

Negative Effects of Over-Reaction in the Aftermath of Radiological Emergencies

Negatywne skutki nadmiernej reakcji w następstwie sytuacji zdarzeń radiacyjnych

Yehoshua Socol, Moshe Yanovskiy
Jerusalem College of Technology, Israel

Abstract: Despite the vast amount of literature on radiological emergencies, to the best of our knowledge there is no systematic review of probable scenarios and their consequences. A red team simulated best efforts to inflict maximal damage to the society by various means of radiological attacks. It turned out, that the direct radiogenic health consequences of any conceivable radiological accident, natural or man-made, are much less dangerous than those which are usually perceived. In each scenario, direct health effects are only a small part of the damage caused by fear and over-reaction; the damage is somewhat independent of the small health effect predicted for most of the scenarios. The reason is that nuclear radiation has become perceptually connected with nuclear apocalypses. This connection has caused the emotional description of radiological emergencies to frequently substitute quantitative considerations. Therefore, it is vital to educate decision makers, first responders and the public about the factual extent of possible radiological consequences, as well as about the very real danger of over-reaction. Since the extent of the countermeasures deployed is unavoidably connected, in the eye of the public, with the extent of the danger, we suggest launching educational campaigns that explain the factual extent of the radiation risk, followed by easing regulations and narrowing safety margins. Such measures will probably be the most efficient method of countering radiological terrorism: by depriving any adversary of the most important ability which is to cause an over-reaction.

Keywords: nuclear power, radiation safety, dirty bomb, radiation, health effects, radiophobia, education.

Streszczenie: *Pomimo ogromnej ilości literatury na temat sytuacji nadzwyczajnych związanych z promieniowaniem, według naszej wiedzy nie przeprowadzono dotychczas systematycznego przeglądu prawdopodobnych scenariuszy i ich konsekwencji. Zespół „czerwonych” (symulujących przeciwnika) symulował wszelkie możliwe działania mające na celu wyrządzenie społeczeństwu maksymalnych szkód za pomocą różnych metod ataków radiologicznych. Okazało się, że bezpośrednie konsekwencje zdrowotne każdego możliwego wypadku radiologicznego, naturalnego lub spowodowanego przez człowieka, są znacznie mniej niebezpieczne niż te, które się powszechnie uważa. W każdym scenariuszu bezpośrednie skutki zdrowotne stanowią jedynie niewielką część szkód spowodowanych strachem i nadmierną reakcją; szkody te są w pewnym stopniu niezależne od niewielkiego wpływu na zdrowie przewidywanego w większości scenariuszy. Powodem jest to, że promieniowanie jądrowe zostało percepcyjnie powiązane z nuklearnymi apokalipsami. To powiązanie sprawiło, że emocjonalny opis zagrożeń radiologicznych często zastępuje rozważania ilościowe. Dlatego niezwykle ważne jest edukowanie decydentów, służb ratowniczych i społeczeństwa o faktycznym zakresie możliwych konsekwencji radiologicznych, a także o bardzo realnym niebezpieczeństwie nadmiernej reakcji. Ponieważ zakres zastosowanych środków zaradczych jest nieuchronnie związany, w opinii publicznej, ze skalą zagrożenia, sugerujemy przeprowadzenie kampanii edukacyjnych wyjaśniających faktyczny zakres ryzyka radiacyjnego, a następnie złagodzenie przepisów i zawężenie marginesów bezpieczeństwa. Takie środki będą prawdopodobnie najskuteczniejszą metodą przeciwdziałania terroryzmowi radiologicznemu: pozbawiają każdego przeciwnika najważniejszej zdolności, jaką jest wywołanie nadmiernej reakcji.*

Słowa kluczowe: energia jądrowa, bezpieczeństwo radiacyjne, brudna bomba, promieniowanie, skutki zdrowotne, radiofobia, edukacja.

1. Introduction

Due to historical factors, ionizing radiation has instilled fear in people due to its association with nuclear catastrophes. Well before the testing or deployment of the first atomic bomb, an official report cautioned that “civilization would have the means to commit suicide at will” (Smyth 1945) [18]. It appears that both the United States and the USSR, as superpowers, had a vested interest in amplifying the consequences of radiation to bolster their nuclear deterrence capabilities (Jaworowski 1999) [12].

