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SAFETY RANKING OF CHERNOBYL RADIOACTIVE LEGACY SITES SITUATED IN POPULATED AREAS FOR PRIORITIZATION OF REMEDIAL MEASURES

Methodology and results are presented for the "safety ranking" of legacy radioactive material storage sites that are situated in populated areas adjacent to the Chernobyl Exclusion Zone and contain wastes from clean-up and decontamination operations carried out in 1986 - 1989. Based on this safety ranking, recommendations regarding the order of remediation and management strategy for these sites are provided. The results suggest that remedial works for radioactive legacy sites can be optimized, and waste volumes that may require retrieval and further disposal in engineered facilities can be considerably minimized. It is recommended that the managing organization (Kyiv Inter-Regional Special Combine of UkrSC "Radon") should focus their characterization, monitoring and maintenance works on the relatively few higher risk legacy sites identified in this study, while low-risk sites can be eventually released from regulatory control.

Keywords: Chernobyl accident, remediation of contaminated land, radiological safety assessment.

1. Introduction

The Chernobyl accident of 26 April 1986 caused serious contamination of large areas surrounding the Chernobyl Nuclear Power Plant (ChNPP) by radioactive fallout. Shortly after the accident, the approximately 30-km radius evacuation zone around the ChNPP (so called Chernobyl Exclusion Zone - ChEZ) was established, from which the population was relocated, further access of the public was restricted, and "normal" industrial and agricultural activities were prohibited. The majority of radioactive contamination of Chernobyl origin, including radioactive wastes from construction of the "Sarcophagus" to cover the ChNPP Unit 4, wastes from clean-up of the industrial site of ChNPP, and other post-accident clean-up activities, are located inside the ChEZ [1].

In addition, the radioactive legacy of the Chernobyl accident in Ukraine includes numerous radioactive material storage (localization) sites that are situated outside the ChEZ in adjacent areas, where radioactive materials resulting from clean-up activities in villages (so called Decontamination Waste Storage Facilities – DWSF) and waste resulting from decontamination of transport vehicles (so called Special Decontamination Stations – SDS) are stored [2]. The registry ("Cadastre") of these sites is maintained by Ukrainian State Corporation "Radon", which is responsible for management and storage of radioactive wastes of non-nuclear origin (industrial, medical) as well as wastes of Chernobyl origin. The total volume of radioactive materials stored in 47 DWSF and 6 SDS sites situated in Kyiv, Zhytomyr and Chernigov Regions of Ukraine is estimated at 30600 m^3 (as of 2010) [3].

These radioactive legacy sites (DWSF and SDS) are often located near villages and in other areas that are easily accessible to the population (e.g., near transportation roads), and represent a source of potential radiological risks to public. Moreover, the design and radioactive material storage conditions of these radioactive legacy sites, which were created in the emergency situation following the Chernobyl accident, do not comply with the modern Ukrainian regulations for storage (or disposal) of radioactive wastes. Therefore, a number of the Ukrainian national – level programs and Government decrees (e.g., "State special purpose environmental programme for radioactive waste management", approved by Law of Ukraine from 17.09.2008 N 516-VI) require that radioactive waste should be retrieved from DWSF and SDS and directed for disposal to licensed engineered radioactive waste disposal sites in ChEZ such as the "Vector" complex.

The large number of radioactive legacy sites with different possibilities for access by the public, an activity inventory and varying radioactive material storage conditions implies a need to prioritize remedial efforts (while taking into account the limited resources in Ukraine for remedial works). One of the key factors determining the need for remediation is the radiological risk to humans and the environment caused by a legacy site [4, 5].

In this publication, we present the methodology and results of a radiological "safety ranking" of these legacy radioactive waste storage sites which was developed in order to provide recommendations regarding the order of their remediation and waste management strategy. The presented analyses were developed with support from the Instrument for Nuclear Safety Cooperation (INSC) technical assistance Programme to Ukraine by the European Commission Directorate-General for International Cooperation and Development (DG DEVCO) [6].

2. Overview of data on site conditions and radioactivity inventory of legacy sites

2.1. Historical context

The studied radioactive legacy waste storage sites were created during mitigation of the radiological consequences of the Chernobyl accident in the regions adjacent to the ChEZ. These mitigation (clean-up) measures were carried out mostly in 1986 - 1989 [2, 3].

