Radiation Protection Dosimetry (2012), pp. 1–7
doi:10.1093/rpd/ncr450

VERIFICATION OF SCREENING LEVEL FOR DECONTAMINATION IMPLEMENTED AFTER FUKUSHIMA NUCLEAR ACCIDENT

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Received August 23 2011, revised November 3 2011, accepted November 4 2011

The screening level for decontamination that has been applied for the surface of the human body and contaminated handled objects after the Fukushima nuclear accident was verified by assessing the doses that arise from external irradiation, ingestion, inhalation and skin contamination. The result shows that the annual effective dose that arises from handled objects contaminated with the screening level for decontamination (i.e. 100 000 counts per minute) is <1 mSv y^{-1}, which can be considered as the intervention exemption level in accordance with the International Commission on Radiological Protection recommendations. Furthermore, the screening level is also found to protect the skin from the incidence of a deterministic effect because the absorbed dose of the skin that arises from direct deposition on the surface of the human body is calculated to be lower than the threshold of the deterministic effect assuming a practical exposure duration.

INTRODUCTION

Off the Pacific Ocean, near the Tohoku district, an Earthquake occurred at 14:46 on 11 March 2011 JST (Japan Standard Time) and generated a tsunami that inundated the Fukushima Daiichi nuclear power plant of the Tokyo Electric Power Co. (TEPCO), resulting in a nuclear accident of an unprecedented scale and over a lengthy period. As a result of this accident, the pressure venting of primary containment vessels, explosions at reactor buildings and other incidents caused radioactive materials to be released into the environment. According to the estimation of the Nuclear and Industrial Safety Agency of Japan (NISA)(1), 160 PBq of ^{131}I, 18 PBq of ^{134}Cs and 15 PBq of ^{137}Cs were discharged into the air from reactor units 1–3 of the Fukushima Daiichi nuclear power plant during 11–16 March 2011. Countermeasures have been taken, such as the restriction of the distribution and consumption of contaminated foodstuffs(2) and the implementation of a screening level for decontamination.

On 11th March, the Fukushima prefecture determined the screening level required for whole body decontamination at 100 000 counts per minute (cpm) and that partial decontamination by wiping would be performed in the case of detection of radioactivity >13 000 cpm but <100 000 cpm, based on the opinion of experts in radiation medicine dispatched from the Ministry of Education, Culture, Sports, Science and Technology (MEXT), and doctors and other professionals from the National Institute of Radiological Sciences (NIRS) and guidelines of Fukushima Medical University(3).

Meanwhile, on 19th March, the Nuclear Safety Commission of Japan (NSC) determined the screening level for decontamination to be 100 000 cpm. The revised screening level corresponds to a dose rate of 1 μSv h^{-1} at a distance of 10 cm, stipulated as a standard for decontamination in the case of contamination on the surface of the body for general residents in the Manual for First Responders to a Radiological Emergency(4) given by the International Atomic Energy Agency (IAEA). The measured values are those measured using a Type TGS-136 GM survey meter with a 5-cm bore.

With regard to the contamination of residents, the Fukushima prefecture has been implementing screening surveys for residents in the prefecture including people evacuated from within 20 km of the Fukushima Daiichi nuclear power station in cooperation with the Nuclear Emergency Response Local Headquarters. Most of the 219 743 people checked as of 20th August were under the 100 000 cpm limit. Decontamination was performed for 102 people exceeding 100 000 cpm, but their contamination levels fell to below the criterion after such decontamination(5).

The screening level for decontamination of 100 000 cpm determined by the NSC has been applied to not only the surface of the body for general residents but also contaminated objects handled by emergency workers (e.g. vehicles, equipment, machinery, tools). The authors have developed a dose assessment model for surface-contaminated objects such as manually, closely and remotely handled objects to derive isotope-specific clearance levels for surface contamination(6–8). In this study, the screening level for decontamination implemented after the Fukushima nuclear accident is verified from the viewpoint of dose assessment using the dose assessment model developed in previous studies(6–8).

