SAFETY OF RADIOLOGICAL AND NUCLEAR QUASI-EXPERIMENT – CASE STUDY

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Abstract

The aim of this paper is to present the results of the safety level measurement of radiological and nuclear (RN) quasi-experiment (q-E), which was carried out in 2016 in the Chernobyl Exclusion Zone, in Pripyat town, as part of the "End-user driven DEmo for cbrNe" project (EDEN, FP7/2012-2016, under grant agreement no. 313077). The paper analyses the q-E executed in such a radiologically contaminated area of the town to verify a hypothesis that is formulated as follows: providing a safety plan and the correct execution of the q-E, including using appropriate personal protective equipment as well as following strict safety rules, guarantee an acceptable safety level for first responders taking a part in q-E conducted in Pripyat area as per relevant legal regulations. The experimental method with the quantitative measurements of effective gamma dose, using thermoluminescent dosimeters (TLD) and task related monitoring using electronic dosimeters (ED) was utilised. The individual effective gamma doses for each q-E participant, for two days of the exposure, have been measured. The total effective gamma doses for each participant have been calculated and compared with effective dose rates limits regulations. The obtained results proved that the assumed hypothesis was positively verified from the international and Polish legal standpoint, which defines gamma radiation thresholds for exposed personnel and ordinary persons.

Keywords: ionizing radiation, effective dose, CBRNE, quasi-experiment

1. Introduction

Over the past years, disaster management has been continuously facing an enormous challenge of increasing number and severity of natural and man-made disasters with their broad and deep negative impact on widely understood sustainability of a human being (Aifadopoulou et al., 2018; Halkos, Managi, Tzeremes, 2015; Sholoiko, 2017; Telizhenko, Mashyna, Opanasyuk, 2017). Consequently, there is a need to increase capability building upon new techniques, technologies and

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innovative approaches. Current and future challenges require the development and adoption of innovative solutions that are tailored to meet operational needs of practitioners dealing with disaster management, due to the severe impact of disasters of different origin (Zwęgliński, 2020). The efficiency of decisions made prior to a disaster, or in its very initial phase, are more and more dependent on supportive technologies which are used by disaster managers (Izumi, 2019; Shaw, Izumi, Shi, 2016).

The "End-user driven DEmo for cbrNe" (EDEN) project, implemented under the European Commission Seventh Framework Programme (FP7/2012-2016) under grant agreement no. 313077 comprised a series of quasi-experimental activities, tailored to testing and validating the efficiency of new solutions developed within an emerging market, intended to facilitate disaster management in case of CBRN threats. A part of the results of these quasi-experiments q-Es referring to the RN threat have been already published (Kulmala et al., 2016; Kulmala et al., 2020; EDEN, 2016). However, one of the q-Es, executed in the Chernobyl Exclusion Zone, allowed the generation of valid and relevant information, rooted in evidence-based post experience data, provided by practitioners using a set of solutions tested in a nuclear facility breakdown simulated scenario. During this experience-based q-E safety of personnel was considered to be the upmost important issue. In case of CBRNE this raises a lot of doubts since in most cases it literally means that activities have to be executed in truly contaminated areas. At this point it is worth emphasising that for chemical and biological agents it is possible to effectively protect first responders with appropriate personal protective equipment (PPE) (Burgio, Piscitelli, Migliore, 2018). However, for radiological hazard, such as neutron and gamma radiation, it is hardly possible to fully protect them, even if PPE are used. This gives rise to the question whether it is impossible to generate an added value for first responders' operational readiness by undertaking activities in real contaminated zones during q-E, at the same time providing relatively safe environment considering potential negative health effects? However, in order to answer this question, first it is necessary to verify if providing a safety plan and its proper proceeding executing for the q-E, including the use of appropriate personal protective equipment, as well as following strict safety rules, guarantee an acceptable safety level for first responders taking a part in q-E conducted in Pripyat area from the legal standpoint.

