Protection factors of modern armored tanks against enhanced-radiation and fission nuclear warheads

By Sümer Şahin and André Gsponer***

Abstract

The radiation protection capability of the tanks of the generation from the 1940's through the 1980's against nuclear weapons is analyzed. Different mathematical models for the estimation of the biological dose inside the tank are reviewed and compared with transport calculations (in S_8-P_3 approximation), which are presented here. The results show that modern tanks have enhanced protection capability against neutron bomb radiation, making the deterrance potential of the latter questionable. On the other hand, older-generation tanks are vulnerable targets for neutron weapons as well as for modern conventional anti-tank weapons.

Zusammenfassung

Abschirmfaktoren von Panzern moderner Bauart gegen die Neutronenbomben und Kernspaltungswaffen

Das Strahlenabschirmungsvermögen von Panzern der Bauarten von 1940 bis 1980 wird analysiert. Verschiedene Rechenmodelle zur Abschätzung der biologischen Dosis innerhalb des Panzers werden überblicksweise vorgestellt und mit den Ergebnissen der hier dargestellten Transport-theoretischen Berechnungen (in S_8-P_3-Näherung) verglichen. Die Ergebnisse zeigen, daß moderne Panzer eine hohe Abschirmung gegen die Neutronenbombe gewährleisten, was das Abschreckungspotential der letzteren in Frage stellt. Andererseits stellen die Panzer älterer Generationen leicht verwundbare Ziele für die Neutronenbomben und für moderne konventionelle Panzerabwehrwaffen dar.

DESCRIPTORS

ENHANCED RADIATION WEAPONS
NUCLEAR WEAPONS
NUCLEAR BOMBS
ARMORS
TANKS
SHIELDS
NEUTRON TRANSPORT THEORY
NEUTRON ABSORBERS
SHIELDING
NEUTRON LEAKAGE
NEUTRON SPECTRA

1. Introduction

The neutron bomb was first designed by the USA to develop an ultimate defence weapon against massive tank troups. The main idea is to produce a high number of 14-MeV (D, T) fusion neutrons spontaneousely, assuming that these can easily penetrate the tank walls, resulting in the incapacition of the crew, with only limited collateral damage [1].

The effects of the neutron bomb on a tank crew can be analyzed with conventional calculational methods for the radiation shielding. Thus, a series of investigations have been published in the unclassified scientific literature. One of the earliest publications estimated that the radiation protection factor for the crew due to the tank wall would be about 2 if the tank is made of only a conventional armor steel, but this factor rises to higher values (20 to 100) for a modern tank with a composite armor [2, 3]. Different independent investigations have come out with similar conclusions [4–6].

Some other groups have calculated low protection factors for tanks without giving details about the structure of the investigated tank walls [7, 8]. Ref. [9] also reported low protection factors for a tank wall design suggested by *Baruch* [4].

A discussion has taken place between the protagonists of these two different opinions [10–12], focussed mainly on the following items:

a) Effects of the spectral shifts within the neutron bomb itself.
b) Difference in the modelling for the neutron transport calculations.
c) Possibility of the improvement of the protection factors by adding some neutron absorbing materials to the standard tank wall design.

Item (a) has been analyzed thoroughly, with the conclusion that the spectral shifts within the neutron bomb itself lead to even higher radiation protection factors for the tank crew [13–15]. Therefore, these spectral shifts should not be ignored in such investigations.

Low protection factors (about 2) for a representative *medium tank* with a 15 cm thick homogeneous steel armor have also been recently published by the Los Alamos Scientific Laboratory [16, 17]. However, in a study for the West German Defence Ministry, an all-round protection factor of 20 was set as a minimum design goal for a modern *heavy tank* [6]. Unfortunately, low protection factors, calculated for old-fashion tanks, are often quoted for modern tanks also, in some of the popular literature [18].

The main reason for improving tank armor is not the threat of fission or fusion nuclear weapons, but simply to provide better protection against *conventional* anti-tank weapons. However, because these improvements necessitate the use of light-weight and hydrogen-rich materials, it turns out that better protection against conventional anti-tank weapons also provides better protection against radiation from nuclear weapons of all kind.

