Investigating the Localized Fallout of a Nuclear Charge, One Year After Detonation

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The use of a nuclear charge for a non-military purpose is referred to as a Peaceful Nuclear Explosion (PNE). The following paper investigated the potential uses of PNE's in civil engineering applications due to their high explosive yield to weight ratios. The investigation carried out looked at the behaviour of the neutron flux from a 100-kiloton nuclear fission charge in soil, primarily focusing on radiation resulting from the neutron activation of soil. The calculated radiation fields present one year after the subterranean detonation of a 100kt warhead were found to be four orders of magnitude greater than the annual radiation background levels in Canada[10]. The effect of this would cause workers one kilometre from the blast site to exceed Canadian Nuclear Safety Commission (CNSC) standards (50mSv/year) for absorbed dose within one working week (89.2 mSv)[11]. It can therefore be concluded that PNE's are not suitable for civil engineering applications within Canada because of the time it takes for radiation levels to decay down to CNSC standards.

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I. INTRODUCTION

Nuclear fission is a nuclear reaction in which a nucleus is split into smaller "daughter" nuclei, causing a release of energy. In order for a fission reaction to occur, the target nucleus must be either fissionable, meaning it is capable of creating fission reaction, or fissile, meaning that it can do so by absorbing a single neutron [1]. When discussing fissile elements Uranium is typically mentioned, this is for three reasons. The first is that the energy release when a uranium nucleus is split is quite substantial (∼200 MeV), so the reaction has a desirable outcome [2]. The second reason is that the reaction itself does not require a large ignition energy, in fact certain geometries and weights of fissile materials are not feasible due to the probability of spontaneous fission. Finally, under certain conditions the fission reaction can be self-sustaining, meaning that the initial neutrons are replaced during the fission process[1]. Fission is used extensively in two industries, the energy industry and the military industry. In this paper, we will strictly be discussing the usage of fission explosions in non-military applications, otherwise known as Peaceful Nuclear Explosions (PNEs). The military uses uranium as a primary stage in a nuclear warhead, and while there are other fissile isotopes that could be used for this purpose; uranium is by far the most popular choice. The preference of uranium is due to its availability and favorable fissile properties, such as the required critical mass weight and geometry. Note that other possible primaries are very similar in terms of overall explosive yield as well as fallout constituents and volume of radioactive isotopes.

Every nuclear bomb ever built shares the common trait of having a fission primary, even if the fission stage produces a fraction of the total yield. The primary is most commonly detonated by means of implosion, a spherical mass of enriched uranium or plutonium, is surrounded by high-powered chemical explosives, the detonation of said explosives compresses the mass into a "super critical state" [3]. Criticality refers to the production of neutrons between successive generations, a subcritical mass-produces less neutrons than it absorbs, and similarly a super critical mass produces more neutrons than absorbed each generation. When the fissile core is compressed and heated, it is able to reach a state of super criticality, thereby multiplying the number of neutrons produced every generation, and the rate at which this process occurs is the key distinction between the way uranium is used in the energy and military industries. In a nuclear bomb all 50+ generations of neutrons are released in approximately 0.01 microseconds, the number of neutrons generated will be discussed later in the paper [4]. It is also worth noting that the usage of the word "primary" was intentional when describing the fission core, most modern warheads contain multiple stages, each acting as a multiplier for the total yield of the explosion. Typically, the secondary stage of a warhead utilizes nuclear fusion, which releases energy and neutrons by joining light nuclei (i.e. hydrogen). The fusion stage of a bomb is desired due to the comparably smaller level of radioactive fallout and much higher energy yield per unit mass, however to initiate a fusion reaction temperatures exceeding 14 million Kelvin are required[1], which eliminates the possibility of ignition via explosives. In summary, it is impossible to create a nuclear bomb without a fission primary, and thus it is impossible to make a nuclear warhead free of heavy radionuclides.