2. Methodology

Testing new solutions, protocols and technologies should be implemented in the closest possible environment to the one in which the validated items would ultimately work in practice (Weigel, 2010). Therefore, real-life disaster environments are the best testing ground. However, such conditions are highly unpredictable and not easy to be implemented into methodological research processes. Therefore, simulating a disaster environment is the second best option to conduct such a type of research. The deployment of innovative solutions into regular use represents a significant challenge. For this reason the idea of trialling was introduced, in which the term "trial" means a pragmatic and systematic assessment and evaluation process of solutions towards their potential to address current and emerging disaster management needs. The process is implemented with broad and strong involvement of disaster management practitioners in each of its stages in order to ensure relevance, reliability and usability of the trial findings (DRIVER+, 2020; Fonio, Widera, Zwęgliński 2023; Smolarkiewicz, Zwęgliński, Ogrodnik, 2023; Zwęgliński, 2023; Zwęgliński, Smolarkiewicz, 2023). This starts with the need of identification, trial design and steps towards to interpretation of trial results. A trial is always focused on a precisely identified need of a given disaster management organization. This need either stems from specific requirements of a disastrous situation or is related to a gap or need in procedural and/or administrative protocols. The goal should enhance the organization's efficiency in disaster management domain. The trialling approach is a pragmatic, robust and complete method derived from quasi-experimental exercises conducted for finding innovative solutions to close disaster management gaps (Kulmala et al. 2016; Kulmala et al. 2020; Zwęgliński, Maksimenko, Smolarkiewicz, 2019).

The RN q-E the results of which are presented in this paper was conducted as a part of the EDEN project and was held on 17th and 18th May 2016 in the Chernobyl Exclusion Zone, in Pripyat town. 56 participants from 11 European countries took part in a two-day-long emergency q-E. It is obvious that reflecting the entire spectrum and dynamics of real disaster conditions is simply impossible. Neither a correlation study nor true experiments may be used for the RN threat phenomenon. This is due to the multispectral and non-repeatable character of this kind of disaster. This is particularly relevant given research on broad socio-technological domain of decision-making supported by technological tools. The optimal research method is a quasi-experimental approach (Cook, Campbell, 1979; Craig, Hannum, 2006). Notably, disaster management is a highly complex socio-technical process, closely binding human behaviours that correspond to social sciences with technical interaction corresponding to technical sciences. A quasi-experimental activity provides the means to address the challenge in the appropriate manner. It assumes evaluating phenomena that are difficult to replicate in identical conditions and having significant difficulties with assessment of a representative group. Random assignment in the case of testing disaster response processes is difficult or impossible to achieve, since the tested solutions are aimed at specific disaster management needs of a tailored group of practitioners (Price, 2015). Using quasi-experimental approach is justified given the fact that it enables running tests without a random distribution of participants. Furthermore, a q-E is used to assess the impact of an intervention, which suggests a new element introduced to currently working protocols. This intervention is to be observed and measured during a trial, evaluating the performance of newly tested solutions in decision-making facilitation. A q-E does not naturally eliminate the problem of confounding variables since the participants are not randomly assigned, and disaster environment by its nature is not a set of repeatable phenomena. However, as a result it provides new knowledge concerning highly probable responses to a specific problem. Therefore, in terms of internal validity, q-Es are positioned somewhere between correlational studies and true experiments, making the method suitable to validate new solutions in a dynamic socio-technological disaster type testing environments.

To make the RN q-E safe for participants, the ALARP principle was used (ALARP, 2009). ALARP ("as low as reasonably practicable"), a principle utilised in the regulation and management of safety-critical and safety-involved systems. It assumes that the residual risk shall be reduced as far as reasonably practicable (Coates, 1990). As regards the RN hazard, to avoid radioactivity exposure and minimise the effective dose taken three basic protective measures are adopted, and namely: minimizing the exposure time, maximizing the distance from radioactivity source and shielding from radioactivity source. Consequently, taking into account the nature of contamination in the q-E area, radiation protection activities have been focused on the protection of participants against the following:

- gamma and beta external exposure;
- internal exposure via inhalation and oral pathways due to possible formation of dust and airborne in breathing zone during the decontamination activities and use of quadcopters, robotic equipment, etc.;
- radioactive contamination of skin surface;
- radioactive contamination of personal belongings and equipment.

Measures are also envisaged to preclude aggravation of radiation conditions within the q-E area as well as transfer of radioactive contamination off-site.

To minimize the risk of alpha radiation (internal exposure), radioactive contamination of skin surface and of personal belongings and equipment, the participants had been recommended to use protective clothing – the participants were furnished with a hooded jumpsuit, overshoes (personal protective clothes – type 5), nitrile gloves, plastic glasses and a P3 half mask with respirator. Moreover, for safety and measurements purposes they were also equipped with an individual thermoluminescent dosimeter – TLD and electronic dosimeter – ED, calibrated annually, measuring gamma effective doses absorbed by the participants during their presence in the q-E zone. The precise information of the setup of this RN q-E has already been presented (Zwęgliński, Maksimenko, Smolarkiewicz, 2019), and for this reason it is not discussed here in detail. Due to the fact that all the participants were appropriately protected from the internal irradiation through inhalation or radiation, the effective dose was calculated only from the external gamma radiation.

