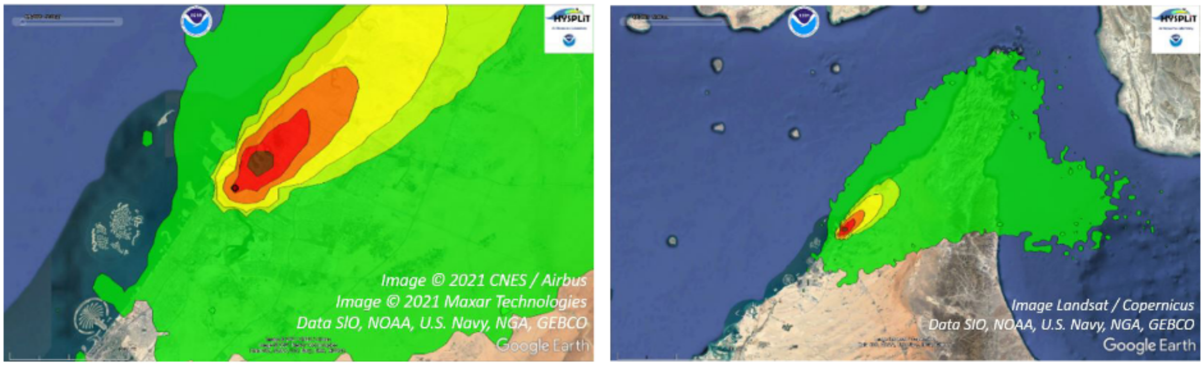
Dubai, United Arab Emirates

Dubai, UAE: 24-hr Total Effective Dose Equivalent

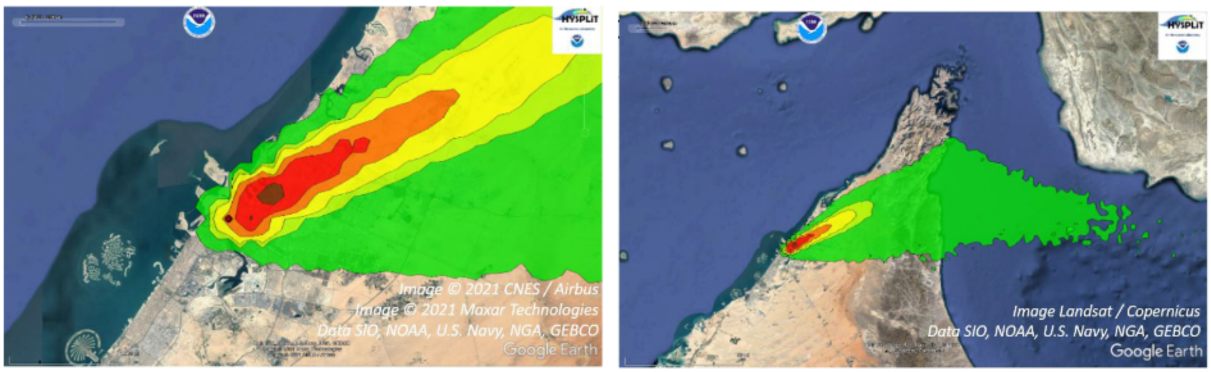
	Dose (rem)	Affected Population		
		Minimum	Maximum	Average
	0.1	5,200	2,900,000	1,700,000
	5	150,000	380,000	250,000
	10	530,000	830,000	700,000
	25	480,000	1,300,000	770,000
	50	190,000	780,000	540,000
	100	85,000	300,000	150,000
	200	0	140,000	59,000
	300	0	480,000	190,000
	500	0	200,000	69,000



