An Engineering Approach to Assessing the Impact of Nuclear Weapons

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1. Introduction

Recently in South Korea, the discussion surrounding nuclear armament has become animated due to the growing nuclear threat and several related circumstances. Those arguments are related to the assumption that deterring nuclear weapons can only be accomplished by nuclear weapons themselves. The idea that nuclear weapons are too catastrophic to be parallelized with any other weapons, stems from the concept of ‘absoluteness’. The term was first used in the earliest nuclear discourse in Brodie’s book *The Absolute Weapon,* published in 1946 [1].

To be delicate, he used the term in a very specific context to describe the equivalence between 2000 and 6000 warheads, both of which are enough to destroy the enemy’s main cities [1]. There is no such implication that nuclear weapons are incomparable in terms of killing effect, nor do they have capability to obliterate humanity dozens of times.

In this context, this paper raises the question: “Is the nuclear weapon truly absolute?” In order to identify whether the nuclear weapon is absolute or not, an engineering approach is adopted to estimate the specific value of the killing radius of nuclear weapons. It includes the data from the Japanese case, numerous nuclear tests, and several nuclear accidents.

This paper begins by calculating the killing radius of a nuclear explosion. Its killing effect can be classified into three aspects: blast wave and overpressure, thermal radiation and fireball, and nuclear radiation. Hence, there will be three killing radii corresponding to each aspect. Next, this paper will suggest some comparisons between nuclear weapons and conventional weapons. It is related to the implications of this paper.

2. On nuclear explosions

It is difficult to obtain detailed information about nuclear explosions. Hence, this paper chose Glasstone’s book *The Effects of Nuclear Weapons*, published in 1962 [2]. Many researchers depend on this book which contains nuclear test data from the US Department of Defense, and other information from other agencies belonging to US government and numerous specialists.

A nuclear explosion differs from an explosion of high-explosive or TNT in three aspects [2]. First, the energy released by an explosion, i.e. the ‘yield’ of a nuclear weapon is usually hundreds to millions of times greater than that of conventional weapons. It results in ‘blast wave and overpressure’. Meanwhile, the rapid release of energy is a common phenomenon for both nuclear and conventional weapons; therefore, the yield of a nuclear weapon can be expressed as ‘TNT equivalent’. Second, the portion of thermal radiation is much larger in nuclear explosions, and it is almost ignored in conventional explosions. It results in ‘thermal radiation and fireball’. Third, nuclear explosions emit harmful radiation, unlike conventional weapons. It results in ‘nuclear radiation’.

To calculate the killing radius of a nuclear weapon, we assumed a scenario in which North Korea launches a nuclear attack on South Korea, targeting the office of the president with a yield of 100 kt (the estimated yield of North Korea’s sixth nuclear test). Other conditions will be treated as conservatively as possible.

2.1. Blast wave and overpressure

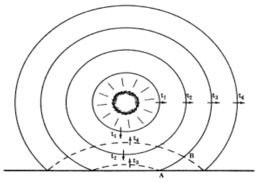

Fig. 1. The Mach effect [2].

When the explosion starts, large amount of energy is released rapidly, causing the temperature and pressure of surrounding materials to rise sharply. This is called the ‘Blast Wave’. It comprises the largest portion of total explosion energy, approximately 50%. When the explosion occurs near ground, the blast wave can reach the ground and reflect. Then the direct and reflected fronts can fuse. This fusion is called the ‘Mach Effect’ and the high-pressure built up at the front of the Mach wave is called ‘Overpressure’, as shown in Fig. 1 [2].

The killing effect due to blast wave and overpressure can be sorted by ‘direct blast injury’ caused by high-pressure, and ‘indirect blast injury’ caused by shrapnel. However, the damage from indirect blast injury is similar to the damage from high-explosive [2]. Hence, this paper will focus only on direct blast injury. In direct blast injury, the ‘duration’ of the positive phase of the overpressure is a significant factor up to hundreds of milliseconds. If the duration of the positive phase of the overpressure is longer than that time, the ‘peak overpressure’ becomes the most dominant factor regarding the probability of injury. Mostly, the conventional weapon’s duration is shorter than that time, while the nuclear weapon's duration is longer than that time. Hence, the determinant of the killing radius of a nuclear weapon due to blast wave and overpressure, is the peak overpressure. And it depends on the yield [2].