The contamination of the Chernobyl Exclusion Zone after the Chernobyl accident was a subject of many scientific studies (Kudzin, et al., 2020; Yoschenko, Ohkubo, Kashparov, 2018; Yeremenko et al., 2021; Kalinichenko, 2020). The main sources of contamination nowadays in the Chernobyl Exclusion Zone comprise ^{90}Sr and ^{137}Cs. The ^{90}Sr contamination generally correlates with ^{137}Cs. The most intense contamination is associated with the northern trace and western sub-latitudinal trace (its narrowest "explosive" zone). Maximal surface contamination within 2–5 km around the Chernobyl Nuclear Power Plant reaches 18 to 40 MBq/m^2, decreasing to 400–1100 kBq/m^2 as the distance approaches 30 km. Near the Chernobyl town the contamination is 200 kBq/m^2, and over the peripheral part of the 30-km zone it equals to 40–200 kBq/m^2, reaching 100–200 kBq/m^2 along its northern border (Gashchak et al., 2009).

The RN q-E area was located in the south-east part of the town of Pripyat and comprises seven areas with high levels of gamma radiation – hot-spots – as well as three areas with low levels of gamma radiation. The seven hot-spots had been measured before the q-E in preparatory phase.

The total time period of the q-E, i.e. the participants' presence in the contaminated area, was 16 hr 58 min. Since all of the participants were appropriately protected from internal irradiation (inhalation), the irradiation effective dose was calculated only from the external gamma radiation. The individual effective gamma doses for each q-E participant, for a two-day exposure, have been measured. The total effective gamma doses for each participant have been compared with effective dose rates set in legal regulations.

3. Results

The seven hot-spots had been measured before the q-E and the results of the radiation dose rates are shown in Table 1. These rates are within the range of measurements published by other researchers (Connor et al., 2020).

Table 1. Radiation dose rate H_w measured in hot-spots during the q-E on May 17 in Pripyat town

No. of Hot-spot	May 17 [μSv · h^{-1}]	
	H_w	**δH_w**
1	27.75	0.12
2	19.30	0.12
3	25.64	0.12
4	47.05	0.12
5	11.24	0.12
6	11.23	0.12
7	20.28	0.12

The individual effective gamma doses absorbed by each participant of the q-E were measured. The effective gamma dose was measured respectively during the first day of the q-E (E_1) with an error of δE_1 = 0.001 mSv, the second day of the q-E (E_2) with an error of δE_2 = 0.01 mSv. The total effective gamma dose for two days was then calculated ($E_T \pm \delta E_2$). Results of those measurements are presented in Table 2.

Table 2. Individual effective gamma doses *E* admitted by Pripyat q-E participants

No.	Home country of the participant	Effective dose per participant					
		May 17		May 18		2 days total	
		exposure time: 5 hr 48 min		exposure time: 11 hr 10 min		exposure time: 16 hr 58 min	
		[mSv]		[mSv]		[mSv]	
		E_1	δE_1	E_2	δE_2	E_T	δE_T
1	PL	0.011	0.001	0.030	0.010	0.041	0.011
2	PL	0.012	0.001	0.030	0.010	0.042	0.011
3	PL	0.010	0.001	0.040	0.010	0.050	0.011
4	NL	0.010	0.001	0.040	0.010	0.050	0.011
5	PL	0.011	0.001	0.040	0.010	0.051	0.011
6	UK	0.012	0.001	0.040	0.010	0.052	0.011
7	NL	0.012	0.001	0.040	0.010	0.052	0.011
8	IT	0.012	0.001	0.040	0.010	0.052	0.011
9	IT	0.012	0.001	0.040	0.010	0.052	0.011
10	PL	0.013	0.001	0.040	0.010	0.053	0.011
11	UK	0.013	0.001	0.040	0.010	0.053	0.011
12	PL	0.014	0.001	0.040	0.010	0.054	0.011
13	IT	0.014	0.001	0.040	0.010	0.054	0.011
14	PL	0.014	0.001	0.040	0.010	0.054	0.011
15	UA	0.014	0.001	0.040	0.010	0.054	0.011
16	IT	0.014	0.001	0.040	0.010	0.054	0.011
17	FI	0.017	0.001	0.040	0.010	0.057	0.011
18	PL	0.017	0.001	0.040	0.010	0.057	0.011
19	LT	0.007	0.001	0.050	0.010	0.057	0.011
20	PL	0.017	0.001	0.040	0.010	0.057	0.011
21	UK	0.019	0.001	0.040	0.010	0.059	0.011
22	PL	0.011	0.001	0.050	0.010	0.061	0.011
23	LT	0.011	0.001	0.050	0.010	0.061	0.011
24	FR	0.012	0.001	0.050	0.010	0.062	0.011
25	DE	0.012	0.001	0.050	0.010	0.062	0.011