DWSF. The DWSF facilities usually contain radioactively contaminated materials resulting from decontamination of local "hot spots" in villages, which were contaminated by the radioactive fallout. Such materials usually are composed of contaminated topsoil, roof materials (e.g., tiles, roof metal, roofing slate etc.), construction debris etc., The DWSF were constructed and closed by USSR Civil Defense units without any appropriate design documentation. They usually consist of a trench, excavation or a disused quarry filled with the decontamination waste. The sizes of different facilities range from 25 × 25 m to 200 × 150 m; the thickness of layer of waste material is approx. 1.5 - 2 m. The waste burial surface was covered in a later period by a protective soil screen (with the thickness ranging from 0.1 to 1 m) and surrounded by drainage ditches for collecting surface runoff. At the time of closure, the areas of these waste storage facilities were fenced by barbed wire and marked by "Radiation Danger" signs. Typically, disposal trenches were dug in local sandy soil and were not equipped with protective bottom liners. In some cases, DWSF were located in areas with a shallow groundwater table. Proper records of DWSF activity inventory were not kept at the time of their use and closure [2].

SDS are the locations where vehicles and machinery (e.g., trucks, buses, etc.) were decontaminated, which were involved in transportation or operations in the ChEZ and adjacent contaminated areas. All 6 SDS facilities considered in this study are situated in the Kyiv region along the highway "Kyiv - Chernobyl". Three of these facilities were established on the basis of existing vehicle workshops in villages; three others were created as temporary field facilities, which were likely deployed by chemical military units involved during the liquidation of the Chernobyl accident. According to available information, no conservation or decontamination works were performed for these field facilities after end of operation, except boundary fencing of the territory and erection of radiation danger signs.

The monitoring and maintenance of the studied radioactive legacy sites during the post-accident period was carried out by the Kyiv Inter-Regional Special Combine (i.e., the regional unit) of the Ukrainian State Corporation "Radon". The monitoring surveys were mostly limited to surface radiometric measurements (gamma dose rate, beta particle fluxes). Due to the limited financial and technical resources and opportunities during the last decade, individual facilities were inspected with the frequency of 1 time per 3 - 4 years.

The first field characterizations of radioactivity inventory of the radioactive legacy sites were carried out in 1993 - 1994 [2]. Inventory studies have employed drilling and gamma-logging of the characterization boreholes through the waste burials, and have used empirical correlations with gamma-count rates to estimate radionuclide (mainly ^{137}Cs) activity concentration in the waste. The results of these studies were used in a later period as a basis for the official waste "Cadastre" of DWSF and SDS [3].

2.2. Radiological characteristics of stored materials

The radioactivity of the fallout released from the ChNPP Unit 4 was determined in the early aftermath of the Chernobyl accident mostly by the ensemble of relatively short-lived radionuclides such as ^{95}Zr (half-life $T_{1/2}$ = 64 days), ^{95}Nb ($T_{1/2}$ = 35.2 days), ^{103}Ru ($T_{1/2}$ = 39.3 days), ^{106}Ru ($T_{1/2}$ = 1.02 years), ^{141}Ce ($T_{1/2}$ = 32.5 days), ^{144}Ce ($T_{1/2}$ = 284 days), etc. (e.g., [7, Table 3.1]). During the three decades which have passed since the Chernobyl accident, significant decay of short lived radionuclides has occurred, leading to decrease of radioactivity of materials contaminated by the Chernobyl fallout (Fig. 1). As a result, the present day activity inventory of the studied legacy sites has apparently significantly decreased compared to the activity at the time of clean-up operations.

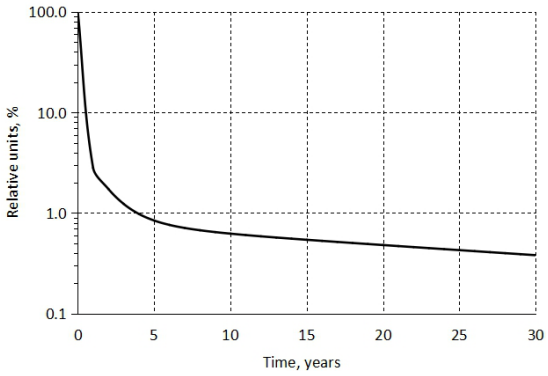

Fig. 1. Evolution in time (starting time 26.04.1986) of integral activity of gamma-emitting radionuclides of Chernobyl fallout (based on "referent" radionuclide composition given in [7, Table 3.1]).

