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Reconsideration of Significant Quantity (SQ) for Pu Based on the Strategic Impact Investigation of Non-Strategic Nuclear Weapon (NSNW) Using Monte-Carlo Simulations

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The present multidisciplinary study, which is a nexus of engineering and political science, investigates how the modernization of Non-Strategic Nuclear Weapons (NSNWs) affects the IAEA safeguards system based on the likelihood of the use of nuclear weapons. To this end, this study examines the characteristics of modernized NSNWs using Monte Carlo techniques. The results thus obtained show that 10 kt NSNWs with a Circular Error Probability (CEP) of 10 m can destroy the target as effectively as a 500 kt weapon with a CEP of 100 m. The IAEA safeguards system shows that the Significant Quantity (SQ) of 1 of plutonium is 8 kg, a parameter that was established when strategic nuclear weapons were dominant. However, the results of this study indicate that in recent years, low-yield nuclear weapons such as NSNWs have been more strategically interesting than strategic nuclear weapons as NSNWs require less plutonium than strategic nuclear weapons. Therefore, we would like to conclude that reducing the SQ of plutonium can result in more robust safeguards and non-proliferation strategies.

Keywords: Non-strategic nuclear weapon, Low-yield nuclear weapon, Monte Carlo simulation, Nuclear Safeguards, Significant quantity, Plutonium

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1. Introduction

According to the International Atomic Energy Agency (IAEA) safeguards, the significant quantity (SQ) of plutonium is 8 kg. That criterion has been used for a long time. In the past, the yield of strategic nuclear weapons was hundreds of kT or even more. However, modernized non-strategic nuclear weapons (NSNWs), which are low-yield nuclear-tipped warheads mounted on high-precision cruises or ballistic missiles become more interesting. Intuitively, the NSNWs require less plutonium than strategic nuclear weapons. For example, a yield of 1 kT can be achieved by 1–3 kg of plutonium [1]. Therefore, in this study, we would like to discuss the necessity of changing the SQ values based on the investigation of the strategic impact of NSNW using Monte-Carlo Simulations.

The world is facing a new nuclear arms race involving NSNWs [2]. Although concerns regarding the existing arms control architecture mount, a number of states worldwide appear to be adding low-yield, high-precision NSNWs to their arsenals rather than subtracting [3]. Since nuclear weapons are often discussed as having indiscriminate and disproportionate effects, the consequences of this development for strategic stability remain unclear.

NSNWs are not new. From the early days of the Cold War, major nuclear states, such as the U.S. and Russia (and, reportedly, from the 1980s onward China, too), have pursued the development of NSNWs so as to offset each other's conventional forces. Yet, as these major nuclear states continue to modernize their nuclear forces, technological improvements are rendering NSNWs more effective in relation to strategic missions. In theory, the more robust and credible that their nuclear forces are, the stronger the deterrent effects that nuclear states will have. However, it is also possible that technological advances in positioning systems, delivery vehicles, and aircraft will render low-yield NSNWs more usable as well as more credible in certain regional conflict scenarios, thereby lowering the threshold for nuclear use and potentially endangering strategic stability.

Facing divided expectations, the lack of empirical data about the technical capacity of NSNW is a salient problem for investigating its impact on international stability. In such situations, the present multidisciplinary study of engineering and political science investigates how NSNWs, due to their having reduced destructive power and enhanced accuracy, would impact on the likelihood of the use of such weapons. For this, the Monte Carlo approach is applied to analyze the strategic and relative effectiveness of nuclear weapons as a function of yield and a circular error probability (CEP). Various previous studies have shown the effectiveness and efficiency of NSNWs. However, most studies have not been conducted in a quantitative manner. Therefore, in this study, we generate quantitative values for comparing the effectiveness of NSNWs with conventional nuclear weapons using the Monte Carlo simulation. Based on this simulation result, the necessity of chaning SQ for plutonium is discussed.

2. Non-strategic Nuclear Weapons: Overview

2.1 What are non-strategic Nuclear Weapons?

There is currently no consensus as to the exact definition of non-strategic nuclear weapons (NSNWs), which are also known as mini-nukes or tactical nuclear weapons. Thus far, the distinction made between strategic and non-strategic nuclear weapons has reflected the military definition, or the arms control definition, or both [4, 5]. From a military standpoint, the key criterion is the observable capabilities of weapons. Strategic nuclear weapons are tipped with high-yield nuclear warheads, and they have a range of thousands of kilometers, which is sufficient to reach and destroy "strategic targets" located in an adversary's territory. Such strategic targets include those targets connected to an adversary's war-making capacity, for example, key manufacturing systems, critical materials, power systems, transportation systems, and communication facilities. In contrast, NSNWs, which are armed with lower-yield warheads and carried by shorter-range means of delivery, are designed to destroy targets on the battlefield or to support more limited and tactical missions.