Following the atomic bombings of Japan and the onset of the nuclear arms race, numerous scientists became deeply concerned about the very survival of humanity. When contemplating the immense dangers of nuclear warfare, one can sympathize with those scientists who emphasized the risks of radiation despite the lack of substantial scientific evidence, hoping thereby to impede the escalation of the nuclear arms race. Nonetheless, it has been suggested that some scientists may have had an additional, less selfless motive for promoting the perception of excessive radiation hazards. This perception would facilitate their acquisition of funding and strengthen their involvement in decision-making processes (Mauer 2009, Ch. 12; Yanovskiy et al. 2019) [15, 24]. The linear no-threshold (LNT) model (Lee and Elmore 2026) [14] then emerged. The LNT model assumes that every radiation dose, no matter how small, increases cancer risk. Although this model is still regarded by official bodies as conservative and prudent for radiation protection purposes (Socol et al. 2019) [20], it remains the subject of serious scientific controversy (Calabrese et al. 2018; Kardamakis et al. 2023; Tubiana 2005;) [4, 13, 21]. Among other things, the LNT hypothesis underlies the current perception of the consequences of accidents in the nuclear power sector.

An unwarranted fear of radiation – radiophobia – has emerged. Furthermore, the unwarranted fear endures even after the conclusion of the Cold War and is exploited by certain groups to advance their own agendas (Mauer 2009, Ch. 12) [15]. The unjustified permanent relocation of Chernobyl (Socol 2015) [19] and the prolonged evacuation of Fukushima (Yanovskiy et al. 2022) [25]; affecting over 100,000 individuals in each case, were actually over-reaction. Actually, adopting a “shelter in place” policy for Fukushima and repopulating the evacuated areas of Chernobyl after one month would have been appropriate (Yanovskiy et al. 2022) [25].

2. Radiological Emergency: Case Study

Radiological incidents, whether resulting from technological malfunctions or deliberate acts of sabotage or terrorism, share many similarities and warrant equal consideration. The primary distinction lies in the fact that terrorist attacks typically target densely populated areas, whereas

the likelihood of a natural accident transpiring in such locations is significantly reduced. Here, we consider sample scenarios involving Cs-137 therapeutic source.

Based on the IAEA (1987) [11] report, we estimate that a typical fresh Cs-137 radiation source used in radiation therapy (RT) possesses an activity level of 0.1 PBq (10^{14} Bq) or 3000 curie (Ci). These sources present very real dangers. Sources utilized in industrial applications such as flow meters, thickness gauges, and well-logging devices are usually weaker.

It is worth noting that the use of Cs-137 in radiation therapy (RT) is diminishing as it has been replaced by Co-60 sources and compact electron accelerators. Co-60, being a metal, poses challenges in handling. On the other hand, Cs-137 sources typically consist of 30-ml ampules containing rice-sized granules of cesium chloride CsCl, which dissolves in water similarly to table salt (IAEA 1987) [11]. Consequently, dispersing CsCl appears relatively straightforward.

Undoubtedly, the high-dose-rate radiation emitted by the source presents significant handling difficulties. As shown below, an unprotected individual can only handle such a source for a brief period of less than half an hour before being exposed to a lethal dose. However, a 2-cm-thick steel plate (or a 20-cm-thick brick pile) attenuates the radiation by approximately an order of magnitude, allowing for an exposure of around one hour before absorbing 1 Gy. A dose of 1 Gy is sufficient to trigger the onset of acute radiation syndrome (ARS), resulting in sickness but with a minimal risk of death. Using a steel plate with a narrow viewing slot can partially address the shielding issue, as only the hands of the person handling the source are directly exposed.

In terms of potential sabotage, the most effective method for dispersing Cs-137 is likely by dissolving the source in water, pouring the solution into an air humidifier, and placing the humidifier in the cargo area of a pickup truck for transportation. The driver can also be shielded by a barrier such as a steel plate or brick pile.

Let us now examine three different scenarios:

Scenario 1: An adversary conceals a Cs-137 source with an activity of 10^5 GBq. Any individual located 1 meter away from the source would be exposed to a dose rate of $8.9 \cdot 10^{-5} \cdot 10^5 = 9$ Gy/h, resulting in a lethal dose of 4 Gy in under half an hour. This type of attack, involving the concealment of such a source in places like cafes or libraries, could be highly effective, causing significant casualties. Arguably, it could be more efficient in terms of casualties compared to conventional methods such as knives, firearms, explosives, or trucks.

Scenario 2: An adversary disperses a Cs-137 source with an activity of 10^5 GBq (10^{14} Bq) over a small area, resembling a “dirty bomb” scenario. Let’s assume, for reference, that the contaminated area is 100 m^2 . The contamination level would be 10^{12} Bq/m^2 , resulting in a gamma

dose rate of $1.6 \cdot 10^{-12} \cdot 10^{12} = 1.6 \text{ Gy/h}$. After one hour of exposure, the accumulated dose would reach 1.6 Gy, surpassing the threshold for the onset of acute radiation syndrome (ARS) at 1 Gy (Glasstone and Dolan 1977) [8]. Although the contaminated area (100 m^2) should be immediately evacuated and undergo extensive decontamination, it remains relatively small. No radiogenic casualties or significant damage are anticipated, provided that first responders are equipped with radiation monitors and limit their time spent in the “hot” zone to 15 minutes.