Experimental measurements of the neutron-dose attenuation by tank-wall-like shields have been made for the West German Defence Ministry [19]. According to these data, measured for 14-MeV neutrons, the protection factor of a shield consisting of 8 cm of steel and 8 cm of polyethylene is about 6, thus 3 times larger than for a steel armor of the same total thickness.

The question whether a modern tank would provide a high or low protection factor against the neutron bomb has a crucial importance for the tactial usefulness of the latter. The high protection factors, reported in references [2–6, 13–15] for modern tanks make the tactial efficiency of the neutron bomb questionable, because they lead to a shrinkage of the kill radii with radiation effects to the size of the kill radii through mechanical effects of the bomb.

In this work, the unclassified military information has been reviewed carefully, for radiation dose calculation model for tanks (item b), the tank-wall technology for modern tanks (like T 80, XM-1, Leopard II) and relatively older tanks (like T 72, M 60) (item c).

In the following Sections, the tank technology is reviewed, different calculation models for tank-wall radiation protection factors are discussed, and realistic radiation kill radii are estimated. A more detailed account of this work can be found in [20].

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2. Anti-tank weapons and tank wall technology

After the second World War, anti-tank technology made great progress. One can distinguish at least 6 different kinds of armor piercing projectiles with different ways of incapacitating the tank crew [21]. The most common techniques are (a) the so-called HEAT (high-energy anti-tank) projectiles in which a shaped charge is exploded at a few tens of centimeters from the tank to form a high-velocity plasma jet [22], and (b) the APDS (armor-piercing discarding-sabot) round consisting of a heavy, small-caliber core surrounded by a much lighter sabot which breaks up as the projectile leaves the gun barrel [23]. Then, the small-caliber core approaches the tank with a very high velocity.

If both the projectile and the armor are incompressible and their relative velocity is high, the final penetration depth is given by the so-called density law [24, 25]

$$D = L \sqrt{\delta_p / \delta_a}$$

where L is the length of the shaped charge jet (usually copper) which is a function of the diameter of the shaped change, δ_p is the density of the projectile, δ_a is the density of the armor. Modern anti-tank weapons, such as AC 300 Jupiter, AT 4 or APILAS can penetrate up to 80 to 90 cm of homogeneous steel [26, 27].

The weight per unit armor area can be derived from Eq. (1) as

$$W = L \sqrt{\delta_p \cdot \delta_a} \; .$$

Thus, a lighter element, for example plexiglass, is, on basis of weight, $\sqrt{7.8/1.2} = 2.5$ times more efficient than steel to stop projectiles.

The second important effect of a light-weight material is its compressibility. For example, in plexiglass, compressibility effects reduce the penetration depth of high-velocity jets by as much as 30% [28]. Thus, plexiglass becomes about 3.3 times more efficient than steel against shaped charges.

Furthermore, low-weight heterogeneous materials such as plastic reinforced fiber glass or kevlar composites are also more efficient than steel in defeating kinetic energy penetrators as well as shaped charges [23, 25]. However, the use of massive quantities of low density materials is not desirable for obvious design reasons.

In practice, the new generation of tanks is made of layers of different materials, such as armor steel, ultra-hard heat resistant ceramic (Al_2O_3 or B_4C or TiB_2 – the latter two are very expensive to fabricate), plastic or composite materials, air spaces, randomly shaped objects (like housings) and most possibly an inner layer of tough plastic [29].

In the course of this study, three generations of tank designs (1940, 1960, 1980) will be evaluated in respect to their protection capabilities against prompt radiation from nuclear weapons (Fig. 1).

a) The 10 cm thick homogeneous steel armor which is typical of World War II and early 1950's tanks. Such armor offers negligable protection against modern anti-tank weapons, and of course the neutron bomb. However, these tanks are still in use in many third-world and few NATO countries, such as in Turkey.

b) Typically the 20 cm thick armor is utilized for the M 60 and T 72 tanks. An external armor steel of 2.5 cm is followed by a layer 8 cm thick of a material such as glass [30], and by a second armor plate of 8 cm which provides structural strength. Addition of 1.5 cm thick boronated (5 weight-%) plexiglass layer to the inner side would enhance the radiation protection factor, as suggested earlier [2, 3, 13–15]. There are other ways to upgrade the existing M 60 tanks, for example with the help of a semi-active (plastic, water, diesel fuel) or active (explosive material) layer. A recent example of active armor plate could be witnessed on the Israeli tanks during the 1982 in Lebanon. This active armor explodes outwards instantaneously in order to break up the incoming HEAT jet.