MATERIALS AND METHODS

Evaluation of radioactive contamination density

Immediately after the atmospheric release of radioiodines (e.g. ^{131}I) and radiocaesiums (e.g. ^{134}Cs, ^{137}Cs) in the Fukushima nuclear accident(1), radioiodines were the main target of measurement for the determination of medical treatment for the thyroid by specialised medical doctors. Now that some months have elapsed and the radioiodines with short half-lifetimes (e.g. 8 d for ^{131}I) have almost completely decayed, radiocaesiums have become the dominant radionuclides considered in the evaluation of radioactive contamination. Figure 1 shows the trend of the concentrations of radioactive ^{131}I, ^{134}Cs and ^{137}Cs in air measured by TEPCO at the site of the Fukushima Daiichi nuclear power plant(9). On the basis of observations such as those shown in Figure 1, in this paper, the surfaces of objects and bodies are assumed to be contaminated with ^{131}I, ^{134}Cs and ^{137}Cs, the ratio of contamination density of ^{134}Cs to ^{137}Cs was set to 1 and the ratio of ^{131}I to these radiocaesiums was set to 100, 10, 1, 0.1 and 0.01.

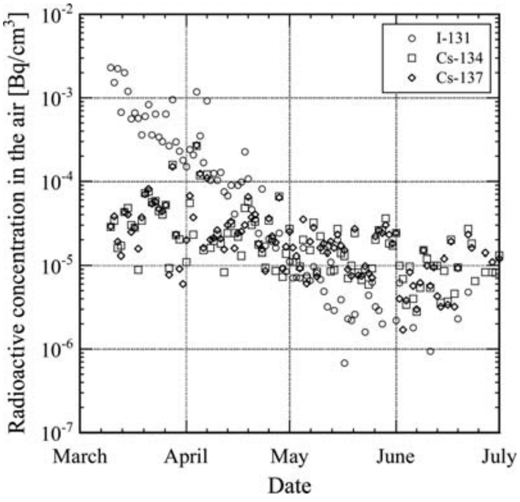

Figure 1. Radioactive concentration of ^{131}I, ^{134}Cs and ^{137}Cs in the air measured at the site of Fukushima Daiichi nuclear power plant.

The surface density of radioactive contamination is given by equation (1), where A_i (Bq cm^{-2}) is the surface density of radioactive contamination for radionuclide i, N (count s^{-1}) is the measured count rate, N_b (count s^{-1}) is the background count rate, $\varepsilon_{e,i}$ (% $2\pi^{-1}$) is the instrument efficiency for radionuclide i, W (cm^2) is the area of the detector window, $\varepsilon_{s,i}$ is the source efficiency for radionuclide i and f_i (%) is the emission rate of beta ray for radionuclide i.

$$A_i = (N - N_\mathrm{b})/(\varepsilon_{e,i} \times W \times \varepsilon_{s,i} \times f_i). \tag{1}$$

A count rate of 100 000 cpm corresponds to 1670 counts per second. The background count rate should be higher after Fukushima nuclear accident, but here it was conservatively set to zero. The beta-ray emission rates of ^{131}I were set as 89.4 % for an energy of 606 keV, 7.4 % for an energy of 334 keV, 2.1 % for an energy of 248 keV, 0.6 % for an energy of 304 keV and 0.4 % for an energy of 807 keV, and those of ^{134}Cs were set as 70.2 % for an energy of 658 keV and 2.5 % for 415 keV, those of ^{137}Cs were set as 94.4 % for an energy of 514 keV and 5.6 % for 1.176 MeV. The instrumental efficiency for beta rays was uniformly set as 0.4, conservatively considering the maximum beta-ray energies of ^{131}I, ^{134}Cs and ^{137}Cs. The source efficiency was set as 0.4 in accordance with the ISO 7503-1(10), considering that the maximum beta-ray energies of ^{131}I, ^{134}Cs and ^{137}Cs are higher than 0.4 MeV, although an experimental study has shown a higher source efficiency of radiocaesiums for various materials(11). The area of the detector window was set as 20 cm^2, which is that for an Aloka Type TGS-136 GM survey meter with a 5-cm bore that has typically been applied for the measurement for screening after the Fukushima nuclear accident.