In 2013 - 2015, repeat work on characterization of the inventory of 6 SDS and 11 DWSF facilities located in Kyiv region outside of the ChEZ (Fig. 2) was carried out by State Enterprise (SE) "NTC KORO" in order to update data from surveys carried out in 1993 - 1994. These studies have shown that the major contributors to the radioactive inventory of legacy waste storage sites at the present time are ^{137}Cs and (to a lesser degree) ^{90}Sr. In a few cases ^{241}Am was found in activities exceeding exemption levels for low level waste. Maximum ^{137}Cs activity in stored wastes ranged for different facilities from 0.4 to 300 kBq/kg; maximum ^{90}Sr activity ranged from 0.1 to 100 kBq/kg; maximum ^{241}Am activity reached 6 kBq/kg. In many cases the activity of stored materials is below the relevant threshold activity criteria (exemption levels) for radioactive wastes defined by Ukrainian regulations (e.g., 10 Bq/g for ^{137}Cs) [8]). At the same time, these materials usually have specific activity above the clearance levels (e.g., 0.1 Bq/g for ^{137}Cs) [9].

Fig. 2. Map of the studied Chernobyl radioactive legacy sites in Kyiv region.

Comparison of results of the characterization efforts of SE "NTC KORO" carried out in 2013 - 2015 with data of surveys from 1993 - 1994 has shown a poor agreement in radioactivity inventory data [6]. This was attributed to the use in the 1993 - 1994 studies of analytical procedures with low accuracy (e.g., using beta radiometry rather than beta-spectroscopy or radiochemical methods for strontium-90 activity measurement). Therefore, a need for characterization of legacy sites in order to provide adequate and up to date radioactivity inventory data has been identified as a priority issue (in particular, for those facilities for which the only source of information is data from 1993 - 1994) [6].

2.3. Radioactive materials storage conditions

The surveys carried out in 2013 - 2015 established that, in many cases, the storage conditions of radioactive materials within the legacy sites can be described as "unsatisfactory": fences were ruined or stolen; radiation danger signs were missing; drainage ditches were overgrown by vegetation and clogged by soil; monitoring wells were not in a functional condition; etc. Similar observations were made by the authors of this publication during field visits to a number of legacy waste storages situated in the Kyiv region in April 2016. The worst site conditions were observed at DWSF "Pisky-1" (situated in the Ivankiv District of Kyiv region, see Fig. 2) where the soil cover of the radioactive waste storage facility was ruined by recent excavations, which were evidently created by scrap metal hunters searching for metal pieces (such as sheets of roof metal etc.) that were disposed to this trench-type waste burial in 1987 - 1989 following decontamination works in the nearby village of Pisky. The dose rate in excavations reached ~ 6 - 7 μSv/hour [6].

These unsatisfactory waste storage conditions indicated that, at some parts of the legacy sites, conditions could potentially lead to increased radiation exposure of the public. The mitigation of such risk to the public requires consideration and eventual implementation of remedial measures (ranging in scale/complexity from simple repair of fences and restoration of danger signs to full retrieval of waste with further disposal to engineered facilities in the ChEZ).

3. Approach and criteria for safety ranking

3.1. Input data for safety ranking

The safety ranking analyses presented below are limited to legacy sites situated in the Kyiv region (6 SDS facilities and 11 DWSF facilities) that were repeatedly characterized by SE "NTC KORO" in 2013 - 2015 (see Fig. 2). (Reliable safety ranking cannot be carried out for legacy sites where the only source of data are surveys from 1993 - 1994 due to inadequate radioactivity inventory data [6]).

