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Assessment of total annual effective doses to representative person, for authorised and accidental releases from the Nuclear Medicine Department at Cattinara Hospital (Trieste, Italy)

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ABSTRACT

Purpose: Clinical procedures in a Nuclear Medicine Department produce radioactive liquid and solid waste. Regarding waste release into the environment from an authorised hospital, it is mandatory to verify the compliance with European Directive 2013/59/EURATOM, adopted by the Italian Government via the Legislative Decree 101/2020.

Methods: Different activity release pathways into the environment from Trieste Nuclear Medicine Department have been analysed: liquid waste from patients' excreta discharged by sewage treatment system into the sea, and atmospheric releases following solid waste incineration. Reference models, provided by NCRP and IAEA guidelines, have been implemented to assess the impact of the discharged radioactivity for coastal waters and atmospheric transport conditions. Finally, an accidental fire event occurring in Radiopharmacy Laboratories has been simulated by HotSpot software.

Results: Advanced screening models give an effective dose to population of $5.3 \cdot 10^{-3} \mu\text{Sv/y}$ and $1.4 \cdot 10^{-4} \mu\text{Sv/y}$ for introduction by sewage system into coastal waters and atmospheric releases by the incinerator, respectively. Workers involved in the maintenance of the sewage treatment plant receive a total annual effective dose of $3.8 \mu\text{Sv/y}$, while for incinerator staff the total annual exposure is $5.9 \cdot 10^{-8} \mu\text{Sv/y}$. For the accidental fire event the maximum total effective dose to an individual results $3.8 \cdot 10^{-8} \text{ Sv}$ with mild wind, and $4.1 \cdot 10^{-7} \text{ Sv}$ with strong wind.

Conclusions: The total annual effective doses estimated to representative person, due to both Nuclear Medicine authorised clinical practices and in case of an accidental fire event, are in compliance with regulatory stipulations provided by Directives.

1. Introduction

Safe management of radioactive liquid and solid waste produced in clinical procedures by an authorized Nuclear Medicine (NM) Department is the main task in obtaining controlled disposal [1]. Therefore, the Council Directive 2013/59/ EURATOM has established the basic safety standards for protection against the dangers arising from exposure to

ionising radiation [2], transposed by the Italian Government into Legislative Decree 101/2020 [3,4]. For the Italian legislation it is mandatory to determine the activities contained in patients' excreta, produced both in the NM Department and elsewhere, when patients return to their original hospital clinics or home. In particular, the risk is negligible when the total effective dose received by the representative person [5], due to the liquid waste releases discharged directly from the hospital

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Fig. 1. View of the Servola sewage plant pipes, extending into the Trieste gulf [12].

facility, is less than or equal to $10 \mu\text{Sv/y}$. The same limit has to be assessed for atmospheric release due to the incineration of solid waste [4].

An evaluation of the total activity released by patients' excreta is derived by the total activity administered both diagnostic and therapeutic procedures, considering the clinical NM practices performed throughout a year. The fraction of the administered activity excreted at a certain time is evaluated according to [6]:

$$f_i(t) = \sum_i \frac{F_{s,i} \cdot a_i \cdot \lambda_i}{\lambda_i + \lambda_p} \left(1 - e^{-(\lambda_i + \lambda_p) \cdot t}\right)$$

where $F_{s,i}$ is the fraction of the administered activity to organ or tissue S for the single radionuclide i and a_i is the $F_{s,i}$ radionuclide fraction eliminated, λ_i and λ_p are the biological elimination and the physical decay constants of the i-th radioisotope, respectively [6].