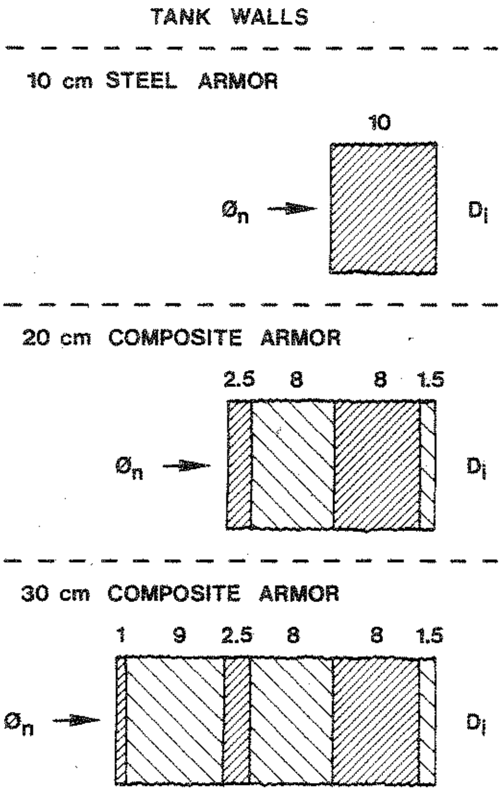

Fig. 1: Tank wall models for numerical calculations. Dense hatchings: armor steel; sparce hatchings: light weight material

c) The 30 cm thick armor is typical of modern tank designs, such as the XM-1, Leopard II and T 80. Its structure is the same as NATO's triple composite heavy-tank target [26, 27]: the first, third and fifth layers are made of armor steel of 1, 2.5 and 8 cm thickness, respectively; The gaps between the steel plates are filled with various layers of composite materials, ceramics, plastics, etc. For neutron physics calculations, these gaps, as well as the last layer behind the steel can be replaced by boronated plexiglass (density 1.2 g/cm^3) containing 5 weight-% of natural boron. For the three types of tank walls, high-strength armor-steel [31] with a density of 7.83 g/cm^5 [32] has been used. This armor steel contains, besides iron, 5.5% Ni, 0.7% Cu, 0,6% Mn, 0.47% Mo, 0.38% C, 0.08% Al and 0.08% V. In all calculations, the non-steel layers were replaced by 5% boronated plexiglass. In the 20 and 30 cm armors, the thickness of the 1.5 cm inner layer also takes into account the various hydrogen rich materials (diesel fuel, ammunition, plastic and fiber glass components, etc.) which provide additional neutron protection to the crew [29, 33].

3. Numerical calculations

The radiation effects of the nuclear explosions in the atmosphere can be studied with the help of neutron generators experimentally, and numerically with the help of computer simulation. There are different ways of numerical simulation which will be reviewed briefly.

3.1. Numerical methods

Numerical methods to assess the biological dose from a neutron bomb explosion can be divided into three groups:

a) Multi-dimensional, multi-group models [33],
b) One-dimensional, multi-group models [3, 7–9],
c) Single-group models [6, 20].

3.1.1. The vehicle code system (VCS)

The VCS [33] of the Oak Ridge National Laboratory uses a two dimensional discrete-ordinate air-transport calculation coupled to a three-dimensional adjoint Monte Carlo calculation. The reference problem is illustrated in Fig. 2.

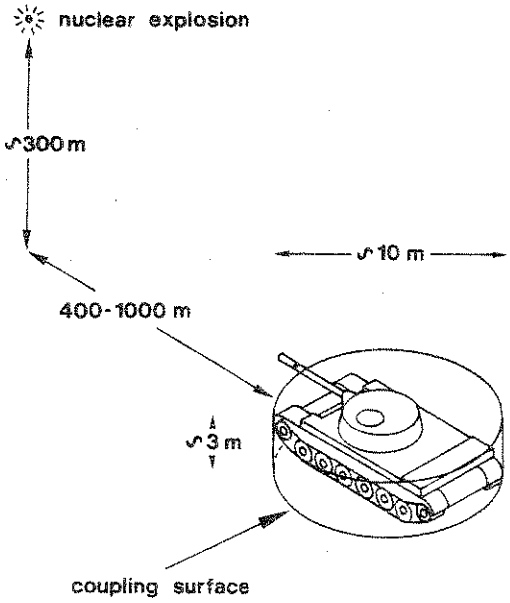

Fig. 2: Vehicle code system model used to calculate the nuclear weapon radiation dose on a tank crew