The methods used by SE "NTC KORO" to characterize activity inventory of waste storage sites included gamma-logging of characterization boreholes drilled through the waste trenches to outline the subsurface geometry of the waste body (e.g., 15 - 20 boreholes per site with a vertical interval of gamma-logging of 0.2 m), and also laboratory radiometric analyses of the drill core samples. Radiometric laboratory analyses were usually carried out on the aggregate samples collected from the waste trench using the "envelope" technique (i.e., an aggregate sample was composed from 5 sub-samples collected from the corners and center of the sampled area). Usually at least 4 aggregate "envelope" samples per site were collected, with size of sampling envelopes of ~ 5 × 5 m.

Data on radionuclide content in waste material in the legacy sites, which are used in the further safety ranking analyses, are summarized in Table (columns 2 - 5). Within several contaminated sites ^{241}Am was measured in waste material. The ^{241}Am is usually associated with the so called "fuel" component of the Chernobyl fallout, representing micron- size nuclear fuel particles. Therefore, in such cases, the presence of plutonium isotopes (^{238}Pu, ^{239}Pu, ^{240}Pu and ^{241}Pu) can be expected which are also related to fuel fallout. In dose assessment calculations presented below, Pu isotope activity in waste material was estimated using experimental data [1] on radionuclide ratios in the fuel of the Chernobyl Unit 4. For SDS "Demydiv", SDS "Dymer" and SDS "Ivankiv" the only available data are surface gamma dose rate measurements. As the gamma dose rate surveys have not revealed contamination "hot spots", the SE "NTC KORO" did not collect additional samples for radiometric laboratory analyses from these sites.

3.2. Approach for safety ranking

The proposed approach for safety ranking uses a set of criteria related to radiological safety of general public with regard to current and/or potential impact from the legacy sites, which are used for inter-comparison of sites for ranking purposes (to define remediation priorities) and for a preliminary evaluation of radiological hazard posed by each site. (It should be pointed out, however, that, the presented calculations are not a substitute for a full-scale risk assessment analysis which should be carried out at the stage of developing a remedial project design for a specific legacy site.) These criteria are explained in more detail below.

Input radiological data (based on characterization works by SE "NTC KORO") and results of safety ranking of radioactively contaminated legacy sites situated outside the ChEZ

Name of legacy site (registration No in Cadastre) *	Radionuclide activity in waste (max), kBq/kg **			Gamma dose rate (max, at 1 m), μSv/h	Regional contamination by ^{137}Cs, kBq/m^2 (kBq/kg)	Activity ratio "Waste : Background Soils" (for ^{137}Cs) ***	Effective doses for screening risk assessment scenarios, mSv/year ****		
	^{137}Cs	^{90}Sr	^{241}Am				Scenario 1	Scenario 2	Scenario 3
1	2	3	4	5	6	7	8	9	10
Sites in areas with unrestricted access									
DWSF Kolentsy (29)	1.10	0.13	--	0.13	36 (0.23)	4.6	0.08	0.003	0.1
DWSF Orane (30)	2.07	0.73	--	0.21	66 (0.44)	4.7	0.13	0.005	0.3
DWSF Pisky-1 (31)	**52.7**	**101.3**	**0.66**	1.36	87 (0.58)	**91.2**	**0.82**	0.135	**21.3**
DWSF Pisky-2 (32)	1.60	0.25	--	0.15	87 (0.58)	2.8	0.09	0.004	0.2
DWSF Prybirsk (33)	1.37	0.04	--	0.13	57 (0.38)	3.6	0.08	0.003	0.2
DWSF Stary Sokoly (34)	0.37	0.17	--	0.23	47 (0.31)	1.2	0.14	0.001	0.1
SDS Demydiv (45)	no data	--	--	0.3	13 (0.09)	1.7	0.18	--	--
SDS Dymer (46)	no data	--	--	0.25	27 (0.18)	1.8	0.30	--	--
SDS Ivankiv (47)	no data	--	--	0.17	49 (0.33)	1.2	0.20	--	--
SDS Orane (48)	**300.4**	**146.4**	**5.89**	6.1	66 (0.44)	**686.1**	**3.66**	0.30	**56.0**
SDS Rudnya Shpilivska (49)	**39.8**	**43.4**	**1.06**	3.2	55 (0.37)	**108.9**	**1.92**	0.04	**11.1**
SDS Sydorovichy (50)	**11.11**	**8.41**	**0.10**	1.4	25 (0.16)	**67.7**	**0.84**	0.01	**2.5**
Sites inside ZUOR									
DWSF Korolivka (37)	1.03	0.25	--	0.23	14 (0.09)	**11.3**	0.14	0.003	0.2
DWSF Nova Markovka-1 (38)	**83.7**	**0.36**	--	3.5	66 (0.44)	**191.1**	**2.10**	0.20	**9.2**
DWSF Nova Markovka-2 (39)	**25.6**	**0.10**	--	0.9	66 (0.44)	**58.5**	0.54	0.06	**2.8**
DWSF Nova Markovka-3 (40)	**9.83**	**0.08**	--	2.4	66 (0.44)	**22.5**	**1.44**	0.02	**1.1**
DWSF Stara Markivka (43)	6.50	0.080	--	0.24	51 (0.34)	**19.1**	0.14	0.02	**0.7**