Scenario 3: Alternatively, an adversary might opt to contaminate a larger area using a moving vehicle equipped with an air humidifier. Let’s assume that the vehicle contaminates a 10-meter-wide zone behind it during several hours of driving, covering approximately 100 km of streets in a large city. The corresponding area would be 10^6 m^2 , resulting in a dose rate of $1.6 \cdot 10^{-12} (10^{14}/10^6) = 1.6 \cdot 10^{-4} \text{ Gy/h} = 1.40 \text{ Gy/year} = 1400 \text{ mGy/year}$. Such contamination poses no immediate risk of acute effects, as the threshold for ARS onset is approximately 1000 mGy if absorbed within 4 days (Glasstone and Dolan 1977) [8]. However, this radiation rate may increase the risk of cancer, necessitating decontamination of the area.

If the adversary chooses to contaminate a smaller area with the same amount of Cs-137, let’s say 10 km of streets, the local dose rate would be higher. Consequently, the decontamination efforts would need to be more intensive but confined to a smaller, more manageable area. In general, it is suggested that decontaminating a smaller area with higher contamination levels would be more cost-effective and easier than addressing a much larger area with lower contamination levels.

3. What to Do?

We cannot dismiss the theoretical possibility of a large-scale sabotage attempt targeting a nuclear power plant or the transportation of spent nuclear fuel. However, the likelihood of such attacks succeeding is extremely low. It is important to emphasize that a special forces team capable of carrying out such an attack would likely have the ability to execute a conventional attack targeting a population, resulting in a significantly higher loss of life. In the past, lone bombers with body-held charges caused approximately 20 casualties each (Brym and Araj, 2006) [2]. Therefore, an adversary would need compelling reasons to target a nuclear facility instead of a densely populated area. One such reason could be associated with an irrational fear of radiation that affects both society and the government. In this case, an adversary may hope that a targeted nuclear incident would have a more enduring impact than a large-scale terrorist attack against people. It is worth mentioning that such hopes are not baseless given the present circumstances. For instance, one can compare the public perception of the Tōhoku earthquake and tsunami,

which claimed a minimum of 20,000 lives but received limited international attention, with the Fukushima nuclear accident, which resulted in no loss of life yet is still regarded worldwide as a major disaster.

Similar considerations apply to any conceivable sabotage involving a radioactive source. While the consequences may be fatal, they are unlikely to be more effective than using conventional weapons such as knives, firearms, or trucks. An essential aspect is equipping every first-response team with radiation monitors and providing them with proper training. However, the primary concern lies in preventing excessive panic among the population and authorities. Instances of prolonged evacuation following Fukushima and permanent relocation after Chernobyl exemplify such overreactions. The key to prevention is through comprehensive education.

Therefore, the most effective approach to combating radiological terrorism is to remove the incentives fueled by anticipation of over-reaction. In other words, the elimination of unwarranted fear of radiation is crucial. It is of utmost importance to educate decision-makers, first responders, and the public about scientifically based assessments of the direct radiological consequences, as well as the genuine risks associated with overreactions like mass evacuations and unrealistic decontamination goals. This educational initiative can commence with brief introductory training sessions for decision-makers, teachers, and first responders. The training should also cover nuclear warfare since, as mentioned in the introduction, ionizing radiation has become inherently linked with nuclear apocalypses.

In the Tables 1–3 (next page) we propose tentative syllabuses for 12-hour training for three target groups:

- (1) decision-makers, first responders, psychologists and social workers (see Table 1),
- (2) history and geography teachers in middle and high school (see Table 2), and
- (3) science and technology teachers in middle and high school (see Table 3).

Regarding the physical security of nuclear facilities, it is important to consider the potential psychological impact of increased investment, which could inadvertently amplify fears. A rational individual associates the level of security with the level of threat and responds accordingly when the threat materializes. For instance, the current plans for secure storage of spent nuclear fuel consider storage in casks designed to withstand antitank weapons, buried 250–1000 meters underground (or even deeper) for safety purposes (WNA 2026) [23]. In such a context, it should not come as a surprise if people react with alarm (or even overreact, such as mass evacuation over an extended area) when a cask is breached during transportation.