For arms control experts, the exclusion from strategic arms control treaties, such as the new Strategic Arms Reduction Treaty (START), has become a more important means of distinction. For instance, the new START specifies strategic nuclear weapons to be delivered by intercontinental ballistic missiles (ICBMs), submarine-launched ballistic missiles (SLBMs), and heavy bombers. In this sense, nuclear cruise missiles, gravity bombs, and torpedoes are not considered to fall within the category of strategic nuclear weapons regardless of their yield.

When referring to NSNWs, however, recent studies appear to rely on the military definition, that is, the yield of the warhead, as the distinguishing characteristic rather than focusing on the exclusion from strategic arms control treaties [4, 5]. The different recognized types of NSNWs "include air-to-surface missiles, short range ballistic missiles, gravity bombs, and depth charges for medium-range bombers, tactical bombers, and naval aviation, as well as anti-ship, anti-submarine, and anti-aircraft missiles and torpedoes for surface ships and submarines, a nuclear ground-launched cruise missile." [3].

Nonetheless, it is important to note that the use of NSNWs is not confined to theater- or tactical-level missions. Indeed, former Secretary of Defense James Mattis has claimed, "I don't think there is any such thing as a 'tactical nuclear weapon.' Any nuclear weapon used any time is a strategic game changer." [6]. This suggests that, when delivered by long-range, high-precision vehicles, NSNWs could, in fact, be employed to achieve strategic objectives that impact strategic stability. In this regard, the term NSNWs could be used to refer to those weapons designed to provide specific tailored effects that are carried by high-precision means of delivery and have low-yield warheads.

2.2 What Patterns Characterize the Acquisition of NSNWs?

It is important to recognize that NSNWs are not new and have been pursued to balance against adversary's conventional power. During the early stages of the Cold War, NSNWs were not appropriate for use in strategic missions, since neither ballistic missiles nor bombers exhibited the necessary accuracy to successfully reach and attack hardened targets, such as missile silos and command facilities, inside an adversary's territory [7, 8]. However, NSNWs were thought effective in terms of attacking theater or tactical targets, such as assembled troops and support facilities, if deployed alongside troops at forward bases. For instance, in West Germany, Pershing intermediate-range ballistic missiles were deployed during the 1960s. These missiles were inaccurate, with a circular error probability (CEP) of 400 meters (m), but they could be used against ground troops because they had a range of about 400 kilometers (km), with a 60 to 400 kiloton (kt) yield [9]. In particular, these nuclear weapons were considered an indispensable part of NATO's flexible response strategy in Europe due to the need to counter the massive number of the Warsaw Pact mechanized divisions. Therefore, NSNWs were intended to be used to defend NATO countries from the Soviet invasion if conventional defense failed although it risked a limited nuclear war [10]. The Soviet Union also integrated NSNWs into its military doctrine, with the intention of using them for both surprise and preemptive attacks [11, 12].

At the end of the Cold War, however, the U.S. acknowledged that there was no need to maintain non-strategic nuclear weapons to deter and defeat the Warsaw Pact army because "the threat of a simultaneous, full-scale attack on all of NATO's European fronts has effectively been removed." [13]. Following the negotiation and signing of the INF Treaty in 1987, President George H.W. Bush announced the withdrawal of all land- and sea-based non-strategic nuclear weapons. Today, only about 1,100 of these nuclear weapons remain in the U.S.'s active stockpile [4]. In contrast, Russia still maintains a relatively large arsenal of between 3,000 and 6,000 NSNWs, of which 2,000 are deliverable in various forms from ground-launched cruise missiles to nuclear torpedoes [3, 14]. Meanwhile, China has reportedly also developed NSNWs, since it has conducted a number of nuclear blast simulations and training sessions concerning the use of NSNWs from tactical aircraft [14]. These countries are likely to pursue the acquisition of NSNWs because such weapons would offer military advantages in regional conflicts in Europe and East Asia [8, 15]. Such countries may lack the necessary military power to defeat the U.S. in a full-scale conventional or nuclear war. Thus, they may escalate to the use of NSNWs in an effort to pursue their political goals below the threshold of outright war. As these nuclear weapons could offset the U.S.'s conventional military superiority, the threat of their use may block U.S. force projection to a conflict region or potentially coerce the U.S. into withdrawing in the midst of a conflict. The U.S. relied on such an approach in Europe during the Cold War, and potential adversaries are now replicating the U.S.'s former approach.

3. Characteristics of Modern NSNW

Advance in technology and each country's modernization efforts are changing the characteristics of NSNWs. New weapons technologies make modern NSNWs reach target accurately, reduce the yield of warheads, and produce the benefits of limiting destructiveness, while offering various choices of launchers. Therefore, these NSNWs are becoming more suitable for strategic missions and rendering the use of NSNWs more feasible.