No.	Home country of the participant	Effective dose per participant					
		May 17		May 18		2 days total	
		exposure time: 5 hr 48 min		exposure time: 11 hr 10 min		exposure time: 16 hr 58 min	
		[mSv]		[mSv]		[mSv]	
		E_1	**δE_1**	**E_2**	**δE_2**	**E_T**	**δE_T**
26	DE	0.013	0.001	0.050	0.010	0.063	0.011
27	UA	0.013	0.001	0.050	0.010	0.063	0.011
28	UK	0.013	0.001	0.050	0.010	0.063	0.011
29	NL	0.013	0.001	0.050	0.010	0.063	0.011
30	NO	0.013	0.001	0.050	0.010	0.063	0.011
31	FR	0.013	0.001	0.050	0.010	0.063	0.011
32	CZ	0.014	0.001	0.050	0.010	0.064	0.011
33	NL	0.014	0.001	0.050	0.010	0.064	0.011
34	PL	0.014	0.001	0.050	0.010	0.064	0.011
35	UK	0.015	0.001	0.050	0.010	0.065	0.011
36	UK	0.015	0.001	0.050	0.010	0.065	0.011
37	CZ	0.015	0.001	0.050	0.010	0.065	0.011
38	PL	0.015	0.001	0.050	0.010	0.065	0.011
39	IT	0.016	0.001	0.050	0.010	0.066	0.011
40	FI	0.016	0.001	0.050	0.010	0.066	0.011
41	PL	0.016	0.001	0.050	0.010	0.066	0.011
42	UA	0.017	0.001	0.050	0.010	0.067	0.011
43	UK	0.007	0.001	0.060	0.010	0.067	0.011
44	NO	0.018	0.001	0.050	0.010	0.068	0.011
45	NL	0.018	0.001	0.050	0.010	0.068	0.011
46	UA	0.018	0.001	0.050	0.010	0.068	0.011
47	UK	0.020	0.001	0.050	0.010	0.070	0.011
48	FR	0.013	0.001	0.060	0.010	0.073	0.011
49	PL	0.013	0.001	0.060	0.010	0.073	0.011
50	UK	0.014	0.001	0.060	0.010	0.074	0.011
51	UK	0.014	0.001	0.070	0.010	0.084	0.011
52	IT	0.014	0.001	0.070	0.010	0.084	0.011
53	NL	0.015	0.001	0.070	0.010	0.085	0.011
54	NL	0.015	0.001	0.070	0.010	0.085	0.011
55	NL	0.021	0.001	0.070	0.010	0.091	0.011
56	UK	0.014	0.001	0.080	0.010	0.094	0.011
AVERAGE GAMMA EFECTIVE DOSE		**0.0139**	**0.0004**	**0.0491**	**0.0014**	**0.0630**	**0.0015**

The received effective doses differ slightly one from another depending on the places where the given person was operating in the q-E. The highest effective dose measured was 0.094 mSv, which constitutes 9.4% of the acceptable yearly dose per person (1 mSv). It should be borne in mind that under the conditions of the natural gamma background inherent in this territory (0.12 μSv· h^{-1}) for 16 hr 58 min an expected individual dose is 0.002 mSv.

4. Discussion

The q-E seems to be the most optimal method for testing new solutions in socio-technological environment in a major disaster response context. It is not only because of difficulty to reproduce conditions of the test as has previously been justified in this paper. It is also because of highly impossible involvement of numerous participants in the test at the same time and conditions, which naturally generates a limited response rate. Moreover, it is difficult to gather a representative and randomly assigned group of participants, at least from the statistical standpoint. This is also due to the fact that the solutions are suited for specific needs and addressed at clearly dedicated, relatively narrow groups of practitioners. The quasi-experiment (q-E), as a scientific method, has actually been developed to explore phenomena that are characterized by such experimental limitations. However, making the RN q-E safe for its participants is the crucial requirement while conducting such exercises (IAEA, 2018).