Given the aforementioned considerations, we propose that relaxing regulations and narrowing safety margins, preceded by educational campaigns to elucidate these

Table 1. Target audience: Decision-makers, first responders, psychologists and social workers.**Tabela 1.** Grupa docelowa: decydenci, pierwsi respondenci, psychologowie i pracownicy socjalni.

Topic no.	Topic	Hours
1	Basic concepts in nuclear physics. Ionizing radiation	1
2	Nuclear reactor: a) Reactor layout. Nuclear energy as a clean and effective long-term energy source b) Plutonium production. The problem of nuclear weapons proliferation and ways to address it	1
3	Atomic bomb and hydrogen bomb. Five impact factors	1
4	Hiroshima and Nagasaki. Nuclear tests	1
5	Immediate injury factors and protection against them: blast, heat, and prompt ionizing radiation	1
6	Extent of damage: myths and facts. Comparison with conventional explosives. The panic factor	2
7	Radioactive fallout. Radiation damage and its extent. Chernobyl: myths and facts	2
8	Civil defense: dispersion, hardening, protection, and functioning in the Emergency Response Team (large-scale sudden disaster)	3
	Total	12

Table 2. Target audience: History and geography teachers in middle and high school.**Tabela 2.** Grupa docelowa: Nauczyciele historii i geografii w szkołach średnich i gimnazjach.

Topic no.	Topic	Hours
1	Basic concepts in nuclear physics. Ionizing radiation	1
2	Nuclear reactor: a) Reactor layout. Nuclear energy as a clean and effective long-term energy source b) Plutonium production. The problem of nuclear weapons proliferation and ways to address it	1
3	Atomic bomb and hydrogen bomb. Five impact factors	1
4	Hiroshima and Nagasaki. The contribution of nuclear weapons to the end of World War II	2
5	The Cold War and its end. Nuclear proliferation. The arms race and the collapse of the USSR	2
6	Immediate injury factors and protection against them: blast, heat, and prompt ionizing radiation	1
7	Extent of damage: myths and facts. Comparison with conventional explosives. The panic factor	1
8	Radioactive fallout. Radiation damage and its extent. Chernobyl: myths and facts	2
9	Civil defense: dispersion, hardening, protection, and functioning in the Emergency Response Team (large-scale sudden disaster)	1
	Total	12

Table 3. Target audience: Science and technology teachers in middle and high school.**Tabela 3.** Grupa docelowa: Nauczyciele przedmiotów ścisłych i technicznych w szkołach średnich i gimnazjach.

Topic no.	Topic	Hours
1	Basic concepts in nuclear physics: fission, critical mass, fusion, and ionizing radiation. Uses of radiation in medicine	2
2	Nuclear reactor: a) Reactor layout. Nuclear energy as a clean and effective long-term energy source b) Plutonium production. The problem of nuclear weapons proliferation and ways to address it	2
3	Atomic bomb and hydrogen bomb. Five impact factors	1
4	Nuclear explosion: review of the five damage factors	1
5	Immediate injury factors and protection against them: blast, heat, and prompt ionizing radiation	1
6	Extent of damage: myths and facts. Comparison with conventional explosives. The panic factor	1
7	Radioactive fallout. Radiation damage and its extent. Chernobyl: myths and facts	2
8	Civil defense: dispersion, hardening, protection, and functioning in the Emergency Response Team (large-scale sudden disaster)	2
	Total	12

measures, can enhance radiological security. For instance, we can recommend the following:

1. **Adjustment of legal limits for radiation exposure:** 0.2 cGy/day for radiation workers, in accordance with the norms effective in 1920th and 1930th (ICR, 1931; Calabrese, 2009) [10, 3], and half of this level, 0.1 cGy/day, for the general public. For radiation workers, 0.2 cGy/day corresponds to approximately 50 cGy/year, which is ten times the current U.S. limit and twenty-five times the EU limit.
2. **Relaxation of regulations governing medical and scientific radioactive sources that pose no discernible danger:** specifically, we propose lifting all limitations on the storage, transportation, and disposal of sources that produce radiation at a dose rate below 0.05 cGy/day (half of the permitted dose rate for the general public) at a distance of 1 meter.

Certainly, the above mentioned steps should be carefully considered and preceded by educational campaigns.