Methodology of dosimetric assessment

The dose rate depends on the surface area of radioactive contamination regardless of the contamination density, although the applied screening level for decontamination of 100 000 cpm has been set upon considering a dose rate of 1 μSv h^{-1} at a distance of 10 cm from a radioactive surface(4). Here the dose rates at a distance of 10 cm from a surface were calculated for various contaminated areas (i.e. 100, 300 cm^2, 0.1, 0.3, 1, 3, 10 m^2) using the QAD-CGGP2 code(12), assuming that the whole area was uniformly contaminated by ^{131}I, ^{134}Cs and ^{137}Cs with surface density levels that correspond to the screening level for decontamination of 100 000 cpm calculated by equation (1).

With regard to the methodology of dose assessment from surface-contaminated objects, the original dose assessment model for the derivation of isotope-specific surface clearance levels (Bq cm^{-2}) was developed by integrating the existing stylised approach of IAEA for protecting people in the waste and transport safety fields given by the Safety Reports Series No. 44(13) and TECDOC-1449(14), so that an appropriate conservative model can be comprehensively applied to the radiation, transport and waste safety fields(6–8). In the dose assessment, the exposure scenario was classified into three categories: manually handled objects, closely handled objects and remotely handled objects. The assessed exposure pathways were external irradiation and the inhalation of resuspended radionuclides from closely and remotely handled objects, and ingestion via contaminated hands and skin contamination from manually handled objects.

In the developed model, the external irradiation was assessed using the QAD-CGGP2 code(12) assuming independent surface-contaminated areas for closely and remotely handled objects. The inhalation was assessed using the resuspension rate (h^{-1}), the volume of the room (m^3), the exchange rate (h^{-1}), the breathing rate ($m^3\ h^{-1}$) and the dose conversion coefficient of inhalation for each radionuclide (Sv Bq^{-1}) as parameters. The ingestion was assessed using the area for ingestion from the contaminated area (cm^2), the transfer factor from contaminated objects to the hands, the transfer factor from the hands to the mouth, the frequency of ingestion (h^{-1}) and the dose conversion coefficient for each radionuclide (Sv Bq^{-1}) as parameters. The dose conversion coefficients for inhalation and ingestion were given in International Commission on Radiological Protection (ICRP) Publication 68(15) for workers and in Publication 72(16) for the public. The deterministic approach was applied in the derivation of isotope-specific surface clearance levels(6) following the stylised approach developed by IAEA(13, 14), and moreover the probabilistic approach was applied using a Monte Carlo calculation code to verify the validity of the deterministic approach(7). For further details of the assessment methods, see relevant papers by Ogino and Hattori(6–8).

Table 1 shows the dose conversion factors (mSv y^{-1} Bq^{-1} cm^2) of ^{131}I, ^{134}Cs and ^{137}Cs developed for each type of surface-contaminated object. The effective dose from whole body exposure and the skin-absorbed dose that arise from these objects were calculated using the dose conversion factors given in Table 1.