The unit typically used to describe a nuclear warhead is "ton", referring not to the weight of warhead, but rather its explosive yield. When "ton" is used to describe a warhead it makes reference to the energy release by 1 ton of TNT, which is approximately $4.2\text{x}10^{12}$ joules (J), so a 10kt

TABLE I: NUCLEAR WARHEAD YIELDS [3]

Warhead	Yield (kt)	Warhead Weight(lbs):Yield	TNT Weight(lbs):Yield
W44	1	280	2000000
W55	5	135	
W25	1.5	555.33333	
B43	1000	2.06	
W56	1200	1.8333333	
W53	9000	0.9194444	

warhead for example could generate as much energy as a 20 000 lbs TNT equivalent[5]. However, the interesting thing about nuclear weapons is that given their incredibly high explosive yields they maintain an astonishingly low weight to energy ratio when compared with the equivalent volume of TNT. Even more interesting is how non-linear this proportionality is, as can be seen in Table I.

The above data gives reason to suspect that in some non-military applications, the usage of nuclear warheads may provide a more efficient means of obtaining one's goals. Some potential areas in which warheads could possibly be used are as follows: fracking, mining, demolition and large-scale civil engineering tasks (i.e. landscape manipulation). The following paper will investigate the utility of nuclear charges for non-military applications, the key parameter that will be focused on is the relationship between the explosive yield of nuclear bomb and the fallout that remains over time and distance from the epicenter. This is the most important parameter to focus on as it will determine the safety of the work area following the explosion, thus determining the likelihood that nuclear warheads will ever be used as PNEs.

II. EXPERIMENTAL

To determine whether or not nuclear warheads can be used for non-military applications the residual effects of the detonation must first be analyzed to determine whether or not the blast area would be safe to work in after a reasonable amount of time has passed. For the purposes of this paper it is assumed that if any hazards are present after one year has passed, then this method would likely not be considered by the civil engineering industry. It is also assumed that the site of the explosion would be underground; this assumption was made to provide a better estimate for lasting radiation. Above ground detonations are not considered in this paper due to the inconsistency of fallout distributions when subjected to weather patterns. Charge size studied in this paper was chosen for two reasons; the first was so that PNE papers published by the Soviet Union could be used and compared. The second was to provide radiation estimates for a bomb that would be realistically used in non-military applications (i.e. sub megaton range). Being that the Soviet Union has already experimented with PNE's with a yield of 100kt, this was the charge size that calculations were based off of [4].

TABLE II SOIL COMPOSITION AND CROSS SECTION [6-8]

ELEMENT	**Earth Soil (mg/kg)**	**Thermal Cross Section (barns)**	**Fast Cross Section (barns)**	**% Soil**
AL	71300	0.231	5.00E-04	3.82%
CA	13700	4.30E-01	1.34E-05	5.38%
C	45000	0.0035	1.16E-04	4.50%
FE	38000	2.556	2.11E-04	2.23%
K	13600	2.1	3.57E-05	1.34%
O	490000	1.90E-04	7.57E-09	49.00%
SI	330000	0.171	5.00E-04	28.90%
H	15000	0.3326	2.98E-03	1.50%

To determine the residual radioactivity we first calculated the neutron flux from a 100kt bomb, this was approximated by assuming on average 1.4 neutrons are created per fission, each fission releases 200 MeV and that the entire warhead yield is a product of the fission reaction. For a 100kt bomb, this would mean that at the epicenter the energy released would be $2.615x10^{27}\, MeV$ resulting in $1.8305x10^{25}$ neutrons released. The primary sources of residual radiation were from neutron-activated soil and from radioactive bomb fragments. The analysis of neutron activation in soil considered the following elements.

Though there are far more elements present in soil, this approximation was made to simplify the neutron activation analysis; that said, the elements covered in this analysis make up approximately 96% of earth's soil, so while many elements were left out the above elements should provide an accurate estimate. The next step is to determine how neutrons will behave in this environment or more specifically how they are attenuated. Using Equation 1, assuming that the intensity of the final neutron beam (I_F) can be considered negligible when attenuated by a factor equal to the reciprocal of its magnitude ($1x10^{-25}$). It was found that the maximum neutron attenuated radius was 59.33 km in soil.