In the first two hours after the administration, patients have to stay in the NM Department and use the dedicated toilets, so that their excreta are collected in the decay tanks. The total non-intercepted excreted activity released into the sewage system by inpatients, returning to other hospital clinics, is $S_{iw}(\text{env})$ and it is expressed as [7]:

$$S_{iw}(\text{env}) = Q_i(\text{env}) \times R_i \times (f_i(\infty) - f_i(a)) \quad (2)$$

where $Q_i(\text{env})$ is the total annual administered activity for the radionuclide i; R_i is the fraction of hospitalized patients; $f_i(\infty)$ is the total excreted fraction; $f_i(a)$ is the excreted fraction in the first two hours. In order to estimate the contributions due to outpatients, who return to their home after the clinical exams, the non-intercepted excreted activity released outside the hospital is given by [7]:

$$S_{iw}(\text{hom}) = Q_i(\text{env}) \times (1 - R_i) \times (f_i(\infty) - f_i(a)) \quad (3)$$

Regarding the activity present in solid waste produced from NM procedures, it consists in non-administered activity, which is obtained from data provided by radiation protection experts. Moreover, the activity decay resulting from solid waste storage in the deposit, before the disposal via a waste company, has to be considered [7,9].

1.1. Environmental screening models

An analysis of the hospital not-intercepted radioactive liquid waste released into the sewage system, excreted by all patients, and of the atmospheric releases produced by incinerated solid waste, it is essential to estimate the amount of radionuclide concentrations discharged into the environment. The evaluation of the radiological impact of radioactive releases from a hospital facility by a NM Department is assessed through the screening transport models, which are provided by international guidelines. These models are implemented depending on the medium in which radioactivity is released (e.g. surface waters or atmosphere) [10,11].

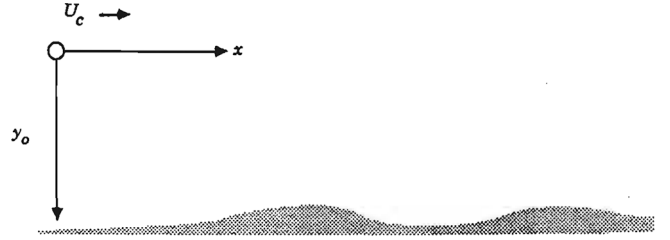


Fig. 2. View of coastal region with the diffusion parameters reported [10].

1.1.1. Surface water model

An advanced assessment method, which provides a more detailed water surface transport model (screening level II), has been used to evaluate the radionuclide concentrations into coastal waters. This model is intended to be used for routine long-term continuous releases of radionuclides from an emitting point source [10,11]. It meets our local environmental scenario, since the sewage treatment plant based in Trieste extends into the Adriatic Sea (see Fig. 1) [12].

The advanced screening coastal waters model is based on the following two-dimensional diffusion equation [10]:

$$U_c \frac{\partial C}{\partial x} = k_y \frac{\partial^2 C}{\partial y^2} - \lambda_i C \quad (4)$$

where C is the radionuclide concentration (Bq/m^3), U_c (m/s) is the velocity of the coastal current, k_y (m^2/s) is the lateral dispersion coefficient, λ_i (s^{-1}) is the radioactive decay constant of the i-th radionuclide, y (m) is the lateral direction distance from the shoreline and x (m) is the receptor position along the sea current at which the concentration is calculated (see Fig. 2). If U_c is not available a default value of 0.1 m/s is used [10].

Assuming that a constant release point is located at a distance y_0 from the shoreline and D (m) is the water depth of the radionuclide effluent outfall at the discharge point, the conditions that x and y must satisfy in order to apply this model are [10]:

$$7D < x \quad \text{and} \quad \left| \frac{y - y_0}{x} \right| \ll 3.7 \quad (5)$$

The concentration along the shoreline, at the receptor position, is given by solving Eq. (4) setting the lateral direction distance (y) equal to zero [10]:

$$C^{\text{shoreline}}(x) = \frac{962 W_0 U_c^{0.17}}{D x^{1.17}} \times \exp\left(-\frac{7.28 \cdot 10^5 U_c^{2.34} y_0^2}{x^{2.34}}\right) \times \exp\left(-\frac{\lambda_i x}{U_c}\right) \quad (6)$$

where W_0 (Bq/s) is the radionuclide release rate at the discharge point. The radionuclide concentration has been evaluated at a distance x from the release point where it is conceivable that water usage will expose reference person to radiation; if the receptor position is unknown it is