* Higher priority legacy sites based on results of safety ranking are marked in bold.
** Activity values above exemption criteria for radioactive waste according to Ukrainian regulations are marked in bold.
*** Activity ratios above threshold value of 10 are marked in bold.
**** Dose assessment results close or above reference level of 1 mSv/year are marked in bold.

Criterion 1. Accessibility of sites to general public. SDS and DWSF sites can be differentiated based on location of the legacy sites in different administrative "zones of radioactive contamination" established after the Chernobyl accident that are defined by the "Law of Ukraine On The Legal Status of the Territory Exposed to the Radioactive Contamination resulting from the ChNPP Accident". Location of studied sites in one or other zone of radioactive contamination determines conditions of accessibility of the sites by the public. In particular, a number of the studied legacy sites are situated inside the so called "Zone of Unconditional (Obligatory) Resettlement" (ZUOR). The ZUOR (along with the ChEZ) represents the zone with the highest contamination by the Chernobyl fallout. The ZUOR was established in 1991 based on criteria of annual doses to the population of more than 5 mSv/year (as of 1991). The above-cited Law established the administrative regime of ZUOR that is similar to the regime of ChEZ, including resettlement of populations and prohibiting "normal" industrial activities. Within the Kyiv region, the ZUOR was fenced and access to it was restricted. Considering restrictions for access of the general public, the legacy sites situated inside the "Zone of Unconditional (Obligatory) Resettlement" are given in this study lower priority compared to facilities in less contaminated zones, where no such restrictions are in place.

Criterion 2. Comparison of inventory of the legacy waste storage facility with background contamination by the Chernobyl fallout. An important aspect is that the studied legacy sites are situated in close vicinity of the ChEZ in areas with relatively high levels of contamination by the Chernobyl fallout. In the case that the activity of materials stored within the legacy site is on the same order of magnitude as the regional topsoil contamination, a remediation of legacy site was deemed not to be justified, as it does not have potential to improve the overall radiological situation. Such an approach conforms with the recommendations of the national radiation safety regulations [10].

To carry out the comparison described above, information on average surface contamination density by the Chernobyl fallout in the vicinity of the legacy sites was taken from official "dose passports" of villages in the Chernobyl affected areas [11]. From the data mentioned above the topsoil specific activity was calculated (assuming that the ^{137}Cs inventory is concentrated in the upper 10 cm soil layer of topsoil). This topsoil contamination vicinity of the site is compared to ^{137}Cs activity in waste material contained within the legacy site.

Criterion 3. Dose assessment for a set of model scenarios. Screening dose assessment calculations were carried out, which considered a set of model scenarios of exposure of the general public. The annual dose to an adult was used as a calculation endpoint. Exposure scenarios, which are most relevant and also relatively simple with respect to data requirements and calculation procedures were used. Maximum activities of waste materials in legacy sites were conservatively used in the dose assessments.

Scenario 1. Regular visits to the site. This scenario was relevant to the current day situation, and assumed regular visits to the site by a member of public (e.g., using the site for recreational purposes). The main pathway in this scenario was external exposure. The maximum value of gamma dose rate measured within the site was used in calculations. The time of exposure was set to t=1000 hours/year (which is a "reasonably conservative" value), which conforms to the assumptions in used in similar assessment methodologies (e.g., [12]).