$$\frac{I}{I_0} = e^{-\frac{\sigma N_A \rho}{A} * x} \qquad (1)$$

In Equation 1[1], I is the final neutron intensity, I_0 is the initial source intensity, σ is the weighted average of the fast neutron cross section of soil in cm^2, ρ is density in g/cm^3, A is the atomic weight of the element in question in g/mol and x is the attenuation distance in centimeters. Note that for this analysis only fast neutrons are being considered, this assumption was made to simplify the problem, though it is important to note that fission neutrons are primarily born in the fast range (> 99%)[1]. Furthermore, the usage of fast neutrons will create an underestimation for the total dose, so that in the event that the dose rate is too high, there will be less doubt regarding the validity of the result. Upon examining the possible neutron activation products it was found that only iron, silicon, and aluminum yielded radionuclides with half-lives exceeding a day and decay products that are unstable. Furthermore, due to the relatively short half-life of aluminum radionuclides their dose contribution drops off almost entirely after one month reducing the relevance of activated aluminum over the course of a year. Neutron activation was modeled by considering the flux distribution degradation radially from the epicenter (See Equation 2[1]), and by considering the radioactive decay of activated nuclei (See Equation 3[1]).

TABLE III: NEUTRON ACTIVATION

	IRON			
DISTANCE	**Time (Days)**			
(M)	0	1	30	365
0	7.31E+6	3.00E+5	1.91E+5	1.03E+3
1000	2.77E+6	1.14E+5	7.25E+4	3.91E+2
2000	1.05E+6	4.29E+4	2.74E+4	1.48E+2
4000	1.51E+5	6.17E+3	3.93E+3	2.13E+1
8000	3.11E+3	1.28E+2	8.13E+1	4.38E-01
16000	1.32E+0	5.42E-2	3.45E-2	1.87E-04
	SILICON			
DISTANCE	**Time (Days)**			
(M)	0	1	30	365
0	7.31E+6	9.56E+5	3.41E+8	1.85E+6
1000	2.77E+6	3.62E+5	1.29E+8	7.00E+5
2000	1.05E+6	1.37E+5	4.90E+7	2.65E+5
4000	1.51E+5	1.97E+4	7.04E+6	3.81E+4
8000	3.11E+3	4.07E+2	1.45E+5	7.86E+2
16000	1.32E+0	1.73E-01	6.18E+1	3.35E-1

$$N\lambda = I\sigma N_A\left(1 - e^{-\lambda t}\right) \qquad (2)$$

$$N\lambda = N_0\lambda e^{-\lambda t} \qquad (3)$$

The results of the activity analysis over varying times and distances are shown in Table III.

The activity, now as a function of time and distance, allowed dose rates to be determined. To determine the dose rates provided by iron and silicon, one first needs to consider the modes by which each isotope decays; it was found that in each case the primary mode is Beta decay, with Betas exceeding 0.5MeV. A high-energy beta particle allowed the following exposure approximation to be used[1]:

$$\dot{X} = \frac{2.7x10^5 A}{r^2} \qquad (4)$$

Where $\dot{X}$ is the exposure rate in rad/hr, and r^2 is the radial distance from the source in meters. In order to provide an accurate estimate for exposure rate at a distance from the epicenter, the exposure due to radionuclides a distance R_1 from the epicenter must be added with those present at the location of the observer, as well those behind the observer from a distance of R_2 (See Figure 1).

Using an arbitrary distance of 1km for R_1, the neutron activation radius determined by Equation 1 would make R_2 for exposure rate calculations up until 950m, then switching to a step size of 1m until 1000m it was found that at a time t of 720 hours after detonation the total exposure rate from radionuclides within R_1 was 20.7 Rad/hour. Contributions from R_2 were calculated using a step size of 1m to a distance of 1050m from the epicenter, after which the step size increased to 50m; values were once again calculated 720 hours after the explosion. The exposure rate from nuclides outside of 1km contributed approximately 20.5 Rad/hr, thereby making the overall exposure rate at 1km equal to 40.2Rad/hr 720 hours after detonation. For exposure rate totals at times closer and further from the detonation please refer to table IV.

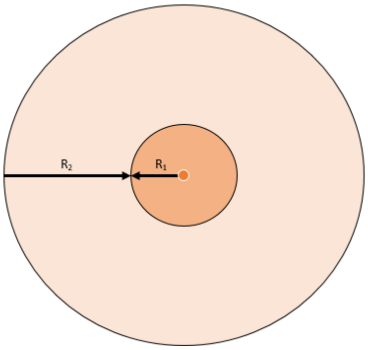

Figure 1: Radiation Exposure from Neutron Activated Soil with Increasing Distance from 100kt Epicenter

To see how the total exposure rate behaves spatially, please see Figure 2. Finally, this data was converted into a dose rate by assuming that all dose is uniformly distributed over the subject's body, providing a final dose rate of 2.23 $mSvh^{-1}$.