In the assessment of skin contamination, there should be a direct pathway after the Fukushima nuclear accident, such as radiocaesiums existing in the atmosphere being deposited on the human body, in addition to the above assessment via the handling of a surface-contaminated object. Here the assessment of the skin-absorbed dose and the effective dose through dermal absorption becomes important. The skin-absorbed dose that arises from such direct deposition is given by equation (2), where $E_{q,i}$ (mGy) is the skin-absorbed dose for radionuclide i, A_i (Bq cm^{-2}) is the surface contamination density of the body for radionuclide i, $CF_{\beta,i}$ (mSv h^{-1} Bq^{-1} cm^2) is the skin-absorbed dose rate to the basal layer of the skin epidermis for beta irradiation (4 mg cm^{-2}) for radionuclide i, $CF_{\gamma,i}$ (mSv h^{-1} Bq^{-1} cm^2) is the skin-absorbed dose rate to the basal layer of the skin epidermis for gamma irradiation (7 mg cm^{-2}) for radionuclide i and T (h) is the exposure duration. These skin-absorbed dose rates are given in Radiation Protection 65 of Commission of the European Communities(17).

$$E_{q,i} = A_i \times (CF_{\beta,i} + CF_{\gamma,i}) \times T. \qquad (2)$$

On the other hand, it can be considered that the methodology for the dose assessment of dermal absorption is still under development, in contrast to the completed methodologies for the skin-absorbed dose and internal exposure pathways (i.e. inhalation and ingestion), although the National Council on Radiation Protection and Measurements (NCRP) has recently developed a biokinetic model for radionuclide-contaminated wounds and procedures for their assessment, dosimetry and treatment in Report

Table 1. Dose conversion factors for each surface-contaminated objects.

Radionuclide	Dose conversion factors					
	Manually handled objects		Closely handled objects		Remotely handled objects	
	Ingestion[a]	Skin[b]	External[a]	Inhalation[a]	External[a]	Inhalation[a]
^{131}I	1.2×10^{-3}	5.2×10^{-4}	7.9×10^{-5}	1.7×10^{-6}	5.9×10^{-5}	2.6×10^{-7}
^{134}Cs	1.9×10^{-4}	1.7×10^{-1}	1.5×10^{-3}	5.7×10^{-6}	7.3×10^{-4}	8.6×10^{-7}
^{137}Cs	1.5×10^{-4}	1.9×10^{-1}	6.8×10^{-4}	4.8×10^{-6}	3.2×10^{-4}	7.1×10^{-7}

[a]Effective dose for external irradiation, ingestion and inhalation (mSv y^{-1} Bq^{-1} cm^2).
[b]Skin-absorbed dose rate for skin contamination (mGy y^{-1} Bq^{-1} cm^2).

No. 156(18). Considering the above, one is not concerned here with the assessment of the effective dose through dermal absorption in this paper, the aim of which is to prove a reasonable starting point for the verification of screening levels for decontamination after the Fukushima nuclear accident.

RESULTS AND DISCUSSION

Table 2 shows the set of surface contamination densities that correspond to the screening level of 100 000 cpm. Figure 2 shows the calculated dose rates at a distance of 10 cm from a radioactive surface for different areas. It was found that the dose rate becomes higher than 1 μSv h^{-1} when the area of the radioactive surface is >200 cm^2 assuming case V and >500 cm^2 assuming case I. From these results, it was found that the notification by the NSC that 100 000 cpm corresponds to a dose rate of 1 μSv h^{-1} at a distance of 10 cm from the surface is conditionally applicable, and that the dose rate becomes higher than 1 μSv h^{-1} when the surfaces of objects are contaminated over a large area as shown in Figure 2.

Table 2. Surface densities for radioactive contamination that correspond to the screening level for decontamination (100 000 cpm) for each case.