In the first step, the neutron and gamma-ray fluxes are calculated on a *coupling surface* surrounding the vehicle. In the second step, the dose inside the vehicle is calculated, using the fluxes on the coupling surface as an input. The protection factor is defined as the ratio of the radiation dose at about 1 m above ground with the vehicle absent (the free-field dose, D_f), to the dose with the vehicle present (the in-vehicle dose D_i):

$$PF = D_f/D_i \; . \qquad (3)$$

Although the VCS represents one of the most sophisticated models of simulation, the multi-dimensional, multi-group character of the system requires very high computer expenses. Hence, for parametric studies, it is more convenient to use one-dimensional multi-group models, as described in the following sections. In these models, one generally assumes a spherical symmetry. This corresponds to the requirement that a tank should have an all-round nuclear protection factor at least equal to that provided by its frontal armor.

3.1.2. The coupling surface model

The main features of the coupling surface model are summarized as follows:

a) For the kind of shields considered in this work, the prompt gamma-ray dose is always smaller than the prompt neutron dose. The gamma radiation is therefore neglected relative to the neutrons.
b) The neutrons reflected by the armor have only a small probability of interacting with the tank a second time. Therefore, it will be a good approximation for the incident neutron flux at the coupling surface to be taken equal to the free-field neutron flux (with the tank absent).
c) In the first step, neutrons are transported in a sphere of air surrounded by 0.5 m of earth. This determines the free-field dose D_f, the energy and angular spectrum of the neutron flux at the coupling surface, 5 m above ground.
d) In the second step, the neutron transport is calculated in a plane geometry through the layers of 5 m air, the tank wall, 1 m air and 50 cm ground (Fig. 3).
The in-vehicle dose D_i is taken in the middle of the 1 m air. The protection factor is calculated as described in [3].

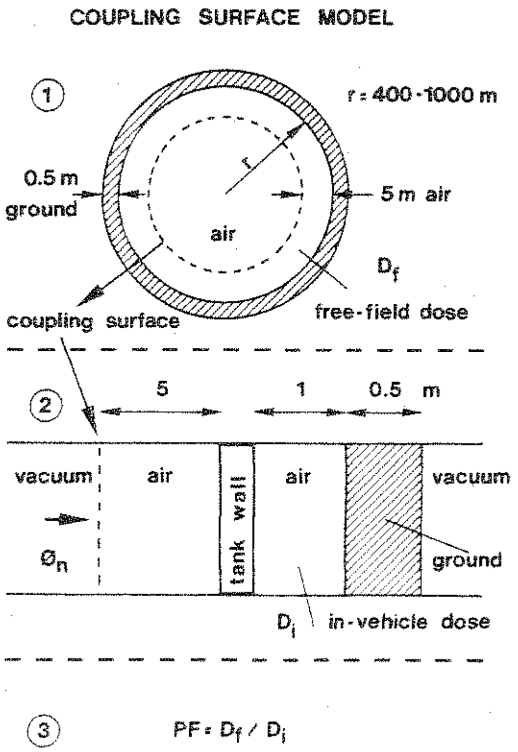

Fig 3: Coupling surface model. Step 1: assessment of the free field dose; step 2: calculation of the in-vehicle dose; step 3: definition of the tank protection factor

3.1.3. The shell model

The coupling surface model requires the transfer of a considerable amount of data (angular fluxes at the coupling surface) between the first (item c) and second (item d) steps.

The coupling surface model can be simplified by carrying out the second step also in spherical geometry with the incorporation of the tank wall 1 m above the ground. Then, the protection factor *PF* is defined as the ratio of the free-field dose D_f 1 m above the ground with the tank absent (first step) to the in-vehicle dose D_i behind the tank wall (second step). It turns out that the shell-model gives comparable results to the coupling surface model. Fig. 4 describes the shell model.