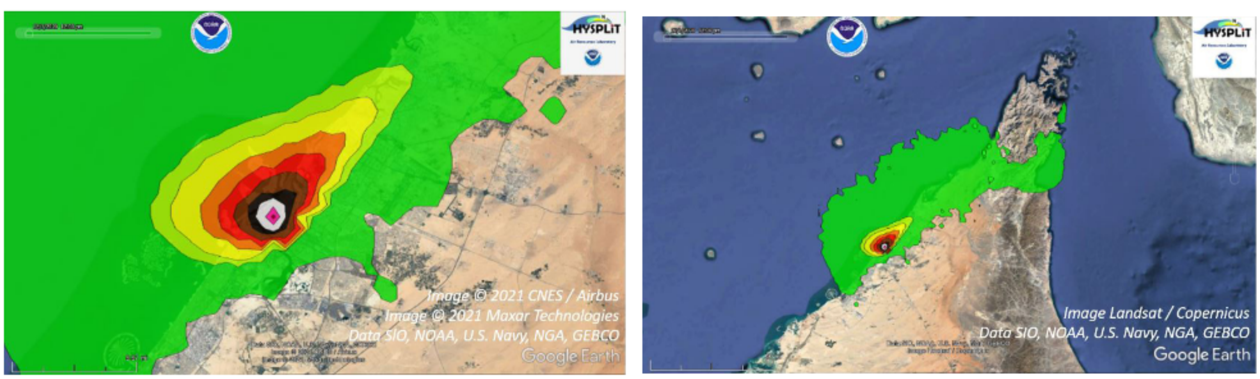
June 1st, 2020 @ 0800 GST



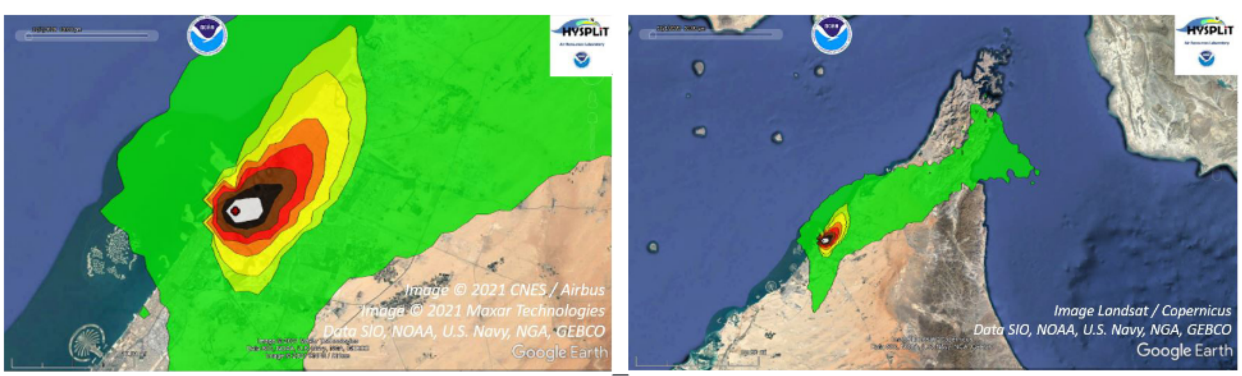
June 1st, 2020 @ 1800 GST



December 1st, 2020 @ 0800 GST



December 1st, 2020 @ 1800 GST



4. Conclusion

Even though 1 kt is considered low-yield by nuclear weapon standards, we should be concerned about the construction and detonation of these weapons. Simulations of 1-kt surface-level nuclear detonations in Middle Eastern cities show that the death and injury tolls on highly-dense modern-day populations can be *equal to or greater than* the casualties at Hiroshima (90,000-166,000 deaths) and Nagasaki (60,000-80,000 deaths). Furthermore, depending on the weather, radiation dose to the population due to nuclear fallout may greatly increase the casualty count. This is due to nuclear fallout being more deadly following detonations at or near surface-level.

These findings have implications on the requirements of effective nuclear material inspections. The current IAEA SQ values of 8 kg of Pu or 25 kg of U-235 in HEU seem far too high to support the timely detection of nuclear diversions to make nuclear weapons that can cause hundreds of thousands of deaths. The IAEA, however, uses these high SQ figures to set their timeliness detection goals. These, in turn, affect the timeline and frequency of IAEA inspections used to verify the NPT and the US-Iran Joint Comprehensive Plan of Action (JCPOA). However, for a 1-kt weapon, as little as 1-3 kg of Pu or 2.5-8 kg of U-235 in HEU is required. This means that the frequency of routine IAEA inspections may be insufficient to detect diversions of nuclear material for weapons with yields as low as 1 kt.

This suggests the IAEA reevaluate its significant quantity values and decreasing them to values that better reflect the fissile material requirements of weapons with much lower yields than are currently assumed to bound the agency's minimal concern.

Appendix: Simulation Methodology

The following programs and data sources were used to simulate and estimate the effects of a 1-kt uranium implosion nuclear device detonated at or near the surface.

Google Earth: Visualization of Population Centers and Ground Zero geographic areas; Visualization of the extent of prompt weapon effects and fallout.

HotSpot Health Physics Codes[18]: Calculation of the Prompt effects of a nuclear surface-burst and the lethality and injury thresholds associated with each effect.

"Weapon Effects" and "Blast Effects" programs (1984): Calculation of Prompt Effects based on distance from ground zero in supplement to *HotSpot.*

QGIS: Geographic Information System mapping software used to process and rescale population data; Used to calculate the population size affected within each fallout contour.