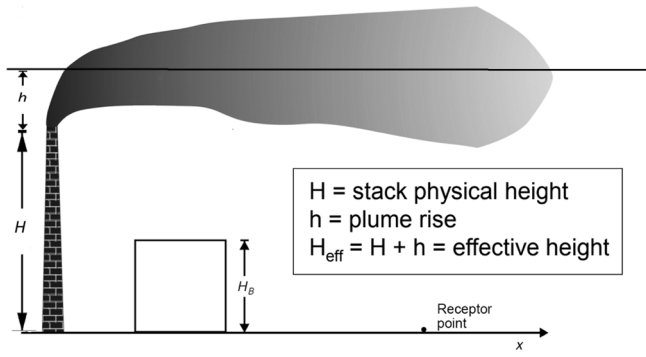


Fig. 3. Plume distribution in undisturbed dispersion condition, without building wake effect ($H > 2.5 H_B$) [11].

approximated at 50 times the water depth [10,11].

1.1.2. Atmospheric dispersion model

An atmospheric dispersion model is recommended to estimate the environmental impact of the incinerated solid waste. A detailed screening assessment for the evaluation of the average concentration of a radionuclide in the atmosphere at a certain receptor distance (x) is provided by the dispersion Gaussian plume model (screening level II), which is designed to be used for intermittent long-term releases from point sources occurring over a period of a year [10]. If the height of the release point (H) at plant smokestack is greater than 2.5 times the height of surrounding buildings (H_B) (see Fig. 3), the wake effect due to the presence of other buildings can be neglected [11].

Then the average radionuclide air concentration C (Bq/m^3) at the ground level is computed as [11]:

$$C = \frac{f \times Q \times P}{u} \quad (7)$$

where f and Q (Bq/s) are the fraction of the time the wind blows toward the receptor of interest (a default value is 0.25) and the average discharge rate value for the specific radionuclide, respectively; u (m/s) is the average wind speed at the height of the release point and P (m^{-2}) is the Gaussian diffusion factor for an appropriate value of the release height and of the downwind receptor distance. The Gaussian diffusion factor P is evaluated with the following equation [11]:

$$P = \frac{12}{\sqrt{2\pi^3}} \times \frac{\exp\left[-\left(\frac{H^2}{2\sigma_z^2}\right)\right]}{x\sigma_z} \quad (8)$$

where σ_z (m) is the vertical diffusion parameter, which depends on the stack release height. As shown in the Fig. 3, the effective plume height (H_{eff}) is higher than the physical release height (H), because the rise of the plume (h) increases the air plume distribution. However, if it is not possible to estimate H_{eff} , the physical height of the stack can be selected for the screening evaluations [13]. This model assumes that the terrain surrounding the incinerator stack is completely flat [11].

1.1.3. Accidental general fire

A general fire event involving radioactive materials has been evaluated through a simulation software. For the NM Department the most probable scenario is an accidental fire occurring in the working area, specifically in Radiopharmacy Laboratories where unsealed radionuclides are manipulated; this possible scenario has been simulated through HotSpot Health Physics Codes [14]. A three-dimensional Gaussian model is used to evaluate the time-integrated radionuclide concentration C ($\text{Bq}\cdot\text{s}/\text{m}^3$) of atmospheric dispersion at any point in the space, by the following equation [13]:

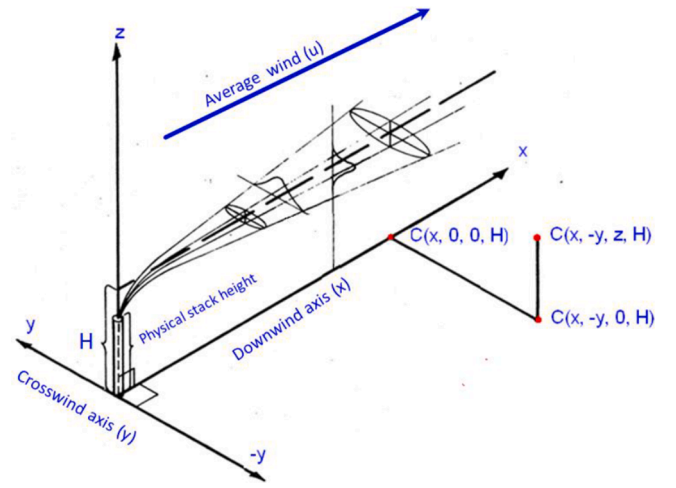


Fig. 4. 3D Gaussian air plume extension with respect to the software coordinate system [13].

$$C(x, y, z, H) = \frac{Q}{2\pi\sigma_y\sigma_z u} \exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right] \left\{ \exp\left[-\frac{1}{2}\left(\frac{z-H}{\sigma_z}\right)^2\right] + \exp\left[-\frac{1}{2}\left(\frac{z+H}{\sigma_z}\right)^2\right] \right\} \exp\left[-\frac{\lambda x}{u}\right] DF(x) \quad (9)$$

x : downwind distance (m); y : crosswind distance (m); z : vertical axis distance (m); H : effective release height (m); Q : activity source term (Bq); u : average wind speed at the effective release height (m/s); σ_y : standard deviation (SD) of the integrated concentration distribution in the crosswind direction (m); σ_z : standard deviation (SD) of the integrated concentration distribution in the vertical direction (m); λ : radioactive decay constant (s^{-1}); $DF(x)$: plume depletion factor.

The plume depletion factor considers that the source term can decrease with the increase of downwind distance. The HotSpot software allows the selection of the appropriate meteorological atmospheric conditions, which could be selected between six stability classes, based on five categories of solar insolation. The receptor is assumed to remain at the same downwind location throughout the passage of the plume and the release duration of radioactive material lasts 10 min by default (see Fig. 4) [13].

1.2. Total annual effective dose estimation

To assess compliance with directives [2,4], the NCRP Report defines the Screening Value SV (Sv/y) as the total annual effective dose received by a representative person due to the contribution of a single radionuclide released into the environment [10]:

$$SV = C \times SF \quad (10)$$

where C (Bq/m^3 or Bq/m^2) is the concentration of the radionuclide released at the exposure point, in a specific medium, and SF (Sv/y per Bq/m^3 or Sv/y per Bq/m^2) is the screening factor coefficient, which depends on the type of radionuclide and the exposure pathways; it considers the total annual effective dose (Sv), received both from external irradiation and internal contamination. The sum of the screening values for all the discharged radionuclides is the total annual effective dose to be compared with the dose limit introduced by current regulations [10,11].

1.2.1. Effective dose exposure of sewage workers

In order to evaluate the annual dose exposure of sewage workers doing maintenance of the sewage treatment plant, the IAEA assessment