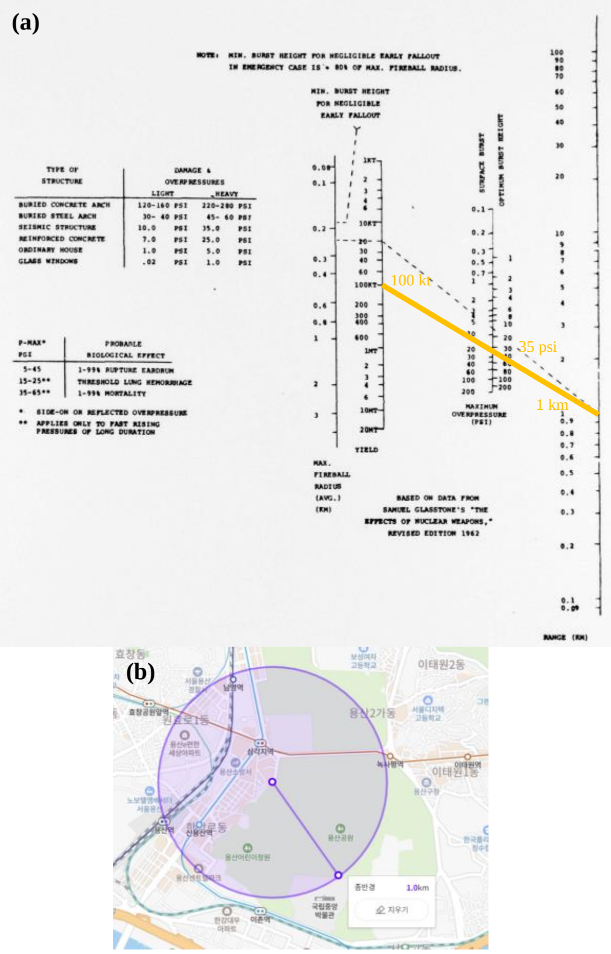

Fig. 2. (a) Nomogram for overpressure [3], (b) The circle has a center at the office of the president and a radius of 1 km.

Fig. 2(a). shows the nomogram that Cramer [3] rearranged Glasstone's data. According to the results of nuclear tests, the required peak overpressure for 1% mortality rate is 35 psi. And the corresponding range for 100 kt and 35 psi is 1 km. To sum up, the mortality rate for the population at a distance of 1 km is 1%, see Fig. 2(b).

2.2. Thermal radiation and fireball

When a nuclear weapon explodes, massive amount of energy is released through thermal radiation. This is called 'Primary Thermal Radiation', and its temperature reaches tens of millions of Kelvin. However, at lower altitudes where the air density is high, the primary thermal radiation is completely absorbed by the air within a few feet and it serves to heat the air immediately around the explosion. This is how the 'Fireball' forms. Then some of the energy re-emits, comprising 35% of total explosion energy. This is called 'Secondary Thermal Radiation' [2]. This paper focuses solely on secondary thermal radiation as its range of killing effect is longer than that of fireball.

The killing effect due to the thermal radiation mostly appears as burns. An indicator of burn is the energy transferred per unit area. If attenuation were due only to absorption in uniform atmosphere, the energy transferred per unit area that is normal to the direction of propagation, Q is represented as follows [2]:

$$(1)\ Q = \frac{E_{tot}}{4\pi D^2} e^{-\kappa D}$$

when D is distance in miles and κ is absorption coefficient. To be more useful, we can utilize the theory that the absorption coefficient becomes a function of distance when scattering of the radiation occurs. Q is as follows [2]:

$$(2)\ Q\ (cal/cm^2) \approx \frac{1.04WT}{D^2}$$

when at air burst, W is yield in kt and T is transmittance.