Case no.	Assumed ratio of radionuclides	Surface density for radioactive contamination (Bq cm^{-2})		
	(^{131}I:^{134}Cs:^{137}Cs)	^{131}I	^{134}Cs	^{137}Cs
Case I	100:1:1	560	5.6	5.6
Case II	10:1:1	360	36	36
Case III	1:1:1	150	150	150
Case IV	0.1:1:1	23	230	230
Case V	0.01:1:1	2.4	240	240

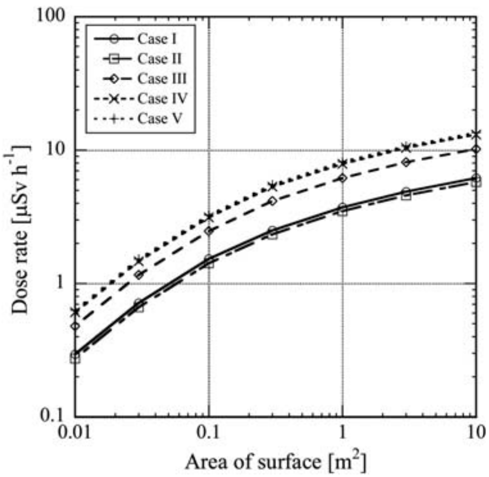

Figure 2. Dose rate at 10 cm distance from a radioactive surface as a function of area of surface contamination.

The annual doses that arise from handling objects contaminated with the screening level for decontamination are shown in Table 3. The dominant pathway for cases I and II was found to be ingestion from manually handled objects, and the annual effective doses were calculated to be 0.68 and 0.45 mSv y^{-1}, respectively. Other pathways such as external irradiation and inhalation from closely handled objects and remotely handled objects were calculated to be lower than the ingestion from manually handled objects. On the other hand, the dominant pathway for cases III–V was found to be external irradiation from closely handled objects, and the annual effective doses were calculated to be 0.35, 0.51 and 0.53 mSv y^{-1}, respectively. Doses from other pathways such as ingestion from manually handled objects and inhalation from closely and remotely handled objects were calculated to be lower than that for external irradiation.

Considering the practical screening under high-radiation conditions after the Fukushima nuclear accident, the effect of the counting loss due to the resolving time of the GM survey meter should be taken into account. With regard to the types of radiation considered in this paper, gross count rates are assumed to only consist of beta rays emitted from both radioiodines and radiocaesiums as shown in equation (1), although gamma rays emitted from these radionuclides can also be measured with lower counting efficiency than that for beta rays. The counting loss is no longer negligible under high-radiation conditions such as where the screening level of decontamination was raised to 100 000 cpm owing to the relatively long resolving time of the order of 100 μs(19). By using a correction formula for the counting loss given by equation (3), where τ (s) is the resolving time, m (count s^{-1}) is the measured count rate and n (count s^{-1}) is the true count rate (count s^{-1}), the factor for counting loss, defined as the ratio of the true count rate to the measured count rate, was calculated to be ~1.2, when the TGS-136 GM survey meter indicated a count rate of 100 000 cpm and the resolving time was assumed to be ~100 μs for the Aloka TGS-136 GM survey meter, which was typically applied in the practical screening after the Fukushima nuclear accident(3).

The above result implies that the surface contamination densities in the practical screening under high-radiation conditions where counting loss is no longer negligible may be ~1.2 times higher than those shown in Table 2, and the factor for counting

Table 3. Dose assessment for handling surface-contaminated objects with the screening level for decontamination (100 000 cpm).

Case no.	Annual dose					
	Manually handled objects ($0.1\ m^2$)		Closely handled objects ($1\ m^2$)		Remotely handled objects ($10\ m^2$)	
	Ingestion[a]	Skin[b]	External[a]	Inhalation[a]	External[a]	Inhalation[a]
Case I	6.8×10^{-1}	2.3×10^{0}	5.6×10^{-2}	1.0×10^{-3}	3.9×10^{-2}	1.5×10^{-4}
Case II	4.5×10^{-1}	1.3×10^{1}	1.1×10^{-1}	1.0×10^{-3}	3.9×10^{-2}	1.5×10^{-4}
Case III	2.4×10^{-1}	5.6×10^{1}	3.5×10^{-1}	1.9×10^{-3}	1.7×10^{-1}	2.8×10^{-4}
Case IV	1.1×10^{-1}	8.3×10^{1}	5.1×10^{-1}	2.4×10^{-3}	2.4×10^{-1}	3.6×10^{-4}
Case V	8.5×10^{-2}	8.7×10^{1}	5.3×10^{-1}	2.5×10^{-3}	2.5×10^{-1}	3.8×10^{-4}