Scenario 2. Excavation of the site. This scenario assumed an excavation of the waste site (e.g., by a scrap metal hunter). Main exposure pathways in this scenario are: external exposure, inhalation of radioactive aerosols (dust), and occasional ingestion of small amounts of waste soil. The time of exposure in this scenario was conservatively set to t = 20 hours/event. Maximum values of radionuclide specific activity in waste material are used in the dose assessment. Calculation procedures for this scenario are described in IAEA TECDOC-1030 (Scenario SCE7B, p. 111) [13].

Scenario 3. On site residence. This last scenario assumed that the contaminated site is used as a site of permanent residence by a member of the general public, and thus this scenario represents the "worst case" scenario of potential exposure. Taking into account conditions observed currently at many of studied legacy sites (no fences, no warning signs) it was conservatively assumed that this scenario could occur anytime (including in the very near future), so that no additional radioactive decay of the activity inventory of the legacy site was taken into account. Calculations for this scenario followed the procedures described in the Annex 5 of the Ukrainian regulations NRBU-97/D-2000 for the dose assessment of near surface radioactive waste disposal facilities [14].

Dose criteria for remedial action. Results of the dose assessment calculations are eventually checked against a set of dose criteria (or "reference levels"). The studied legacy sites fall into the category of "existing exposure" situations corresponding to the definition given in [5]. Existing exposure situations

are usually regulated by establishing "reference levels", which are typically expressed as an annual effective dose to a representative person in the range of 1 - 20 mSv/ year [5]. Remedial measures shall be considered once the estimated doses from "existing radiation sources" are above the corresponding reference level. In accordance with the above-cited international recommendations, a dose criterion of 1 mSv/ year was used as a lower threshold level for further consideration of remedial actions for the studied legacy sites. This reference level was coordinated with the Ukrainian regulatory authorities.

4. Results and discussion

4.1. Results of safety ranking

The results of the safety ranking are summarized in Table (columns 7 - 10).

Criterion 1. Accessibility of sites to general public. From the 17 legacy sites with adequate data (i.e., those characterized by SE "NTC KORO" in 2013 - 2015) 4 facilities are situated inside the ZUOR with restricted access by public. These sites were given lower priority in ranking for remediation compared to other sites (see Table, column 1).

Criterion 2: Comparison of legacy site inventory with background contamination by Chernobyl fallout. The results of comparison of activity inventory in legacy sites with the background contamination of the surrounding territory are summarized in column 7 of Table. When considering information presented in Table, it should be kept in mind that for comparison we used maximum measured ^{137}Cs activities in stored waste materials, while background contamination values represent an average of contamination levels of topsoil in nearby settlements. For SDS "Demydiv", SDS "Dymer" and SDS "Ivankiv", the activity ratio "Waste: Background Soils" listed in column 7 of Table was calculated based on the ratio of gamma dose rates at the facility site and in the background area (as this is the only available characteristic for these sites). The soil surface contamination by ^{137}Cs within villages in the studied region usually exhibited spatial variability by at least a factor of 2 - 3 within the same village. Considering the variability of background contamination, we have judged that the activity inventory of a legacy site is significantly higher than the background contamination levels of the territory by fallout if the ratio of maximum waste ^{137}Cs activity was higher than the average contamination level of soil in the area by a factor of 10 or more.

Based on the above-described criteria, activity inventory of 8 of the DWSF/ SDS sites (from the 17 analyzed) appeared to be generally comparable to adjacent surface contamination by fallout radionuclides. In total, 8 sites contain significantly (~ by a factor of 50 and more) higher activity inventory compared to background levels (2 of these higher inventory sites are located inside the ZUOR). The sites with relatively high activity inventory located outside ZUOR are DWSF "Pisky-1", SDS "Orane", SDS "Rudnya Shpilivska" and SDS "Sydorovichy".

Criterion 3. Dose assessment for a set of model scenarios. The calculation results for Scenario 1 (regular visits to the site; see column 8 of Table) show that for 6 sites the estimated doses are close to or higher than the criterion of 1 mSv/year (2 such sites are situated in the ZUOR).