III. RESULTS AND DISCUSSION

A 100kt nuclear charge detonated underground resulted in a dose rate of $2.23mSvhr^{-1}$ at a distance of 1km from ground zero, one year from the date of the explosion. When compared to annual dose rate data collected by the Canadian Nuclear Safety Commission (CNSC), it was found that the dose delivered by the 100kt charge was 10 851 times greater per year than the annual background received by Canadians even after one year of decay. The dose rates present after 1 year are far too high to be considered "safe" by any metric, not just the CNSC's. That said, a number of assumptions made throughout this calculation need justification before the acceptance of this result.

TABLE IV: EXPOSURE RATES FOLLOWING A 1KT DETONATION

	Time (hrs)		
	0	**720**	**8760**
	Exposure Rate (Rad/hr)		
R_1	7.31E+06	7.19E+06	2.48E+04
R_2	2.77E+06	2.73E+06	9.39E+03
TOTAL	1.05E+06	1.03E+06	3.56E+03

The effect of assuming all neutrons are born in the 14MeV range ultimately made the solution to Equation 1 much larger than it would be in reality. Neutron absorption cross section scales inversely to neutron energy prior to resonance absorption peaks, therefore the calculated neutron attenuation radius would appear larger than it should be[1]. That said, this would not affect the overall activation of the soil surrounding the bomb, instead a lower cross section would result in a lower concentration of radiation spread over a larger area rather than highly concentrated radiation appearing in a smaller radius. Therefore, the overall dose rate would be much greater at the epicentre if the thermal cross section of soil was used to calculate the attenuation rate. Considering that the overall point this paper is to investigate whether or not these charges can be used without exceeding CNSC safety standards, this assumption is validated on the grounds that the dose rates must be safe at any radius from the explosion. Another effect on neutrons not considered in this paper is the thermalization of fast neutrons, or the neutron scatter cross section. This effect lowers the neutrons energy as it inelastically collides with atoms, which both lowers the attenuation radius and deposits a large amount of energy in the soil, which is re-emitted as gamma and x-rays. This effect was neglected due to the lack of empirical data for neutron cross sections with varying neutron energy, however the thermalization of neutrons would once again only alter the nuclide distribution in soil, not the overall concentration, therefore by the same reasoning this assumption is acceptable. The last factor not included in this dose estimate is the efficiency of the 100kt bomb used. Nuclear warhead efficiencies refer to the volume of the fission core that is burnt up in the explosion, this efficiency is largely dependent on the pressures and temperatures generated prior to fireball expansion. Efficiency in this case is impossible to determine without first selecting a bomb and then detonating it, though data from Fat Man and Little Boy suggest that efficiencies approaching 50% in a pure fission warhead are not likely [3]. The effect of an inefficient bomb detonation is the scattering of heavy, highly radioactive particulates over the blast radius. Even if the bomb in question was 100% efficient, a well-known component of the radiation dose comes from the neutron activation of bomb components, most of which are heavy elements with large neutron cross sections [3]. It is therefore reasonable to assume that the bomb components and core fragments do not add to the overall dose in this particular case, being that the neutron activation of soil alone eliminates the prospect of a radiation free work environment 1 year after detonation.