While some may view deregulation as compromising safety and security (for brevity, we refer to safety), the truth often lies in the opposite direction. Every functional system, whether technological or not, possesses an optimal range of safety measures. Deviating from this optimum in either direction jeopardizes safety. This fundamental principle of common wisdom can be traced back to sources such as the Pentateuch: “do not add... and do not subtract” (Deut. 4:2, 13:1). The medieval Jewish scholar Rabeinu Bahya (1050-1120) expressed it as follows: “It is a matter of caution not to be over-cautious”. Let us consider the example of vehicle speed. Excessive speed is evidently hazardous, but on a highway excessively slow speed also poses great risks: A vehicle moving at an exceptionally slow pace becomes a hazardous obstruction that other drivers (riding at high speed) must avoid. Another example – though 30 km/h speed limit is widespread, we are not aware of lower speed limits despite lowering impact speed from 30 km/h to 20 km/h decreases pedestrian fatality rate threefold (FEVR, 2013; see Fig. 6 there) [7].

There are at least three reasons why excessive caution and over-regulation undermine safety:

- Each additional feature, including safety measures, introduces complexity to a system. Over-regulation leads to excessive complexity, and complex systems inherently tend to be unsafe (Cook 1998; Dekker 2016; Perrow 1999) [5, 6, 17].
- Regulatory bodies often prioritize easily controllable aspects, such as demanding extensive documentation. Furthermore, the limited accountability of government officials reinforces these incentives (Tullock 1965) [22]. Interestingly, terms like “lazy bureaucrat” (Arkin et al. 2003) [1] and “lazy cop” (Offner and Ojakian 2014) [16] have emerged in industrial engineering and game theory.
- Over-regulation imposes a significant burden on industries, often without proportionate contributions to

safety. For instance, the requirement for extensive documentation may divert resources from addressing more subtle safety aspects.

To exemplify the above points, we present a case of successful deregulation that significantly improved safety. The deregulation of the US railroad industry, initiated in 1980, was named as the first among the causes of the notable decline in rail-related fatalities and accidents (Haley 2007) [9]: Between 1978 and 2005, the annual number of rail-related fatalities decreased by almost half, from 1,646 to 888, while the total number of rail-related accidents decreased more than six-fold, from 90,653 to 13,969 (Haley 2007) [9].

There is a valid concern that drastic changes to current regulations and guidelines may undermine public trust in authorities and potentially cause more harm than good. However, we firmly believe that if existing guidance is overly cautious to the extent that it results in more loss of life than preservation, it should be rectified promptly. To err is human, and regulators, being human, should be willing to acknowledge mistakes to enhance public trust.

Reducing the regulatory burden presents an opportunity to attract new players and investors to the nuclear energy sector and other industries involving radioactive materials. Increased investment, heightened competition in safety and security practices, and collaboration with local communities to ensure the safety of nuclear facilities are expected to enhance security by bolstering public trust in the guidance provided by authorities.

Furthermore, emerging firms and non-profit organizations in growing industries are likely to show greater interest in conducting outreach campaigns compared to established players. The latter are currently focused on survival and may lack a long-term perspective. Additionally, if the population (that is, the voters) has a better understanding of the actual risks involved, elected politicians are more likely to respond to rational approaches for enhancing the safety and security of nuclear facilities.

Implementing such measures not only reduces the incentives for nuclear terrorism but also facilitates the implementation of post-accident countermeasures.

4. Conclusions

The true health impacts of radiological accidents, whether they occur naturally or as a result of a terrorist attack, are generally much less severe than commonly believed. Population evacuation should be deemed necessary only in exceedingly rare circumstances. The major humanitarian disasters experienced in Chernobyl and Fukushima were not primarily caused by radiation itself, but rather by the excessive reaction from both the authorities and the public. The unjustified permanent relocation of Chernobyl and the prolonged evacuation of Fukushima, affecting over 100,000 individuals in each case were the consequences of this overreaction. Retrospectively, adopting

a “shelter in place” policy for Fukushima and repopulating the evacuated areas of Chernobyl after one month would have been appropriate.

We propose launching educational campaigns targeted at decision makers, first responders, and the general public to provide accurate information about the real health consequences of radiological incidents and to raise awareness of the risks associated with overreaction. Then, relaxing regulations and narrowing safety margins will considerably contribute to safety, as the perception of danger is closely tied to the extent of countermeasures in the public’s mind. Our recommendations focus on mitigating radiological terrorism by eliminating the most significant incentive for adversaries: triggering an overreaction.

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Biographical Note

Yehoshua Socol, PhD, received his doctoral degree in physics in 2000 from Weizmann Institute of Science, Rehovot, Israel. Presently with Jerusalem College of Technology, Jerusalem, Israel. His research interests include radiation carcinogenesis, epidemiology, risk assessment, public choice and ethics, as well as statistics and artificial intelligence.

Moshe Yanovskiy, PhD, graduated from the Higher School of Economics, Moscow, Russian Federation. Presently with Jerusalem College of Technology, Jerusalem, Israel. His research interests include political economy, incentives’ analysis, public choice and ethics.

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