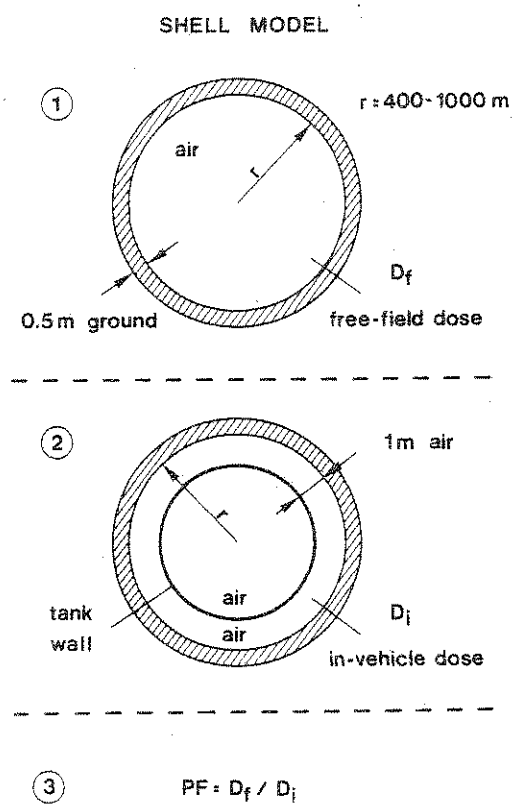

Fig. 4: Shell model. Step 1: assessment of the free field dose; step 2: calculation of the in-vehicle dose; step 3: definition of the tank protection factor

The shell model, reduced to the second step alone, has been used in some of the previous work [7–9]. However, the reflection or absorption in the tank wall can lead to an overestimation or underestimation, respectively, of the protection factor by the second step alone.

3.1.4. The spherical source model

In the spherical source model, the tank is represented as a spherical chamber with a radius of one or two meters, imbedded in an air sphere with a radius equal to the explosion distance [17]. The neutrons from the enhanced radiation warhead (ERW) are distributed on the surface of this external air sphere and move inwards to the center where the tank is located. The protection factor is defined as the ratio of the doses just outside and at the center of the tank.
This model may give the protection factors close to reality, but it does not represent an authentic model to calculate the absolute dose factors. Furthermore, the ground effects are neglected.

3.2. *Neutron source spectra for fission and fusion weapons*

In this work, three different neutron source spectra for fission and fusion weapons have been considered.

3.2.1. Pure (D, T) fusion source (14 MeV)

Neglecting the spectral shifts within the neutron bomb itself, a yield of 1.49×10^{24} neutrons per kt is obtained [16]. This yield is shown in Fig. 5 with the triangle labelled "14 MeV".

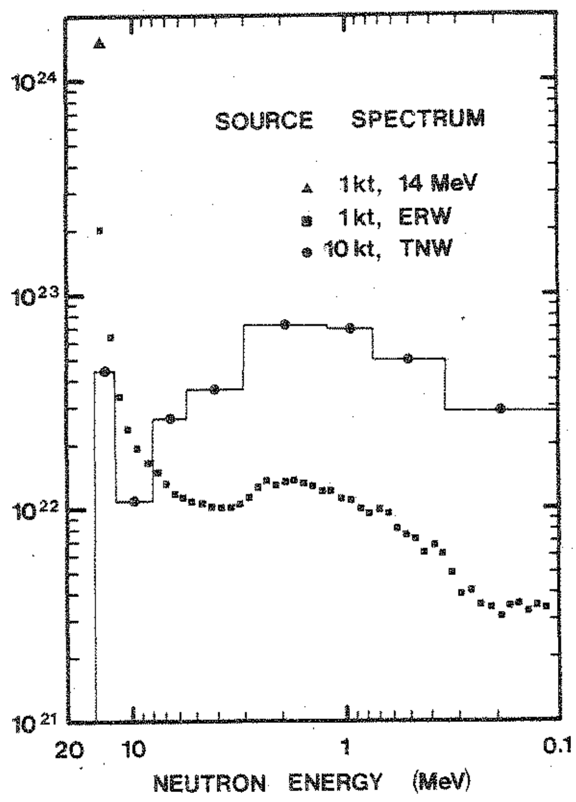

Fig. 5: Neutron source spectra for three different nuclear weapons

3.2.2. Tactical nuclear weapons (TNW)

The neutron leakage spectrum of a fusion-boosted tactical nuclear weapon ([33], p. 35) will be used to compare the enhanced incapacitation potential of the neutron bomb with that of the existing tactical weapons. The energy distribution of the initial neutrons are depicted in Fig. 6 with a total yield of 3.1×10^{24} neutrons for a 10 kt TNW.