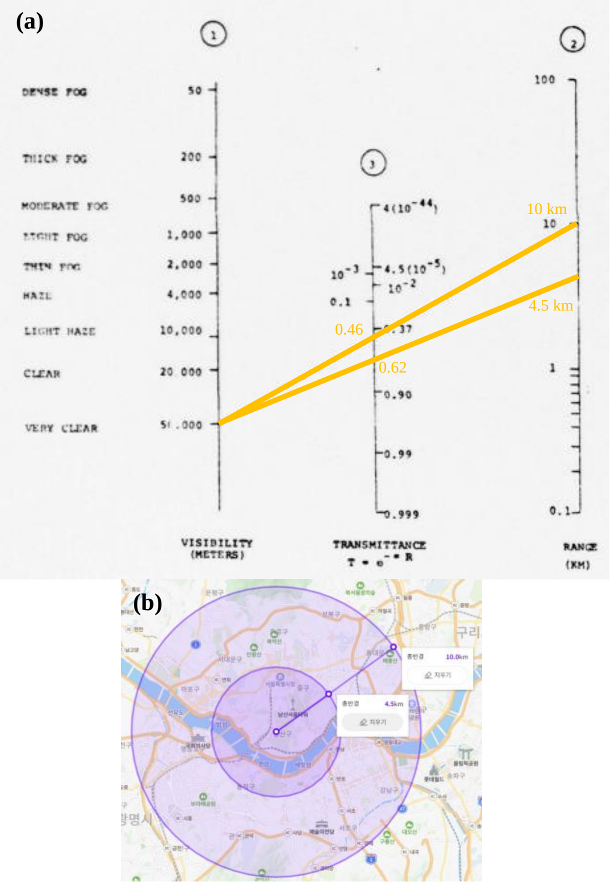

Fig. 3. (a) Nomogram for thermal radiation [3], (b) The Circles have centers at the office of the president and radii of 4.5 km and 10 km.

As well as overpressure, Cramer [3] suggests the nomogram in Fig. 3(a). First-degree burns are experienced with 1-2 cal/cm^2 while second-degree burns are experienced with 5-10 cal/cm^2. If the weather is very clear (related to transmittance), Q value for a 100 kt nuclear weapon is $Q_1 \approx 8.3\ (cal/cm^2)$ at 4.5 km ($T_1 \approx 0.62$) and $Q_2 \approx 1.2\ (cal/cm^2)$ at 10 km ($T_2 \approx 0.46$). Therefore, people in the small circle (r = 4.5 km) will experience second- or third-degree burns, while those near the large circle (r = 10 km) will experience first-degree burns, see Fig. 3(b).

Then, what should be the criterion for the killing radius? The first-degree burns involve only redness of the skin and are similar to a sunburn. Second-degree burns are characterized by the formation of blisters and generally heal within 4 weeks. However, Glasstone chose second-degree burns as the criterion because in the situation of warfare, it is difficult to avoid infection due to poor sanitation and lack of facilities [2][3].

But his criterion may have room for revision. There are three reasons. First, it is because of the trait of the ‘flash burns’. Burns caused by nuclear explosions can be classified into two categories: ‘flash burns’ due to direct exposure and ‘flame burns’ due to a large fire. Since thermal radiation travels in a straight line, flash burns occur only to the skin facing the center of the explosion. Damage due to flash burns will be limited to a specific area, therefore reducing its killing power [2]. Second, damage caused by thermal radiation can be alleviated in several manners. To be inside a building instead of to be outside, and to wear white and loose clothes instead of black and tight clothes, can reduce the damage. Third, before anything else, Glasstone did not consider the fact that this heat transfer could not be fully accomplished. In explosions that occur for such a brief time, the heat transfer is insufficient, and there are even complex interactions on the surface that further delay this [4]. For the aforementioned reasons, we moderated the criterion to less than 4.5 km.

2.3. Nuclear radiation

One of the important characteristics of a nuclear explosion is that it emits a significant amount of nuclear radiation. 5% of total explosion energy is released as ‘Initial Nuclear Radiation’, which includes neutrons and gamma rays within 1 minute, while 10% is released as ‘Residual Nuclear Radiation’, which is due to the decay of various fission products and includes alpha and beta particles. The residual radiation is mostly caused by fallout, forming when fission products combine with other particles in a surface burst scenario [2].

When considering the killing radius, it is important to determine whether the exposure was ‘Acute Exposure’ or ‘Chronic Exposure’ because the latter does not directly result in death. The acute exposure is defined as the exposure within 24 hours after a nuclear explosion, including initial nuclear radiation and early fallout. There is no general agreement on the equivalent dose that causes fatalities in acute exposure. But the Bravo test in 1954 can suggest the guidelines because the residents of the Marshall Islands were unaware of the importance of avoiding exposure. As a result, more than 250 residents consumed contaminated food for 2 days and did not take precautions against the fallout on their skin. Glasstone suggested the criterion as follows. No treatment is necessary when the exposure was 0-100 rem. There is zero fatality if they undergo several weeks of treatment when the exposure was 100-200 rem. The mortality rate is 0-100% when the exposure was 200-1000 rem [2].