In this section, the detail methodology to characterize NSNWs as a function of yield and CEP is presented. Moreover, the procedure to evaluate their secondary effects such as causality and environmental contaminated area are also introduced. To begin with, it is assumed that a hypothetical target is buried underground and constructed using strong concrete so that it can endure up to 10,000 psi (= 68,900 kPa). The various parameters to analyze the characteristics of NSNWs as a function of yield and CEP are explained in the following subsections.

3.1 Parameters

3.1.1 Yield

The energy released by a nuclear weapon explosion is generated by the nuclear fission reactions of fissile materials, for instance, uranium-235 (^{235}U) and plutonium-239 (^{239}Pu), produced by neutrons. Other types of reactions can also occur between neutrons and materials, including the neutron capture reaction, the neutron elastic scattering reaction, and the neutron inelastic scattering reaction. The likelihood of those interactions between neutrons and materials is defined by the neutron cross-section. Such reactions in a nuclear reactor core can be analyzed using a Monte Carlo method, for example, the Monte Carlo N-Particle (MCNP) code [16]. Accordingly, it can be expected that yields of nuclear weapon explosions contain a certain uncertainty and can be varied.

Since 1945, around 2,000 nuclear weapon tests have been conducted by several countries including the U.S., the Union of Soviet Socialist Republics (USSR)/Russia, United Kingdom, France, China, India, Pakistan, and North Korea [17]. The yields of the tested nuclear weapons have varied dramatically, from kilotons to megatons. Information concerning the testing of nuclear weapons can be found in the Nuclear Weapon Archive [18]. Among nuclear weapon tests conducted by the U.S., a number of cases show a mismatch between the expected yield (EY) and achieved yield (AY) as shown in Table 1 [18]. The largest difference between the two values was observed with the Yellowwood test. The expected yield was 2,500 kt, however, 330 kt was observed. The difference between expected yield and achieved yield is evaluated in Table 1. The average of those difference is around 14%.

Table 1. List of mismatches between expected yield (EY) and achieved yield (AY) from U.S. nuclear weapons tests [18]

Test	Day	Location	EY [kt]	AY [kt]	Difference
Ray	April 11, 1953	Nevada Test Site	0.5–1	0.2	> –60%
Badger	April 18, 1953	Nevada Test Site	23	35–40	> 52.2%
Yankee	May 4, 1954	Bikini Atoll	9,500	13,500	42.1%
Turk	March 7, 1955	Nevada Test Site	45	43	4.44
Hornet	March 12, 1955	Nevada Test Site	10 (Max)	4	60%
Dakota	June 25, 1956	Bikini Atoll	800	1,100	37.5%
Yellowwood	May 26, 1958	Enewetak Lagoon	2,500	330	–86.8%
Aztec	April 27, 1962	Christmas Island	> 410	410	-
Questa	May 2, 1962	Christmas Island	1,000	670	–33%
Yukon	May 8, 1962	Christmas Island	< 100	100	-
Mesilla	May 9, 1962	Christmas Island	> 100	100	-
Muskegon	May 11, 1962	Christmas Island	> 50	50	-
Nambe	May 27, 1962	Christmas Island	> 43	43	-
Bumping	October 6, 1962	Johnston Island	> 11.3	11.3	-

At the same time, two nuclear weapons were used by the U.S. during the Second World War. One was called 'Little Boy' and contained highly enriched uranium (^{235}U) and was dropped on Hiroshima in Japan (August 6, 1945). Another, named 'Fat Man', consisted of plutonium (^{239}Pu) and was used on Nagasaki in Japan (August 9, 1945). It was reported that the yields of both weapons were designed to be 20 kt of TNT [19]. Deterministic evaluations of the yields of the two nuclear weapons based on data observed after the explosions were conducted by Malik at Los Alamos National Laboratory [19]. This report concluded that the best estimates of yield were 15 kt for Little Boy and 21 kt for Fat Man. 15 kt over 20 kt corresponds to a 25% loss of yield from the designated weapon, Little Boy. 21 kt from 20 kt represents a 5% gain from Fat Man. This variation in yield uncertainty was dramatic. Therefore, in this study, it is assumed the yield has 10% uncertainty from the original design based on Table 1 and two nuclear weapons used in Japan. Furthermore, we assume that the yield uncertainty follows the normal distribution. In order to compare the features of low-yield NSNW and strategic nuclear weapons, we consider cases with 1, 10, 50, 100, 500, 1,000, and 5,000 kt.