3.2.3. Enhanced radiation warhead (ERW)

Previous work indicated that the spectral shifts within a neutron bomb lead to higher protection factors for the tank crew [13–15]. In this work, the neutron bomb leakage spectrum was calculated through the following procedure:
A fusion yield of 1 kt corresponds to the complete fusion of 12.5 g of (D,T) and releases 1.49×10^{24} 14-MeV neutrons.
In a practical neutron bomb, the fusile fuel (Li_2DT) will be compressed by the black-body radiation of the fission trigger up to 50 times of its original density ([34], p. 31), Fig. 7.

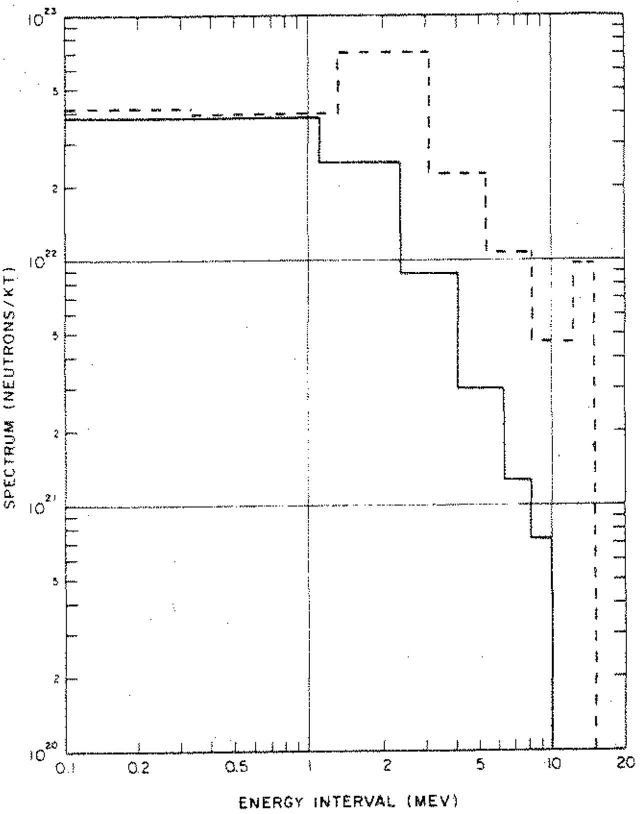

Fig. 6: Unclassified information on the neutron leakage spectra of nuclear weapons per kiloton equivalent total energy yield. Solid line: neutron spectrum for a fission weapon [39]. Broken line: neutron spectrum for an unclassified tactical fission weapon [33]