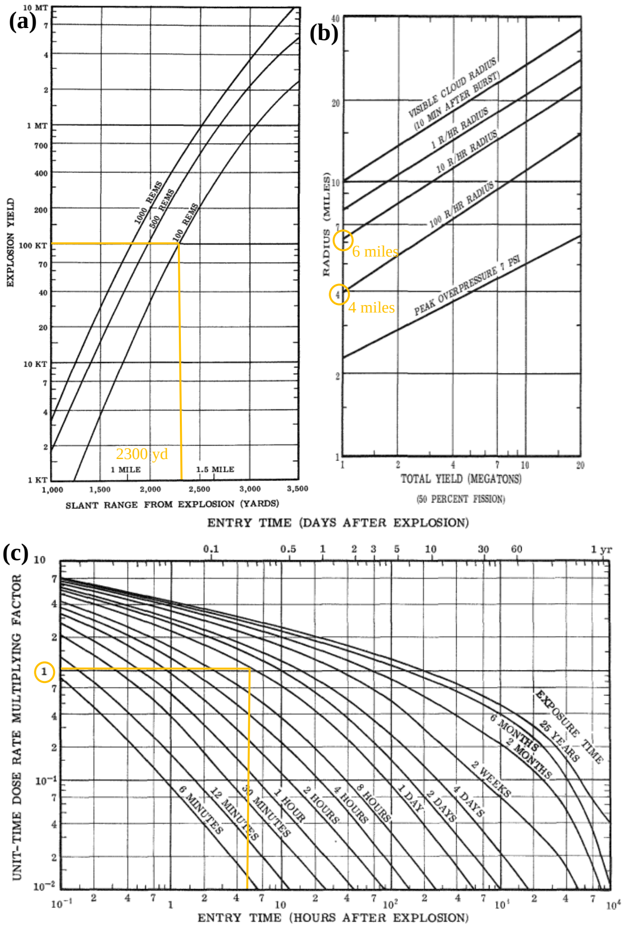

Fig. 4. (a) Exposure due to initial nuclear radiation [2], (b) Radii for unit-time reference dose rates [2], (c) Unit-time dose rate multiplying factor for exposure time [2].

To begin with initial nuclear radiation, the exposure was 100 rem for 100 kt at a distance of 2 km, according to the nuclear tests, see Fig. 4(a) [2].

However, it is an intricate problem to consider the exposure due to early fallout because Glasstone did not clearly summarize it. Since the data is insufficient, the strategy that demonstrates it is negligible even when considering a 1 Mt case, is adopted. According to Fig. 4(b). [2], ‘unit-time reference dose rate’ for 1 Mt at 4 miles is 100 R/hr. Since the fallout normally arrives the ground 6 hours after an explosion, the case that a person starts to be exposed 6 hours after an explosion, and continues to be exposed for a day, is assumed. The ‘unit-time dose rate multiplying factor’, which is required to be multiplied at unit-time reference dose rate to estimate the total dose, is about 1, see Fig. 4(c) [2]. Then, total dose is 100 R for this case. But this is a unit of exposure dose, hence it has to be converted to rem, the unit of equivalent dose.

$$(3)\ 1\,R = \frac{1}{3880}\,X\,unit = \frac{34}{3880}\,Gy\,(in\ air)$$

Gray is the unit of absorbed dose. To calculate an equivalent dose, it is required to know Radiation Weighting Factor W_R^i, because $H_T = \sum_i W_R^i \times D_T^i$. Although the early fallout includes alpha and beta particles, since alpha particles cannot travel long distances in the air, the alpha particles can be disregarded here. Then there are only betas, and according to ICRP 103 [5], the Radiation Weighting Factor for beta particles is 1. Hence, Eq. (3) can be directly converted to rem. Therefore, the exposure due to early fallout in this case is 0.9 rem. Additionally, the equivalent dose for a 1 Mt at 6 miles is 0.09 rem. However, 0.9 rem and 0.09 rem are both negligible considering the exposure due to initial nuclear radiation, which is 100 rem at 2 km. Hence, this paper assumes that the exposure due to early fallout is ignorable for any distance. Even in Bravo, their symptoms were not serious enough to result in death.

Fig. 5. The circle has a center at the office of the president and a radius of 2 km.

Therefore, to put it together, at 2 km away from ground zero, the equivalent dose will be about 100 rem, a level at which no treatment is required. See Fig. 5.