Taking into consideration international and Polish regulations (Polish Journal of Laws no. 2021 pos. 1657) the doses absorbed by the participants of the q-E conducted in Pripyat area in 2016 were found to be far lower than the limits authorized by legal regulations. According to the above mentioned Polish regulation, which has been based on international acts, an annual effective dose to the representative person that generally does not exceed a value of 1 mSv. Therefore we can conclude that the average effective dose absorbed by the group of the q-E participants constituted only 6.3% of the yearly acceptable dose for an ordinary person. If we consider that the limit for a person having contact with radiation in routine work is 20 mSv in Poland (in USA regulations – 50 mSv) (Cherry, Sorenson, Phelps, 2012), the average amount absorbed during the q-E constitutes only 0.315% for Polish regulations (0.126% for USA). Comparing the average absorbed dose with other limits imposed by the law, it is worth mentioning that for workers or rescuers working in a radioactive environment in life rescue operations the effective limit dose is 500 mSv. Then the average dose absorbed during the q-E is only 0.013%. The q-E proves that neither individual gamma effective doses nor the average dose even approach a decimal part of the yearly threshold for ordinary persons.

It is quite clear that the doses absorbed by the q-E participants during these several hours are fully acceptable exposures from the legal point of view. It should be underlined that the participants mainly moved along asphalt routes, very rarely in bushes or other potentially more contaminated areas. Since the hot points, as described above, were clearly marked, the participants made sure not to come too close, for an excessively long time to this points in order to carry out the q-E tasks.

5. Conclusions

The two days q-E in Pripyat proved that providing a safety plan for such q-E and its proper implementation assuming the use of appropriate PPE as well as following strict safety rules guarantee an acceptable safety level of all involved. As an effect first responders could benefit in a controlled manner from a realistic surrounding while using such areas for exercising purposes and taking a reasonably acceptable risk of exposure to ionizing radiation. Positively verified hypothesis in the course of the q-E provides new knowledge for first responders and other persons involved in exercises being carried out in radiologically contaminated areas. Moreover, it is a valuable hint for drill organizers since exercising in contaminated areas provides an excellent opportunity to enhance individual skills of first responders as well as increase the coping capacity of CBRNE systems, e.g. by testing and reinforcement of standard operating procedures. Finally, it is also important to emphasise the fact that during well organized and controlled q-E, the risk to the health and life of the first responders and other involved persons coming from radioactive contamination and exposure could be negligibly small.

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BEZPIECZEŃSTWO QUASI-EKSPERYMENTU RADIOLOGICZNEGO I JĄDROWEGO – STUDIUM PRZYPADKU

Abstrakt

Celem pracy jest przedstawienie wyników pomiaru poziomu bezpieczeństwa radiologicznego i jądrowego (RN) quasi-eksperymentu (q-E), który został przeprowadzony w 2016 r. w Czarnobylskiej Strefie Wykluczenia, w mieście Prypeć w ramach projektu „End-user driven DEmo for cbrNe" (EDEN, FP7/2012–2016, na podstawie umowy o dofinansowanie nr 313077). W artykule przeanalizowano q-E przeprowadzone na takim skażonym radiologicznie obszarze miasta, weryfikując hipotezę, która została sformułowana w następujący sposób: zapewnienie planu bezpieczeństwa i właściwe postępowanie podczas q-E, w tym stosowanie odpowiednich środków ochrony osobistej oraz przestrzeganie ścisłych zasad bezpieczeństwa, gwarantują z prawnego punktu widzenia akceptowalny poziom bezpieczeństwa dla pierwszych respondentów biorących udział w q-E przeprowadzonym na obszarze Prypeci. Zastosowano metodę eksperymentalną z ilościowym pomiarem efektywnej dawki gamma, przy użyciu dozymetrów termoluminescencyjnych (TLD) oraz monitorowanie związane z wykonywanym zadaniem przy użyciu dozymetrów elektronicznych (ED). Zmierzono indywidualne, efektywne dawki gamma dla każdego uczestnika q-E, dla dwóch dni ekspozycji. Obliczono całkowite efektywne dawki gamma dla każdego uczestnika i porównano je z przepisami dotyczącymi limitów dawek efektywnych. Otrzymane wyniki wykazały, że przyjęta hipoteza została pozytywnie zweryfikowana z punktu widzenia międzynarodowego i polskiego prawa, które określa progi promieniowania gamma dla personelu narażonego i zwykłych ludzi.

Słowa kluczowe: promieniowanie jonizujące, dawka efektywna, CBRNE, quasi-eksperyment