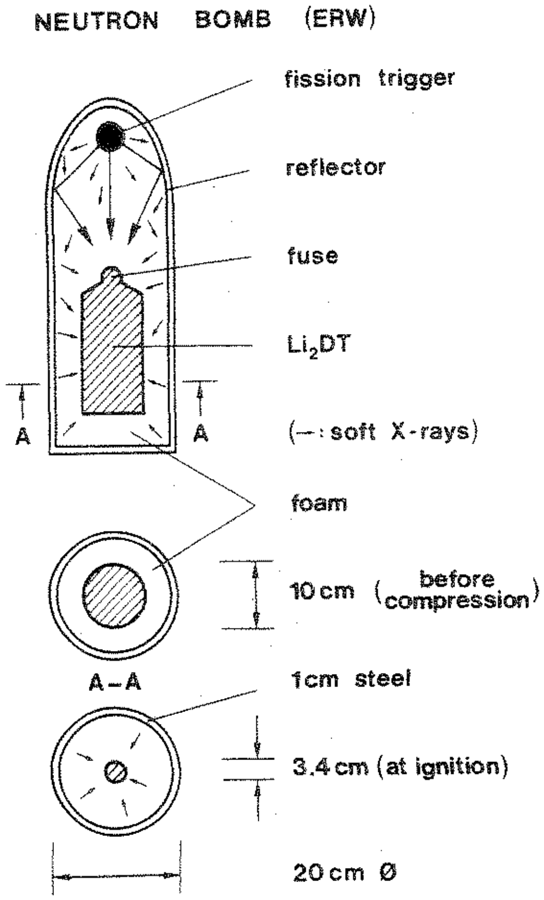

Fig. 7: Neutron bomb model used to calculate the leakage spectrum

As the real compression profile in a neutron bomb is not available in the unclassified literature, it has been approximated to be a linear function ranging from 50 at the center up to 5 at the surface of Li_2DT sphere of 425 g (for a burn-up of 10%).

The fusion reaction rate is proportional to the square of the density, hence most of the neutrons are produced near the center. The leakage spectrum is shown in Fig. 5. The number of neutrons leaking is 1.16×10^{24} with a total energy corresponding to 0.28 kt, i.e., the outcoming neutrons carry only 28% of the detonation energy. 72% of the energy of the neutron bomb will be released in favour of blast and thermal effects. Lower compression and higher fusile fuel burn-up increases the neutron kinetic energy fraction to some degree, but it becomes very difficult to suppress the blast and thermal effects of a neutron bomb below 50%, particularly due to the contribution of alpha particles and the fission trigger. In the evaluation of the neutron leakage spectrum in Fig. 5, the neutrons released by the fission trigger were neglected. The contribution of the fission neutrons to the radiation dose is about one order of magnitude lower, as compared to that of the fusion neutrons in an ERW [12].

3.3. *Protection factor calculations*

A series of neutronic calculations have been performed by solving the Boltzmann transport equation [35] in S_8-P_3 approximation with the help of the code ANISN [36] using the data libraries DLC-2F [37]. Three different weapon neutron source spectra were used, as defined in Section 3.2 and plotted in Fig. 5.

The radiation doses were evaluated for the following cases (cf. Table 1):

- Dose in infinite air D_∞, calculated by using the model in ref. [2, 3, 13–15] and plotted in Fig. 8 in detail.
- Free-field dose D_f, calculated using the shell model described in Section 3.1.3.
- Dose in front of the vehicle D_{fv}, included in Table 1 for comparison reasons as it has been used by other workers [7–9] to evaluate the protection factor.
- In-vehicle dose D_i, calculated in the second step of the shell model (Section 3.1.3.) for three different tank wall models as already described in Section 2 and shown in Fig. 1.

In Table 1, different tank models are grouped as follows:

- 10 cm shield: World War II and early 1950 generation tanks,
- 20 cm shield: 1960 generation tanks, such as M 60, T 72,
- 30 cm shield: 1980 generation tanks, such as XM-1, Leopard II, T 80.

One can easily recognize that old fashioned tanks with 10 cm armor do not offer any significant protection against neutron or tactical nuclear weapons. 1960's generation tanks have a moderate protection against ERWs (around 15), whereas the protection capability of 1980's modern generation tanks is appreciable (30 to 50).

This high protection capability of modern tanks reduces the radiation kill radii drastically, as shown in Table 2. For modern tanks, kill radii by blast or prompt neutron radiation are comparable (280 m) [38]. Hence, the neutron