[a] Effective dose for external irradiation, ingestion and inhalation (mSv y^{-1}).
[b] Skin-absorbed dose for skin contamination (mGy y^{-1}).

loss can also be the same for the results of the dose assessment shown in Table 3. Even when multiplying the results shown in Table 3 by the estimated counting loss, it can be found that the annual doses that arise from handling objects contaminated with the screening level for decontamination are still lower than 1 mSv y^{-1}.

$$n = \frac{m}{1 - \tau m}. \tag{3}$$

The ICRP mentions in Publication 111(20) on the protection of people living in long-term contaminated areas after a nuclear accident or a radiation emergency that the reference level for the optimisation of protection of people living in contaminated areas should be selected from the lower part of the 1–20 mSv y^{-1} band recommended in Publication 103(21) for the management of this category of exposure situation, and that past experience has demonstrated that a typical value used for constraining the optimisation process in long-term post-accident situations is 1 mSv y^{-1}. The ICRP also mentions in Publication 82(22) on the protection of the public in situations of prolonged radiation exposure that an intervention in commodities is exempted if the additional annual dose is ∼1 mSv y^{-1}. Furthermore, the ICRP also mentions in Publication 104(23) that exemption or exclusion for naturally occurring radioactive material-based industries could be handled with an individual dose criterion of ∼1 mSv y^{-1} excluding the dose from radon. In this context, the additional annual dose of ∼1 mSv y^{-1} can be considered as the intervention exemption level in existing exposure situations. Considering the result of dose assessment for handled objects contaminated with the same level as the screening level for decontamination after the Fukushima nuclear accident, it was found that the calculated annual effective doses for all cases are lower than the intervention exemption level.

The effective doses from ingestion via the dominant pathways for cases I and II were calculated to be 0.68 and 0.45 mSv y^{-1}, respectively. These effective doses correspond to equivalent doses for the thyroid of 14 and 9.0 mSv y^{-1}, respectively, considering the ingestion effective dose coefficient of ^{131}I for a 1 y old child upon intake (1.8×10^{-7} Sv Bq^{-1}) given by ICRP Publication 72(16) and the ingestion equivalent dose coefficient of ^{131}I for a 1 y old child upon intake (3.6×10^{-6} Sv Bq^{-1}) given by ICRP Publication 67(24). These dose coefficients are given for a 1 y old child because the dose conversion factors for each of the surface contaminated objects given in Table 2 were calculated for this critical age in previous studies(6–8).

The ICRP mentions in Publication 40(25) on general guidance on dose values for the introduction of countermeasures that the lower equivalent dose level for early- and intermediate-phase countermeasures is 50 mSv y^{-1} for individual organs preferentially irradiated and that the upper equivalent dose level is 500 mSv y^{-1}. The equivalent dose level of 50 mSv y^{-1} for the thyroid recommended by the ICRP has been applied to the food safety regulations implemented after the Fukushima nuclear accident(2). Considering the result of dose assessment for the thyroid from handled objects contaminated with the same level as the screening level for decontamination (i.e. 14 and 9.0 mSv y^{-1}), it was found that the calculated annual equivalent doses are lower than the lower equivalent dose levels for early- and intermediate-phase countermeasures for individual organs recommended by ICRP Publication 40(25).

With regard to skin contamination, the annual absorbed dose that arises from handling surface-contaminated objects was calculated to be 87 mGy y^{-1}, as shown in Table 3, and the calculated

Table 4. Skin-absorbed dose rate from direct deposition on the body with the screening level for decontamination (100 000 cpm).