3.1.2 Circular Error Probability

The accuracy of a missile is discussed using the terminology, CEP. The definition of CEP is "the radius of a circle centered at the target or mean point of impact within which the probability of impact is 0.5" [20]. The mathematical formula for CEP using the bivariate normal distribution can be represented by

$$\iint \frac{1}{2\pi\sigma_x\sigma_y}\left(\exp\left(-\frac{1}{2}\left(\frac{(x-\mu_x)^2}{\sigma_x^2}+\frac{(y-\mu_y)^2}{\sigma_y^2}\right)\right)\right)\mathrm{dxdy} = 0.5 \tag{1}$$

where x and y are the downrange and crossrange miss distances, μ_x and μ_y are the sample means of downrange and crossrange, and σ_x and σ_y are the sample standard deviation of downrange and crossrange [20]. We assumed $\mu_x=\mu_y=0$ and $\sigma_x=\sigma_y=\sigma$. In addition to that, by transforming to the polar coordinates (r,θ), the cumulative distribution function, Eq. (1), was rewritten as

$$\int_0^{2\pi}\int_0^{CEP}\frac{1}{2\pi\sigma^2}\left(\exp\left(-\frac{r^2}{\sigma^2}\right)\right)rdrd\theta = 0.5 \quad (2)$$

By integrating Eq. (2), the σ for the given CEP was evaluated by

$$\sigma = \frac{\mathrm{CEP}}{\sqrt{2\ln(2)}} \quad (3)$$

The limited CEP information for Inter-Continental Ballistic Missile (ICBM) is also available in the Nuclear Weapon Archive [18]. One of the examples from that website was the R-7/SS-6 Sapwood, which the first ICBM developed by the USSR in the 1950s. The CEP of this ICBM was 2,500–5,000 m. However, a modern Russian ICBM, for example, Iskander, has a 10–30 m CEP [21]. It is expected that the CEP for US troops, B61-12, is 5 m or less with a Global Positioning System (GPS) [22]. Therefore, the CEPs assumed in this study are 10, 50, 100, and 300 m.

3.1.3 Blast Waves

The blast wave from an explosion causes catastrophic destruction. Due to the high heat release rate from a nuclear weapon explosion, a very high-pressure and high-velocity blast wave propagates outward. Typically, the speed of the wave propagation is faster than that of sound in air, i.e., supersonic speed. In supersonic propagation, the acoustic waves are overlapped, and a shock wave is formed. The shock wave induces sudden rises in temperature, pressure, and density. When the shock wave passes, the atmospheric air is rapidly compressed and heated, thus becomes very hazardous. Moreover, due to the steep pressure gradient, rapid airflow is generated and damages buildings and humans both directly and indirectly.

To assess the effect of the explosion, it is important to estimate the pressure behind the shock front. The motion and pressure of the blast wave were analytically investigated earlier [23, 24]. This series of papers included a theoretical discussion and comparisons with photographs of atomic explosions. An analytical solution was introduced by solving the equations of motion and continuity with similarity assumptions for pressure, density, and radial velocity. At the shock wave, the solution was simplified using the Rankine-Huguenot relation.

Simpler and empirical formulas to calculate the blast wave pressure have been developed actively for practical purposes. Brode numerically simulated spherical blast waves and suggested an empirical fitting curve relating the shock radius and yield energy to the shock overpressure [25]. A hemispherical blast wave formula was developed based on TNT experiments [26]. This formula was from real-world data in real-world conditions. Therefore, the data includes unstandardized conditions, such as ambient temperature, and wind, etc.

Recently, due to rapid growth in computational power, many detailed numerical simulations have been performed to predict the blast wave more accurately. These efforts include solving the Navier-Stokes equations with detailed chemical kinetics to understand the transient motion and magnitude of the blast wave from the initiation to extinction or during the propagation in inhomogeneous environments [27, 28]. Moreover, the numerical simulations can be further extended to include many other real-world effects, e.g., three-dimensional effects, complex geometries, interactions with structures, and weather conditions, although simulations with these effects may require a very expensive computational cost.

In the current study, a reduced formula based on physics is used to estimate the blast overpressure for the simplification. The pressure is inversely proportional to the area of the spherical shock front, and a function of the explosive yield. In a previous study, [29] an empirical formula was introduced to obtain a rough estimation as

$$P = 60\,W^{2/3} / D^2 \quad (4)$$

where P is the pressure behind the shock front in psi, W is the explosive yield in megatons, and D is the radius of the spherical shock front in miles. It was noted that a blast pressure exceeding 5 psi (= 34.5 kPa) caused fast-flying objects and serious wounds in people [29]. Thus, the area of blast wave influence based on this pressure, A_b, can be estimated by

$$A_b = 38W^{2/3} \tag{5}$$

In addition to that, a typical shelter (e.g., a basement of a large public building) could protect the occupants from up to 15 psi of blast pressure [29]. Using this assumption, the formula to evaluate the area affected by the blast wave and supported by the shelter system was rewritten as