3. The Relativity between the nuclear weapons and the conventional weapons

3.1. The comparison of the killing radii

To summarize the previous discussion, the killing radii of a 100 kt nuclear weapon is 1 km for overpressure, less than 4.5 km for thermal radiation, and less than 2 km for nuclear radiation. In this chapter, comparisons between the killing radii of nuclear weapons and high-yield conventional weapons will be suggested in three ways.

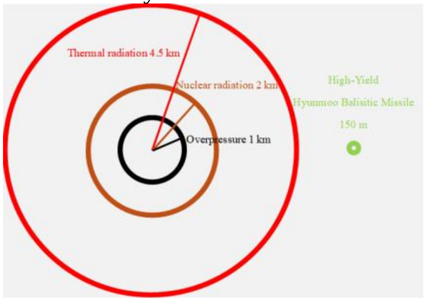

Fig. 6. The diagram of a 100 kt nuclear weapon and High-yield Hyunmoo Ballistic Missile.

First, a comparison between the most powerful weapons currently in North Korea and South Korea is suggested in Fig. 6. The three concentric circles on the left represent the killing zones of a 100 kt nuclear weapon, while the circle on the right represents the estimate of the killing zone of 'High-yield Hyunmoo Ballistic Missile'. The yield of High-yield Hyunmoo Ballistic Missile is the highest in South Korea. Its killing radius is estimated to be similar to that of GBU-43/B [6], since their TNT equivalents are comparable.

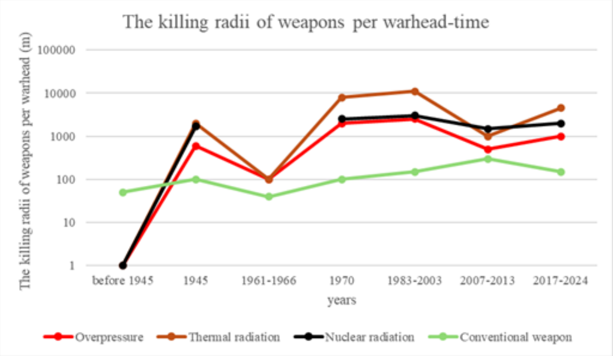

Fig. 7. The killing radii of weapons per warhead-time.

Second, the historical comparison between nuclear weapons and conventional weapons is suggested on a logarithmic scale in Fig. 7. The weapons are selected not because they are the most powerful weapons, but because they are popular in the era. The following weapons' estimated killing radii are presented: Fat Man, W54, W88, B83, the third and sixth nuclear tests of North Korea, 155mm Howitzer, Grand Slam, AGM-65, BLU-82, GBU-43/B, ATBIP, and High-yield Hyunmoo Ballistic Missile. The killing radius of W54 regarding nuclear radiation could not be estimated due to the lack of data.

It can be seen in Fig. 7. that the highest yield of conventional weapons and the lowest yield of nuclear weapons are comparable in terms of the killing radius. That is, the gap between the nuclear weapons and conventional weapons is not infinite. However, it seems hasty to conclude that nuclear weapons are not absolute because the gap between the killing radii of nuclear and conventional weapons has both increased and decreased over time. Therefore, the status of nuclear weapons as absolute weapons may vary depending on the times, making it a controversial issue.

	Overpressure(m)	Thermal radiation(m)	Nuclear radiation(m)	Conventional weapon(m)	Ratio
2006	300	500	1000	50	400
2009-2013	500	1000	1500	60	625
2017-2024	1000	4500	2000	150	900

Table I: The comparison between North Korea's nuclear tests and South Korea's conventional weapons.

Third, in the Korean context, the historical comparison between North and South Korea's weapons is suggested in Table I. It contains the killing radii of the following weapons: the first, third, and sixth nuclear tests of North Korea, 155mm Howitzer, Hyunmoo-II, and High-yield Hyunmoo Ballistic Missile. Regarding the killing radius of Hyunmoo-II, it is assumed that its warhead does not contain cluster bombs, although it does. On the right side, the ratio of the maximum killing zone of nuclear tests to the killing zone of conventional weapons, is presented.

Unlike Fig. 7., Table I limits the data of conventional weapons to South Korea only. The result indicates that the killing zone ratio has increased, despite the advent of High-yield Hyunmoo Ballistic Missile.