For Scenario 2 (excavation of the site; see column 9 of Table) for all sites doses caused by intrusion are low (< 1 mSv/event); however, for DWSF "Pisky-1", SDS "Orane" and DWSF "Nova Markivka-1" estimated doses reach decimal fractions of 1 mSv/event, which is already a level of concern. It should be noted that further use of the excavated contaminated material (e.g., contaminated metal constructions, concrete elements) can cause additional exposure of the general public; however, such consequences are difficult to estimate *a priori* due to the large uncertainties in data and human behavior.

Not surprisingly, for the Scenario 3 (intrusion scenario assuming residence of the reference individual at the contaminated site; see column 10 of Table) conservatively estimated potential doses are the highest ones, reaching 56 mSv/year for SDS "Orane", and 21 mSv/year for DWSF "Pisky-1". (It should be kept in mind that, as discussed above, the calculation procedures employed a number of "worst case" conservative assumptions). At the same time, for 5 sites the estimated doses are by an order of magnitude less than 1 mSv/year criterion, indicating a rather low potential radiological impact. These sites, along with SDS "Demydiv", SDS "Dymer" and SDS "Ivankiv", are candidates for release from regulatory control. The priority sites with estimated doses close to or exceeding 1 mSv/ year for Scenario 1 and 3 situated outside the ZUOR are the same ones as identified using Criterion 2.

It should be noted that since no data are available on specific activity of radionuclide in waste material from SDS "Demydiv", SDS "Dymer" and SDS "Ivankiv", (which are generally low contamination sites based on ambient gamma dose rate measurements), doses assessment for these sites for Scenario 2 and 3 were not carried out.

4.2. Discussion

Application of quantitative criteria, such as Criterion 2 (comparison with the background contamination) and Criterion 3 (dose assessments

for model scenarios) gives a generally coherent picture: sites with inventory that is much higher than the background contamination levels usually are the same ones as those that pose an unacceptable level of radiological risk to general public. It can be also seen that the higher risk sites are usually those sites which contain radioactive waste according to the activity criteria outlined in Ukrainian regulations [8]. Based on the safety ranking analysis described above, the priority sites for considering implementtation of remedial measures are: SDS "Orane", SDS "Rudnya Shpilivska" and SDS "Sydorovichy", and also DWSF "Pisky-1".

The legacy sites situated within the "Zone of Unconditional (Obligatory) Resettlement" were given lower rankings in this study, because they are currently located inside a higher contaminated area with a special administrative regime and restricted access by the public. However, a number of these facilities (in particular "Nova Markivka-1", "Nova Markivka-2" and "Nova Markivka-3") contain relatively high activity inventory and, in case of access by the public, may cause non-negligible radiological risks. In case that the status of the territory of ZUOR will change in the future, these facilities may need re-evaluation of their safety and a need for remediation. Under the current conditions, access control measures (fencing, radiation signs, etc.) and continued monitoring is recommended for these facilities.

The analyses presented above also allowed identification of those facilities, which are candidates for release from regulatory control: these are 8 sites with low activity inventory (which is comparable to the background contamination by the Chernobyl fallout) and posing relatively low current as well as potential radiological impact (<< 1 mSv/year). Release from regulatory control may require additional characterization efforts and risk assessment calculations aimed at confirming existing data on low activity inventory and low radiological risks from these sites.

5. Conclusions

The results of the studies presented above suggest that remedial measures for radioactive legacy sites situated outside ChEZ can be optimized, and waste volumes that require retrieval and further disposal in engineered facilities can be considerably minimized. Ranking analyses of 17 radioactively contaminated legacy sites situated outside the ChEZ suggest that relatively few of these sites (i.e., four sites) are those that may require implementation of remedial measures. From the four higher risk sites, three sites represent transport vehicle decontamination stations situated in close proximity to the ChEZ. Contamination of these sites was probably caused by radioactive materials including hot particles brought accidentally by equipment used in the high contamination areas near the ChNPP accident site. For the majority of the analyzed legacy sites containing wastes from in-situ clean-up operations in the villages carried out in 1986 - 89, nowadays remedial measures do not appear to be justified because their activity inventory has significantly decayed since the time of their creation, and they are comparable to today's background contamination levels of their respective areas by Chernobyl fallout. The rational approach would be that the managing organization (Kyiv Inter-Regional Special Combine of UkrSC "Radon") should focus their characterization, monitoring and maintenance works on the relatively few higher risk legacy sites, while low-risk sites can be eventually released from the regulatory control.