$$A_{b\_Sh} = 13W^{2/3} \tag{6}$$

3.1.4 Fallout and Radiation

The fission reaction of ^{235}U or ^{239}Pu and the decay of those fission products can produce multiple radioactive isotopes whose half-life can range from seconds to many years [29]. The distribution of fallout can vary depending on time, winds, the weight of the particles, and the location of the explosions, etc. According to Broyles' work, the fallout area (A_f) of 450 rem (= 4.5 Sv), which would result in the death of around 50% of the people exposed, at an effective wind speed of 15 miles per hour (=24 kilometer per hour) can be approximated by

$$A_f = 360W(\exp(-0.023/W - \exp(-4.4/W)) \tag{7}$$

In addition to that, a higher dose rate is required for people in a shelter, than for people staying outside of a shelter. For this case, by applying the 0.01 protection factor provided by a shelter, the formula to evaluate the area (A_{f_Sh}) can be rewritten as [29]

$$A_{f\_Sh} = 3.6W(\exp(-2.5/W - \exp(-1140/W)) \tag{8}$$

Not only fallout but also immediate radiation damage is also considerable. The immediate radiation effect area (A_{Rad}) exceed 450 rem (= 4.5 Sv) was evaluated by [29]

$$A_{Rad} = 6.2W^{0.264} \tag{9}$$

Similar to Eq. (8), the reduction in immediate radiation effect area provided by a shelter (A_{Rad_Sh}) was computed by [29]

$$A_{Rad\_Sh} = 1.8W^{0.264} \tag{10}$$

The damaged area by the fallout and radiation is evaluated as a function of yield which is considered as the input parameter. Although the uncertainty of area is not given, the uncertainty of area will be produced after the Monte-Carlo simulation.

3.1.5 Thermal Effect

The major heat energy effect of a bomb is caused by thermal radiation, as it propagates much faster than any other heat transfer processes, i.e., conduction and convection. Since the intensity of radiation is inversely proportional to the square of the distance from the source and the radiation energy is also absorbed by the air during the transfer, the radiation heat energy decreases rapidly with distance from the center of the explosion. Therefore, beyond a certain distance from the explosion center, the radiation effect is relatively low. The effective range depends on the density of the air and the absorption coefficient, and can be calculated using the radiative transfer equation. However, a simpler formula may be useful in practice.

In Bryoles' work, a rough expression for the range of thermal radiation was introduced as [29]

$$r_t = 7W^{0.3} \tag{11}$$

where r_t is the range of thermal radiation in miles from the explosion center. In the formula, the range was based on