LandScan™ Global 2019[19]: Population data at ~1km spatial resolution, representing an "ambient" population distribution (average over 24 hours).

Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) Model[20]: Used to compute fallout particle deposition and accumulated radiation dose in the geographic area around each city, following stabilization and dispersion of the nuclear mushroom cloud, which was modeled based on the HYSPLIT Extended Tutorial "Simulate Smoky Nuclear Test."[21]

Pre-existing Nuclear Weapon Detonation Simulation Methodologies

Although there exist more recent and accurate nuclear weapons effects calculation programs and fallout simulators, these programs (such as HPAC and DELFIC) have become government-classified and no longer accessible by the general public. Furthermore, all the tools used here are completely free to acquire and use, given the wherewithal to learn HYSPLIT and basic knowledge of the Python programming language. Affiliation with a research or corporate organization may facilitate the acquisition of some files and resources.

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18. HotSpot Version 3.1.2 © 2013. Lawrence Livermore National Security, LLC. All rights reserved.
19. Amy N. Rose, Jacob J. McKee, Kelly M. Sims, Edward A. Bright, Andrew E. Reith, and Marie L. Urban, *LandScan 2019*, 2019 (July 1st, 2020), distributed by Oak Ridge National Laboratory, https://landscan.ornl.gov/.
20. *Stein, A.F., Draxler, R.R, Rolph, G.D., Stunder, B.J.B., Cohen, M.D., and Ngan, F., (2015). NOAA's HYSPLIT atmospheric transport and dispersion modeling system, Bull. Amer. Meteor. Soc.,* ***96****, 2059-2077,* http://dx.doi.org/10.1175/BAMS-D-14-00110.1.
Rolph, G., Stein, A., and Stunder, B., (2017). Real-time Environmental Applications and Display System: READY. Environmental Modelling & Software, ***95****, 210-228,* https://doi.org/10.1016/j.envsoft.2017.06.025. (http://www.sciencedirect.com/science/article/pii/S1364815217302360).
21. G.D. Rolph, F. Ngan, R.R. Draxler, Modeling the fallout from stabilized nuclear clouds using the HYSPLIT atmospheric dispersion model, Journal of Environmental Radioactivity, Volume 136, 2014, Pages 41-55, ISSN 0265-931X, https://doi.org/10.1016/j.jenvrad.2014.05.006.

On the other hand, there exist several websites and "games" that can be used to easily visualize and quickly estimate the results of a hypothetical nuclear detonation. Several of these were utilized during the research process and the results were compared. Though these tools are much faster and easier to use, the methodology developed in this study allows the user to (1) understand the underlying process behind estimating weapon effects and (2) more easily customize the assumptions made in the calculation.

Prompt Casualty Calculation Method

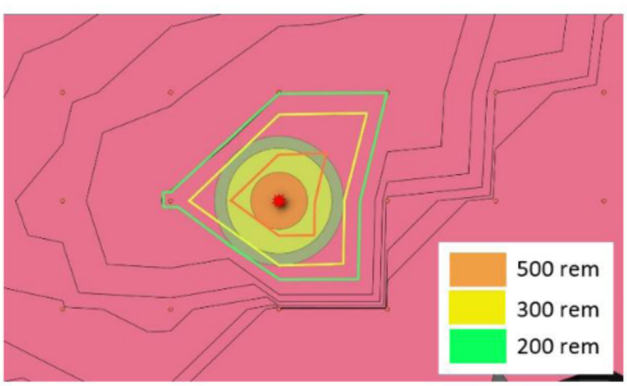
Casualties as a result of a low-yield nuclear surface-level detonation will be caused primarily by weapon effects that occur within the first minute following the detonation, even if death does not occur until weeks later. Regardless of whether the victim succumbed to wounds instantly or within months following the detonation, these casualties are included in the prompt casualty calculation.

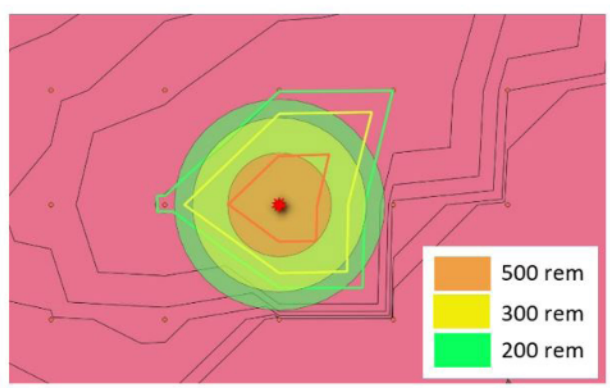
Due to the complex nature of nuclear weapon effects, any attempt to estimate prompt casualties in an urban environment quickly becomes convoluted and highly prone to error. Utilizing the *HotSpot* and *Weapon Effects (1984)* programs, along with information in the afore-mentioned U.S. government response planning pamphlet and *Effects of Nuclear Weapons* (Glasstone and Dolan), a casualty-calculation model estimating the quantitative survival rate based on distance from ground zero was developed and coded in Python. A 12-mile visibility was assumed for all cases, and a neutron Relative Biological Effectiveness (RBE) of either 1 or 3 was assumed in each trial run to approximate a range of urban shielding possibilities.