The same principles (analyses of site accessibility by the public, comparison with background contamination levels, screening dose assessment calculations) can be used for safety ranking of radioactively contaminated sites in other similar situations.

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РАНЖУВАННЯ ДЛЯ ВИЗНАЧЕННЯ ПРІОРИТЕТІВ ЗАХОДІВ ІЗ ПІДВИЩЕННЯ БЕЗПЕКИ ПУНКТІВ ЗБЕРІГАННЯ РАДІОАКТИВНИХ МАТЕРІАЛІВ ЧОРНОБИЛЬСЬКОГО ПОХОДЖЕННЯ, РОЗТАШОВАНИХ У РЕГІОНАХ ПРОЖИВАННЯ НАСЕЛЕННЯ

Представлено методологію та результати ранжування згідно з рівнем безпеки пунктів зберігання радіоактивних матеріалів, що знаходяться в населених районах, які прилягають до чорнобильської зони відчуження і вміщують відходи від робіт із дезактивації місцевості та знезаражування техніки, що здійснювалися в 1986 - 1989 рр. На підставі цього ранжування з безпеки надаються рекомендації щодо черговості рекультиваційних заходів та стратегії поводження з цими об'єктами. Отримані результати вказують, що роботи з рекультивації зазначених пунктів можуть бути оптимізовані, а обсяги відходів, які вимагають вилучення та подальшого захоронення в інженерних сховищах радіоактивних відходів, можуть бути суттєво мінімізовані. Рекомендується, щоб відповідальна організація (Київський міжрегіональний спеціалізований комбінат УкрДО «Радон») зосередила роботи з обстеження, моніторингу та технічного обслуговування на порівняно небагатьох об'єктах з підвищеним рівнем ризику, які визначені в цьому дослідженні. Об'єкти з низьким ступенем ризику можуть бути в подальшому звільнені від регуляторного контролю.

Ключові слова: Чорнобильська аварія, рекультивація забруднених ділянок, оцінка радіаційної безпеки.

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РАНЖИРОВАНИЕ С ЦЕЛЬЮ ОПРЕДЕЛЕНИЯ ПРИОРИТЕТОВ МЕРОПРИЯТИЙ ПО ПОВЫШЕНИЮ БЕЗОПАСНОСТИ ПУНКТОВ ХРАНЕНИЯ РАДИОАКТИВНЫХ МАТЕРИАЛОВ ЧЕРНОБЫЛЬСКОГО ПРОИСХОЖДЕНИЯ, РАСПОЛОЖЕННЫХ В РЕГИОНАХ ПРОЖИВАНИЯ НАСЕЛЕНИЯ

Представлены методология и результаты ранжирования по уровню безопасности пунктов хранения радиоактивных материалов, находящихся в населенных районах, прилегающих к чернобыльской зоне отчуждения и вмещающих отходы работ по дезактивации местности и обеззараживанию техники, которые осуществлялись в 1986 - 1989 гг. На основании этого ранжирования по безопасности даются рекомендации по очередности рекультивационных мероприятий и стратегии обращения с этими объектами. Полученные результаты указывают, что работы по рекультивации указанных пунктов могут быть оптимизированы, а объемы отходов, которые требуют изъятия и последующего захоронения в инженерных хранилищах радиоактивных отходов, могут быть существенно минимизированы. Рекомендуется, чтобы ответственная организация (Киевский межрегиональный специализированный комбинат УкрГО «Радон») сосредоточила работы по обследованию, мониторингу и техническому обслуживанию на сравнительно немногочисленных объектах, которые могут представлять повышенный уровень риска и идентифицированы в данном исследовании. Объекты же с низким уровнем риска могут быть в дальнейшем освобождены от регуляторного контроля.

Ключевые слова: Чернобыльская авария, рекультивация загрязненных участков, оценка радиационной безопасности.

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