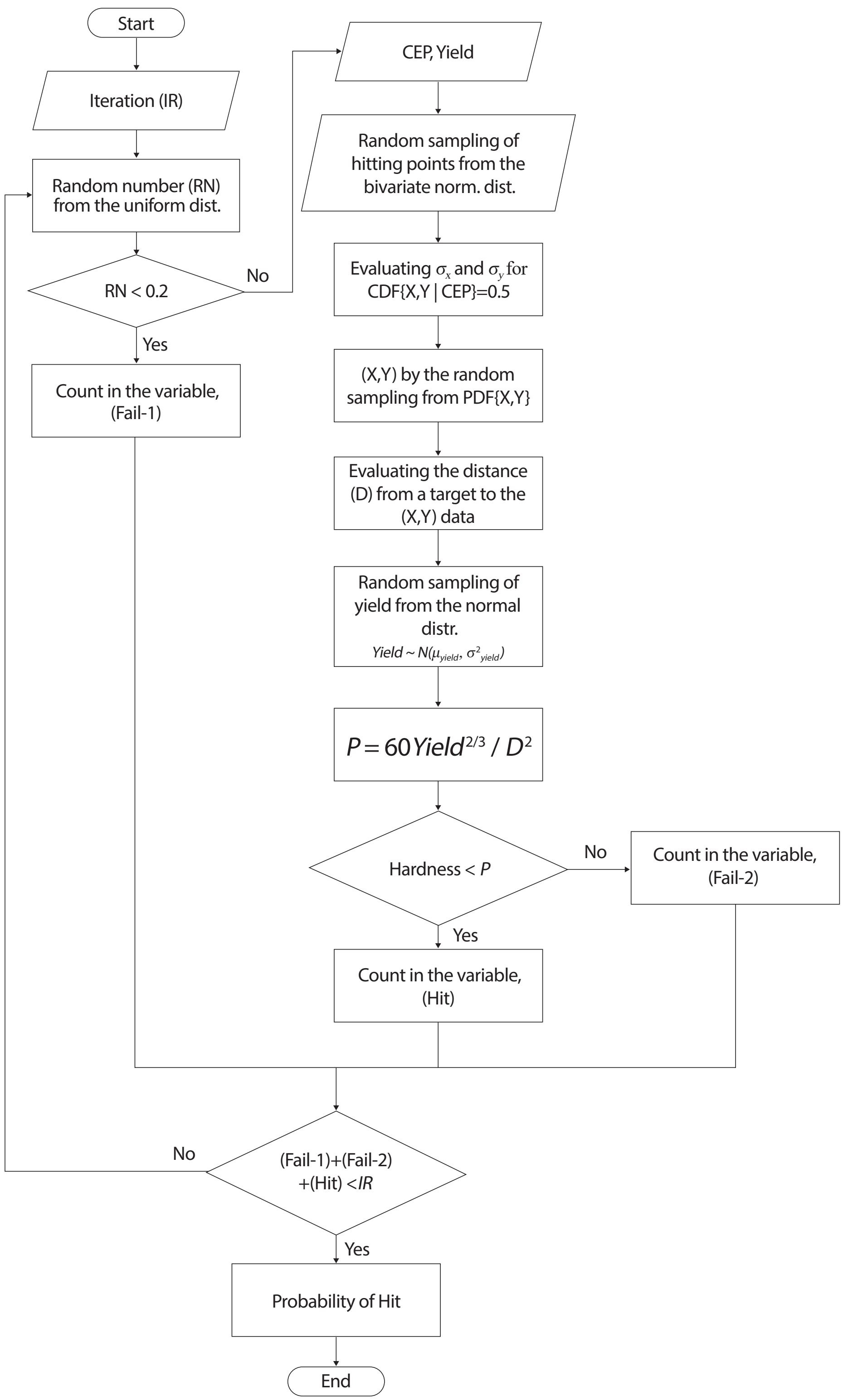

Fig. 1. Flow chart of Monte Carlo simulations used to evaluate the probability of hitting and destroying a target.

50% of the population in the range receiving third-degree burns, but it did not include the effect of shading. The area affected by thermal radiation, A_t, was estimated using the area of the circle created by r_t:

$$A_t = 153W^{0.6} \tag{12}$$

4. Monte Carlo Method

The probability of hitting a target and the expected area with an error bar affected by fallout, blast, and thermal effects are evaluated using the Monte Carlo method. The flow chart for this Monte Carlo scheme used to evaluate the probability of hitting a target is shown in Fig. 1.

To begin with, the failure probability of missile systems is assumed to be 20% [8]. Failure means that the attacking missile system malfunctioned, and a target is not damaged. The random number is generated from a uniform distribution between 0 and 1. If the random number generated is greater than 0.2, the missile system would not fail. The program read the input parameters of the CEP and the yield of the nuclear weapon. Then, the program calculates the appropriate standard deviations that can give a cumulative distribution (Eq. (1)) of 0.5. These standard deviations are used for the random sampling of hitting position from the bivariate normal distribution.

The distance (D) between the hitting point and a target point is evaluated. Moreover, the yield (*Yield*) of the nuclear weapon explosion is randomly sampled using the normal distribution, with the uncertainty given by users, for example, 10%. Finally, the yield and the distance are substituted into Eq. (4) to evaluate the overpressure at that distance (D) from the hitting point. If the overpressure is greater than the hardness in pressure that the target could withstand, which is also given by the user, it is counted and recorded as a success (Hit). If the number of iterating times is less than an iteration defined by users, it restarts with the sampling of a random number from the uniform distribution to determine whether the missile system fails or not. After every iteration, the program counts how many times a target is destroyed. This is represented in percentage. Similarly, the areas affected by fallout, blast, and thermal effects are evaluated using this Monte Carlo sampling scheme.

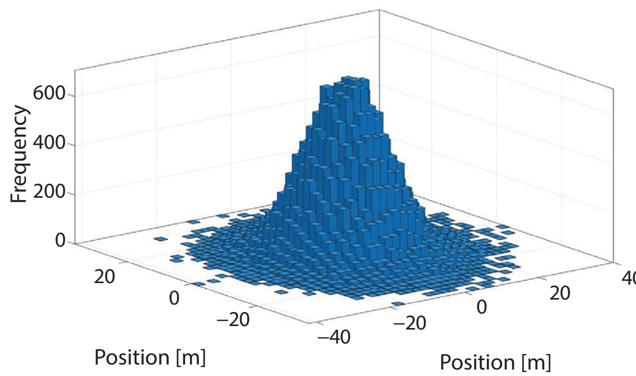

Fig. 2. Distribution for a sampling of hitting point when the CEP is 10 m.

5. Results

For the Monte Carlo simulation, the number of iteration is set to 100,000. The maximum pressure that a target is able to withstand is assumed as 10,000 psi (= 68,900 kPa). Targets usually have their physical structure. However, in this study, it is assumed to be a point target located on the origin in the two-dimensional coordinate. The histogram for 100,000 hitting points by sampling for the 10 m CEP case is shown in Fig. 2. Since the means of X and Y and random variables are zero, the highest peak of the histogram is shown on the origin. The frequency decreases with distance away from the origin. The low peak is distributed at a distance of 20 m or longer from the target due to the 10 m CEP.