It is fairly standard in nuclear casualty simulations to neglect urban shielding, which leads to an overestimate of casualties, since urban environments will provide shielding to the population. The field of research investigating the effects of urban shielding includes a wide variety of methodologies without a standardly-accepted method. The method in this report is a simple approximation, but not unreasonable. Future research work in this area could develop a more precise methodology for estimating the shielding effects due to pollution, building material, building height & density, and other urban characteristics.

Method to Calculate the Casualties due to Cumulative Prompt & Fallout Radiation Dose

For two of the HSYPLIT simulations, one extreme case and one negligible case, the casualty count that would result from a combination of prompt and fallout radiation effects was estimated. For the extreme case in which fallout radiation dose will greatly increase the numbers of dead and injured, high and low estimates were made by approximating the fallout dose extents as circles, as shown in the screenshots of *QGIS* contours below.





The circular approximation was used to facilitate incorporation of fallout dose effects into the prompt casualty Python code, which relies on the definition of various effects at different radii from ground zero. The low estimate (left) assumes a radius of minimum distance from ground zero, and the high estimate (right) attempts to draw circles that more closely match the area of the corresponding contour.

Nuclear Fallout Dispersion Simulation Method

The extent and direction of the radioactive fallout following a nuclear detonation will greatly vary based on the season, wind speech and direction, geography, weapon yield, and other factors. For this project, the fallout deposition pattern and radiological dose to the population was simulated using historical weather data for March 1st, June 1st, September 1st, and December 1st, 2020 for a nuclear blast detonated at 0800 or 1800. In order to develop an understanding of which fallout patterns would be the most likely for each city, more detonation times and dates would need to be simulated, and HYSPLIT settings fine-tuned – a research process that is beyond the scope of this project but could be explored in a future research project.

The HYSPLIT program makes several assumptions and simplifications when converting radioactive particle concentration to dose and dose rate. In particular, HYSPLIT does not accurately consider the decay of fission products into daughter nuclides, which each have their own type of decay. Since different types of decay contribute differently to biological radiation dose in REM, the calculation process shown here is an oversimplification of the actual dose that would accumulate as a result of the explosion. Improving the use of HYSPLIT for dose calculation is reserved for future work or future iterations of this project.

Acknowledgments

The author gratefully acknowledges Dr. Thomas Cochran and Christopher Paine for their contributions to the nuclear nonproliferation field and their 1995 publication entitled *The Amount of Fissile Material Required to Make a Pure Fission Weapon,*[22] in which the original ideas that inspired this study were conceived. I also want to thank Dr. Matthew McKinzie and Dr. Thomas Cochran for their work on simulating 1-kt nuclear weapons, and advising and providing feedback on the methodology development throughout the research process.

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22. Cochran, Thomas B., and Christopher E. Paine. *The Amount of Plutonium and Highly-Enriched Uranium Needed for Pure Fission Nuclear Weapons*. Washington, D.C.: Natural Resources Defense Council, Inc., 1995.

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Eva M. Lisowski is a member of the Nuclear Weapons Education Project at the Massachusetts Institute of Technology, from where she graduated in 2020 with a B.S. in Nuclear Science & Engineering. Her prior research publications and papers include evaluations of the attractiveness of fissile materials in advanced nuclear reactors to WMD-construction, and analysis of fissile material production in India following the U.S.-India Civil Nuclear Agreement. Currently, her work focuses on simulating the consequences of nuclear weapon detonations and missile strikes targeting civilian nuclear reactors. As a young member of the American Nuclear Society and 2019 Summer Fellow at the United States Nuclear Industry Council, Ms. Lisowski has participated in nuclear energy advocacy at the Massachusetts State House and on Capitol Hill in Washington D.C. Ms. Lisowski has previously studied and conducted research at the Tokyo Institute of Technology and hopes to contribute to nuclear security and non-proliferation by strengthening U.S.-Japan research collaboration. She will be attending graduate school overseas beginning September 2021 to pursue a Master's degree in Nuclear Science & Engineering.

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