3.2. Implications

According to the above analysis, the killing zone of nuclear weapons per warhead is much larger than that of high-yield conventional weapons, and the killing zone ratio of nuclear weapons to conventional weapons has even increased in the Korean context. However, the ratio is still comparable and not infinite, to the extent that certain high-yield conventional weapons are stronger than some low-yield nuclear weapons.

Hence, it is important to consider the number of the weapons possessed, when drawing up security strategies such as South Korea's discussion of nuclear armament. However, the number of North Korea's nuclear weapons and South Korea's missiles is not made public. There is no guarantee even that the number of South Korea's conventional weapons is larger than North Korea's nuclear weapons.

One implication of this paper pertains to the discourse surrounding South Korea's nuclear armament. It is still very difficult to catch up the capability of North Korea's nuclear weapons with South Korea's conventional weapons. Nevertheless, since the killing zone ratio is not infinite, the cost incurred by building up conventional weapons instead of nuclear weapons is also not infinite. Significant costs will be incurred, but they can be affordable for South Korea depending on various circumstances. For example, if the nuclear threat becomes more serious, public opinion may be willing to support it. If the killing zone ratio continues to increase in the future and therefore the cost becomes excessively expensive, South Korea may not be able to afford it.

In conclusion, nuclear armament is not the only way to address the nuclear threat. The prudent decision based on a cost-benefit analysis considering the specific situation is necessary.

4. Conclusion

This paper focused on the killing effect of nuclear weapons based on Glasstone's report. It can be classified into three aspects. Regarding blast wave and overpressure, the killing radius of a 100 kt nuclear weapon is 1 km. Regarding thermal radiation and fireball, the criterion for second-degree burns is 4.5 km. However, this paper pointed out three reasons that this criterion may be revised. Regarding nuclear radiation, this paper suggested that the exposure at a distance of 2 km is not sufficient to result in death.

Next, this paper compared nuclear weapons and conventional weapons in three ways. First, the comparison between a 100 kt nuclear weapon and High-yield Hyunmoo Ballistic Missile was suggested. Second, the historical comparison between nuclear and conventional weapons was suggested. Third, the historical comparison between North Korea's nuclear tests and South Korea's conventional weapons was suggested. The results indicated that the gap between nuclear and conventional weapons is significant, but it is still not infinite. Also, the gap has increased over time in the Korean context. To sum up, the question of South Korea's nuclear armament is a difficult question to draw a one-sided conclusion on, as it depends on the circumstances.

In the midst of the situation, this paper's thesis is also related to the attempt to raise the commercial fuel enrichment level. Now, the demand for HALEU (High-Assay Low Enriched Uranium) is increasing, and the possibility of negotiation with the US is also rising. However, as an extension of the argument on nuclear armament, there is a trend of 'Nuclear Latency', which involves possessing capabilities such as uranium enrichment in the absence of nuclear weapons. If the attempt to raise the commercial fuel enrichment level becomes entangled with nuclear latency, the former's persuasiveness may decline. Therefore, to strengthen negotiating power, it is better for the nuclear industry to sever ties with nuclear latency. Here, this paper can help with this because this paper's analysis concludes that even it is difficult to determine whether nuclear weapons are truly superior to conventional weapons for military use. In short, this paper may contribute to decreasing the persuasiveness of nuclear latency to promote economic gain.

REFERENCES

[1] B. Brodie, The Absolute Weapon: Atomic Power and World Order, Yale Institute of International Studies, 1946. pp. 36-37. https://www.osti.gov/opennet/servlets/purl/16380564wvLB09/16380564.pdf. Accessed on August 19, 2024.

[2] S. Glasstone, The Effects of Nuclear Weapons, United States Atomic Energy Commission, 1962. pp. 1-27, 46-47, 109-110, 360-368, 425-493, 556-572, 584, 588-595, 601-611.

[3] W. Cramer, Nomograms for Overpressure, Fireball Radius and Thermal Energy of Nuclear Weapons, pp. 1-5, 1979.

[4] H. Brode. Fireball Phenomenology, The PAND Corporation, pp. 25-29, 1964.

[5] ICRP, The 2007 Recommendations of the International Commission on Radiological Protection, ICRP Publication 103, 2007, pp.63-64.

[6] P. John, GBU-43/B 'Mother Of All Bombs', Global Security, July 7, 2011. https://www.globalsecurity.org/military/systems/munitions/moab.htm. Accessed on August 19, 2024.