The probability of destroying a target with respect to the CEP and yield is plotted in a semilogarithmic graph as shown in Fig. 3. The red circle marker indicates the probability of mission completion when the CEP is 10 m. The results for the 50 m CEP are represented by the black

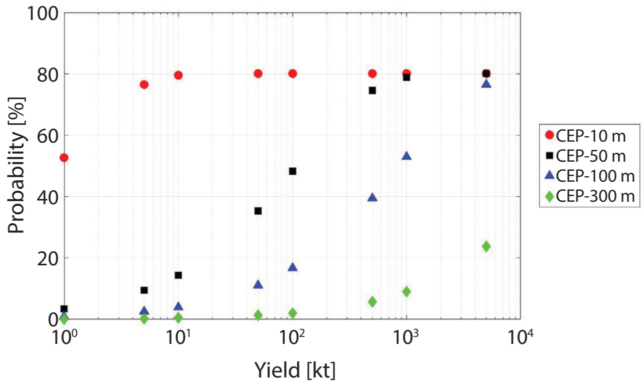

Fig. 3. Probability of destroying a target as a function of CEP and yield.

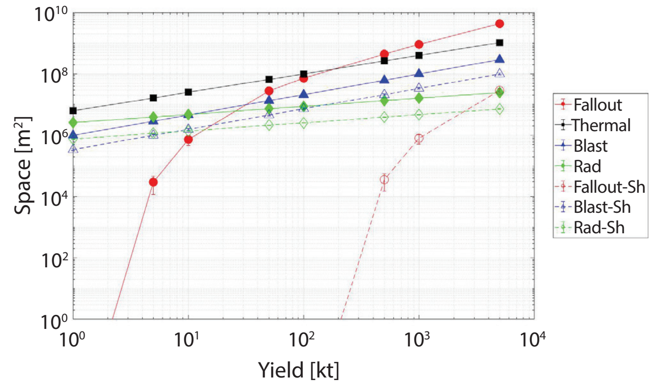

Fig. 4. Area damaged by fallout, thermal, blast, and radiation from different yields of nuclear weapon.

square marker. The 100 m CEP case is marked by the blue triangle. The green diamond marker is used to represent the result for the 300 m CEP case. By increasing the accuracy of the missile, the necessary yield to destroy a target decreases. In particular, the probability of mission completion using a 1 kt nuclear weapon with a CEP of 10 m is significantly greater than that with greater CEPs. In contrast, the expected mission success using the 300 m CEP in the 5,000 kt yield missile is dramatically less than that using more accurate missiles. When the yield of the nuclear weapons is 10 kt, the probability of destroying a target using the 10 m CEP missile reached the saturation level, which is near 80% in this figure. This 80% probability is achieved by assuming a failure probability of 20%, as mentioned in the previous section. Based on the observations in Fig. 3, the advanced missile technology in terms of accuracy and precision could possibly carry out a mission using a low-yield nuclear weapon.

The evaluated areas where people could be seriously damaged by the fallout effect (the red solid circle marker), the thermal effect (the black solid square marker), the blast effect (the blue solid triangle marker), and the radiation directly generated by the nuclear weapon explosion (the green solid diamond marker) are plotted as a function of yield as shown in Fig. 4. The results for staying inside a shelter are represented by the unfilled markers. The cutoff for plotting was 1 m^2. In the case of low-yield, 1 kt, the area affected by the thermal effect is wider than that by the fallout, blast, and radiation effects. The fallout effect is not shown in the figure for the 1 kt case, because the area is less than 1 m^2. It is known that 1 kg of ^{235}U approximately produces the energy equivalent of 20 kt [30]. For 1 kt, around 0.05 kg of ^{235}U is necessary. The area of radiation dose of 450 rem from the fission of 0.05 kg ^{235}U would not be wide. However, the fallout effect could damage the widest area if a high-yield nuclear weapon is detonated. The most sensitive effect dependent on the yield is the fallout effect. It is observed that direct impact from the nuclear weapon explosion could be avoided by applying the shelter effect. In particular, damages from the fallout effect could be dramatically mitigated by staying inside a shelter.