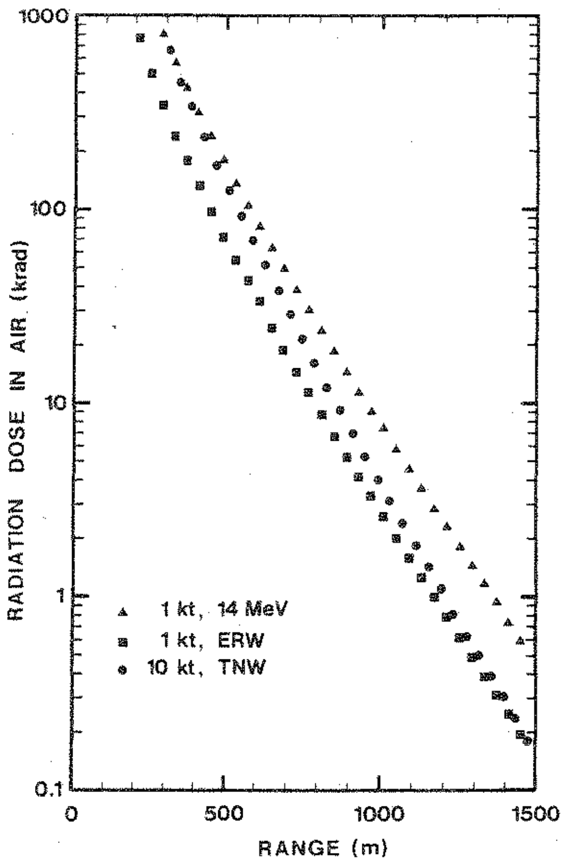

Fig. 8: Biological radiation dose in air resulting from different nuclear weapons

bomb does not represent a deterrent defense weapon against modern tanks.

4. Conclusion

The present study has tackled the question whether the neutron bomb can be considered as an ultimate defense weapon or not against the massive tank troups, taking into consideration the neutron spectrum attenuation within the bomb and the development of tank technology from the 1940's through the 1980's. The main results of this study can be concluded as follows:

a) There are important spectral shifts within the neutron bomb itself, confirming previous investigations [12–15]. These lead to higher protection factors for the tank crew against prompt neutron radiation. Furthermore, a substantial fraction of the neutron energy will be deposited in the bomb, enhancing the thermal and blast effects of the neutron bomb, thus reducing the kill radii through prompt radiation.

b) Modern tanks, which contain substantial quantities of light elements (H, C, O) in their armor against conventional modern anti-tank weapons, also provide a high protection against neutron weapons, thus reducing the radiation kill radii to the order of the kill radii by blast and thermal effects of a neutron bomb. Hence, the latter cannot be considered as an effective defense weapon against modern tanks.

On the other hand, old fashion tanks have negligible

Table 1: Radiation doses for nuclear weapons and tank protection factors

Neutron source	Explosion distance m	Type of armor	D_∞ krad	D_f krad	D_{fv} krad	D_i krad	PF
14 MeV 1 kt	400	none	319	373			
		10 cm			467	163	2.3
		20 cm			366	40.1	9.3
		30 cm			332	15.6	24
	700	none	38.7	46.8			
		10 cm			58.9	19.6	2.4
		20 cm			46.7	3.9	12
		30 cm			42.2	1.4	33
	1000	none	5.83	7.54			
		10 cm			9.57	3.08	2.5
		20 cm			7.58	0.54	14
		30 cm			6.81	0.18	42
ERW 1 kt	400	none	131	145			
		10 cm			195	65.4	2.2
		20 cm			153	12.0	12
		30 cm			132	4.2	35
	700	none	14.5	16.9			
		10 cm			22.5	7.3	2.3
		20 cm			17.5	1.18	14
		30 cm			15.6	0.39	44
	1000	none	2.03	2.57			
		10 cm			3.41	1.08	2.4
		20 cm			2.66	0.162	16
		30 cm			2.38	0.050	51
TNW 10 kt	400	none	278	292			
		10 cm			426	133	2.2
		20 cm			310	11.8	25
		30 cm			265	2.8	103
	700	none	24.9	28.6			
		10 cm			40.5	12.4	2.3
		20 cm			30.3	1.05	27
		30 cm			26.3	0.25	114
	1000	none	2.8	3.57			
		10 cm			4.98	1.5	2.4
		20 cm			3.77	0.13	28
		30 cm			3.30	0.031	115

Table 2: Kill radii by blast and radiation effects.
Radii in m

Kill radii by blast effects [38]

Blast overpressure psi	ERW 1 kt	TNW 10 kt
17	280	640
6	430	910
3	760	1520

Radii at which the radiation dose is 10 krad (kill radii by immediate permanent incapacitation)

Type of armor	14 MeV 1 kt	ERW 1 kt	TNW 10 kt
none	930	780	840
10 cm	790	640	720
20 cm	550	400	420
30 cm	430	280	260

protection against modern anti-tank weapons and also against neutron weapons.

Old fashion tanks are unsafe but modern tanks are relatively safe.

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