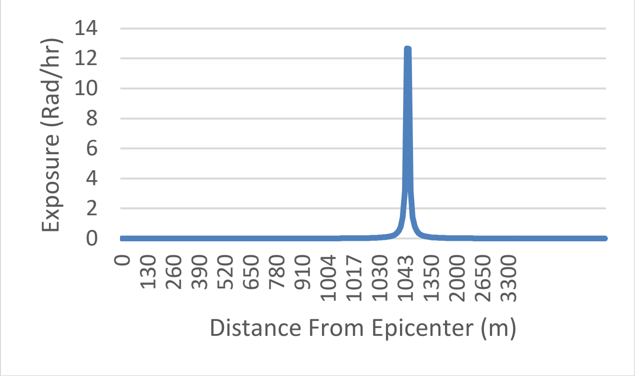

Figure 2: Dose Rate Delivered at 1km from 100kt Epicenter

The largest assumption made in this paper was that the charge to be used would be a 100kt fission bomb, even though more efficient and less powerful nuclear charges exist. The reason that other bomb configurations (thermonuclear) were not selected for testing was simply because the neutron yield from a thermonuclear warhead greatly eclipses that of a standard fission warhead, though it does provide a much higher efficiency [3]. Because the core fragments and activated bomb components were not considered in this paper, the added efficiency of a thermonuclear charge carries no weight, furthermore the increase of neutron flux would overall add to the neutron activation of the surrounding soil. In summary, a thermonuclear charge can eliminate the long-lived isotopes that result from fission, but the increase in neutron flux would reverse this effect. Similarly, with smaller fission charges, there is not a substantial reduction in soil activation, at least not to the point where it is safe after 1 year as can be seen in Table V.

Due to the direct proportionality of neutron flux to dose rate, the reduction in charge size by a factor of 1000 would only reduce the dose rate by the same factor; therefore, the resulting dose would still be an order of magnitude greater than background radiation values per year in Canada.

IV. CONCLUSION

This paper was written to attempt to validate the usefulness of Peaceful Nuclear Explosion, in this particular case the criteria for usefulness was a safe working area within 1 year of detonation. Safe, in this context would be no greater than 50mSv dose received in less than 1 year, it is assumed that the time spent anywhere in the irradiated area corresponds to a 40 hour work week [10, 11]. A 100kt nuclear charge would provide a dose of 89.2 mSv after completing 1 workweek 1 year after detonation from a distance of 1 km. This clearly exceeds CNSC standards, and thus this method is not suitable for civil engineering applications within Canada. The dose rates calculated in this paper are not an accurate reflection of the dose rates that would be present following the detonation of a nuclear charge, however given that the dose rates calculated are an under estimate of the radiation that would be present after detonation, the overall conclusion of this paper still stands. In closing, while the power of a nuclear charge greatly eclipses any other explosive created to date, it comes with a great cost, one that humanity cannot afford.

V. ACKNOWLEDGEMENTS

TABLE V: NEUTRON FLUX FROM EXPLOSIVE YIELD

YIELD		**Neutrons Produced**
KILOTON	**MeV**	
0.1	2.615E+24	1.8305E+22
1	2.615E+25	1.8305E+23
10	2.615E+26	1.8305E+24
100	2.615E+27	1.8305E+25
1000	2.615E+28	1.8305E+26

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VI. REFERENCES

[1] J. Turner, *Atoms, Radiation, And Radiation Protection*, 1st ed. (Pergamon Press, New York, 1986).

[2] R. Vandenbosch and J. Huizenga, *Nuclear Fission*, 1st ed. (Academic Press, New York, 1973).

[3] T. Cochran, W. Arkin and M. Hoenig, *U.S. Nuclear Forces And Capabilities*, 1st ed. (Ballinger Pub. Co., Cambridge, Mass., 1984).

[4] S. Glasstone and P. Dolan, *The Effects Of Nuclear Weapons*, 1st ed. (U.S. Dept. of Defense, [Washington], 1977).

[5] See: http://nuclearweaponarchive.org/Nwfaq/Nfaq4.html for more information regarding the design of fission and thermonuclear warheads; Accessed November 2016

[6] See: http://ncnr.nist.gov/resources/n-lengths/ for more information on neutron cross sections; Accessed October 2016

[7] *Table Of Simple Integral Neutron Cross Section Data Fromjef-2.2, ENDF*, 1st ed. (1994).

[8] V. Alekseenko and A. Alekseenko, Journal Of Geochemical Exploration 147, (2014).

[9] M. Nordyke, Annals Of Nuclear Energy 2, (1975).

[10] See: http://laws.justice.gc.ca/eng/regulations/SOR-2000-203/ for more information on radiation safety regulations

[11] See:http://nuclearsafety.gc.ca/eng/resources/radiation/introduction-to-radiation/radiation-doses.cfm for more information on CNSC radiation requirements