According to the Demographia World Urban Areas report, the population densities of Los Angeles-Riverside (LA) and New York (NY) in the U.S., Paris (PRS) in France, Shanghai in China (SHG), Seoul-Incheon (SL) in the Republic of Korea, and Tokyo-Yokohama (TKY) in Japan are 2,300/km^2 (LA), 1,700/km^2 (NY), 3,700/km^2 (PRS), 6,000/km^2 (SHG), 8,800/cm^2 (SL), and 4,500/km^2 (TKY) [31]. In order to estimate the total causalities for each city, the maximum damaged area at each yield is multiplied by the population density of each city. Finally, the estimated total casualties depending on the selected cities are plotted as a function of the yield as shown in Fig. 5. The solid red marker is used to show the total causalities in LA. The case

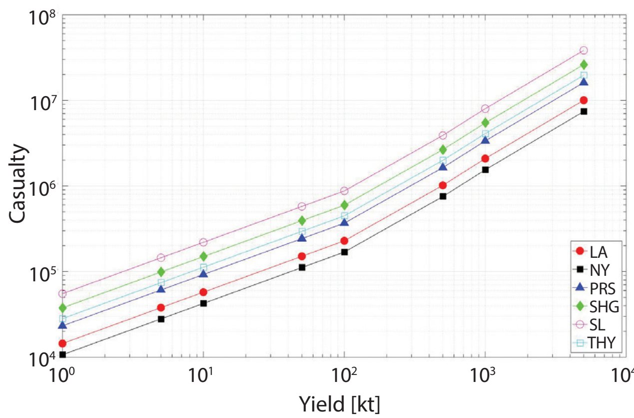

Fig. 5. Estimated total casualties in major cities as a function of yield.

for NY is shown by the black square marker. The estimated total casualties in PRS is presented by the blue triangle marker. The case for SHG is marked using the green diamond marker. The magenta unfilled circle is for the result of SL. Finally, the result for TKY is shown by the cyan unfilled square marker. The total casualties depending on the yield from the nuclear weapon explosion vary dramatically, in the range of 10^4 to 10^8. These results support to claim that a low-yield nuclear weapon reduces the effect on public areas and civilian casualties.

6. Discussion

This study investigated how low-yield, high-precision NSNWs could increase the probability of mission success and also lower the likelihood of collateral damage. When compared to standard nuclear weapons, which have a 500 kt yield and a CEP of 100 m, NSNWs (10 kt yield, CEP of 10 m) would destroy a target twice as successful. Standard nuclear weapons have approximately a 40% probability of success, while eight out of ten low-yield, high-precision NSNWs are expected to be successful. Meanwhile, the reduced yield of the weapons indicates that the use of NSNWs could minimize the number of civilian deaths and unnecessary casualties among soldiers.

Such fact renders the use of NSNWs more effective than the use of standard nuclear weapons, which are still constrained by the so-called nuclear taboo. The increase in the probability of success due to enhanced missile accuracy means that the value of the use of NSNW is high. In which case, a NSNW state will possibly be more prone to the use of the weapons. On the other hand, the reduced probability of civilian causalities and unnecessary deaths among troops should lower the cost of NSNW use. A major constraint on the use of nuclear weapons concerns the indiscriminate nature of such weapons. However, if NSNWs could selectively strike an enemy's hardened facilities, which would otherwise risk the lives of thousands of soldiers when attempting to destroy them through conventional attacks, the public would give the green light to the use of NSNWs. As a result, the use of NSNWs could lower the military, political, and reputational costs.

In sum, as many scholars have previously argued, nuclear weapons have played a key role in preventing war between major states since 1945. However, this peaceful situation is only possible when such weapons are not considered weapons to be used, but rather weapons to have so as to balance credible threats. A credible threat between rival states is an imperative condition that constrains both sides from initiating costly attacks in order to enhance their security. Meanwhile, the modernization of NSNWs has rendered such weapons less destructive, albeit more effective, and therefore, not only credible but more "usable." This usability on the part of NSNWs makes it unclear whether such weapons will improve the credibility of deterrence and contribute to the prevention of outright nuclear war in the same way that strategic nuclear weapons have done for the past seventy years.

The present study estimates how the technical characteristics of NSNWs would influence a state's decision-making. Based on the more effective characteristic of NSNWs comparing to conventional high-yield nuclear weapons, it would lead that the spread of NSNWs would likely increase the probability of an arms race. The study hence argues that strategic stability is likely to be more endangered than in the era of standard nuclear weapons. Furthermore, it could also be argued that the use of a low-yield NSNW would trigger the use of higher yield nuclear weapons because, although low-yield NSNWs were used, they were still a nuclear weapon so that the damaged state might retaliate against an attack of low-yield NSNW with nuclear weapons. Therefore, we need to reassess our belief in NSNWs and question whether they would actually prove effective in terms of reducing the likelihood of war and achieving strategic stability.

The IAEA safeguards are operating based on 1 SQ of 8 kg-plutonium. The meaning of SQ is *'the approximate amount of nuclear material for which the possibility of manufacturing a nuclear explosive device cannot be excluded'* [32]. As mentioned in the introduction section, the yield of 1 kT can be achieved by 1–3 kg of plutonium [1]. Therefore, we would like to conclude that reducing SQ for plutonium can result in more robust safeguards and nonproliferation frames.

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