Case no.	Skin absorbed dose rate (mGy h^{-1})			
	^{131}I	^{134}Cs	^{137}Cs	Total (^{131}I+^{134}Cs+^{137}Cs)
Case I	1.4×10^{0}	1.1×10^{-2}	1.4×10^{-2}	1.4
Case II	8.7×10^{-1}	6.9×10^{-2}	9.2×10^{-2}	1.0
Case III	3.7×10^{-1}	2.9×10^{-1}	4.0×10^{-1}	1.1
Case IV	5.5×10^{-2}	4.4×10^{-1}	5.9×10^{-1}	1.1
Case V	5.8×10^{-3}	4.6×10^{-1}	6.2×10^{-1}	1.1

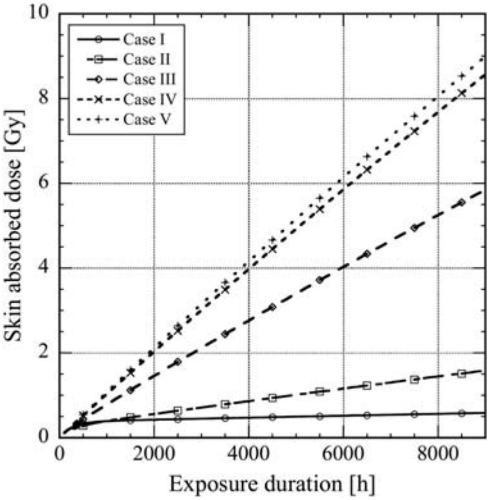

Figure 3. Skin-absorbed dose from direct deposition on body as a function of exposure duration.

absorbed dose rates of skin that arise from the direct deposition of radioiodine and radiocaesiums on the body are shown in Table 4. Figure 3 shows the absorbed dose of the skin from direct deposition on the body for different radioactive surface contamination densities.

The threshold of a deterministic effect on the skin observed in a clinical study on acute irradiation has been reported by the IAEA(26) to be 3–10 Gy for erythema, >3 Gy for epilation, 8–12 Gy for dry desquamation, 15–20 Gy for moist desquamation, 15–25 Gy for blister formation, >20 Gy for ulceration within the skin and >25 Gy for necrosis (deeper penetration).

Even assuming that a similar deterministic effect can be observed in the case where the time integration of the absorbed dose rate of the skin from chronic irradiation (e.g. 1.0 mGy h^{-1}) reaches the lowest threshold of acute irradiation (>3 Gy), the implemented screening level for decontamination can be considered to prevent the skin from the incidence of a deterministic effect such as erythema or epilation, because ∼3000 h of irradiation is required to reach the minimum threshold (i.e. 3 Gy). Furthermore, the entire process of the turnover of the skin, from the birth of basal cells to the formation of surface corneocytes and desquamation, is accomplished within 14–75 d in humans, during which continuous cell proliferation is required in the basal layer to maintain the tissue(27–30).

Finally, although the calculated absorbed doses of the skin were found to be unlikely to reach the threshold of a deterministic effect on the skin in a practical exposure situation, countermeasures for preventing the contamination of the human body should be applied in advance for parts of the body that may be contaminated, and even parts of the body possibly contaminated below the screening level should be decontaminated to a level as low as reasonably achievable to ensure optimal radiation protection.

CONCLUSION

The screening level of 100 000 cpm that has been applied for decontamination of the surface of the human body and handled objects implemented after the Fukushima nuclear accident was verified by assessing the doses that arise from external irradiation, ingestion, inhalation and skin contamination. The annual effective dose from handling contaminated objects was found to be lower than 1 mSv, which can be considered as the intervention exemption level. The screening level of 100 000 cpm can also prevent the skin from the incidence of a deterministic effect assuming a practical exposure duration.

FUNDING

This work was supported by the Radiation Safety Research Project of the Central Research Institute of Electric Power Industry (CRIEPI).

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