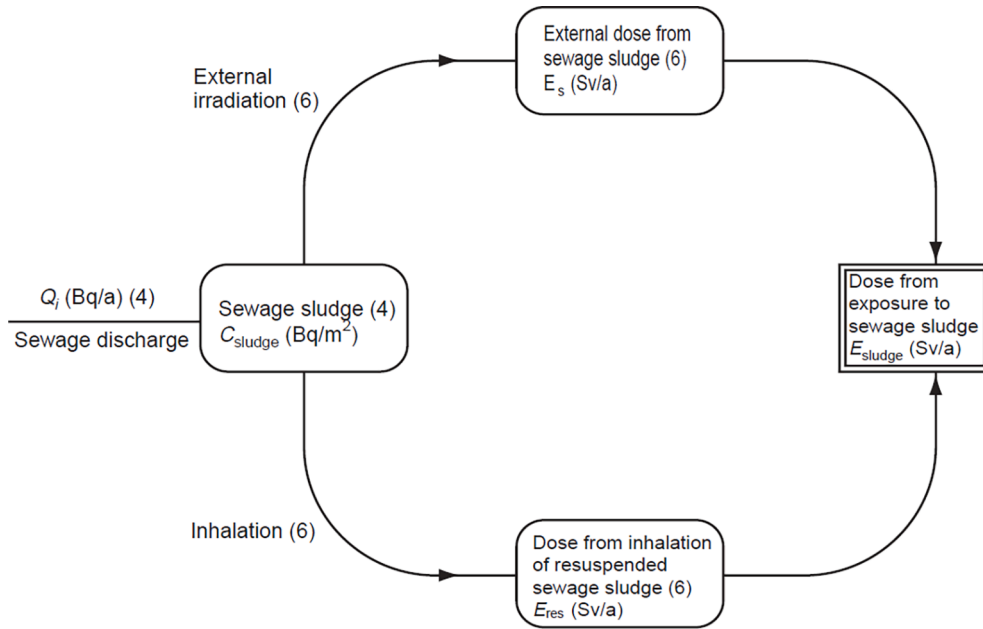


Fig. 5. IAEA assessment method to evaluate annual effective dose to sewage plant workers [11].

method has been used. The two main potential exposure pathways from radionuclides in the sewage plant, which are external irradiation and inhalation of resuspended material from sewage sludge (see Fig. 5), have been used to estimate the maximum dose received by workers throughout the year [11].

The dose from external irradiation exposure $E_{s,i}$ (Sv/y), for each specific radionuclide i , is estimated as [11]:

$$E_{s,i} = C'_{sludge,wet} \times DF_{gr} \times O_f \quad (11)$$

where $C'_{sludge,wet}$ (Bq/m²) is the surface concentration of the radionuclide i per unit area of the sewage sludge. This parameter is obtained from the annual average concentration of the radionuclide in the sludge C_{sludge} (Bq/kg), assuming that the density of sewage sludge is 1000 kg/m³ and the depth of the sewage sludge container is 1 m [11]:

$$C'_{sludge,wet} = C_{sludge,wet} \times \rho \times depth = C_{sludge,wet} \times 1000 \frac{kg}{m^3} \times 1 m \quad (12)$$

DF_{gr} (Sv/y per Bq/m²) is the dose conversion factor for ground contamination (Table XV) [11]. The workers occupation factor O_f is the exposure time fraction during the year, this factor is usually 0.228 based on the average working hours (2000 h/y) [11]. Regarding the effective dose depending on inhalation E_{res} (Sv/y), caused by resuspended material from sewage sludge, it is given by [11]:

$$E_{res} = C_{sludge,wet} \times R_{inh} \times DF_{inh} \times O_f \times DL \quad (13)$$

where the new elements introduced are: R_{inh} (m³/y), that is the annual inhalation rate reported in Table XIV [11]; DF_{inh} (Sv/Bq) which is the dose coefficient for intake by inhalation present in Table XVI [11]; and DL (kg/m³) is the resuspension factor set to $1.0 \cdot 10^{-7}$ kg/m³, which is calculated from direct measurements made around a sewage plant [11].

1.2.2. Effective dose exposure of incinerator workers

Incinerator workers might be exposed to the irradiation from contaminated dusts present around the installation. There are two main exposure contributions, the external effective dose and the one caused by inhalation of airborne material. The annual external effective dose from immersion in the radioactive discharged cloud E_{im} (Sv/y), is computed as [11]:

Table 1

Excreted fractions, total annual administered activity and total activity excreted by patients involved in diagnostic and therapeutic clinical procedures at Trieste NM Department [7,8].

Radiopharmaceuticals	Excreted fraction (2 h) (%)	Total Excreted fraction (%)	Total Administered Activity [MBq/y]	Total Excreted Activity [MBq/y]
Diagnostic procedures				
F-18 (FDG)	11	15	$5.6 \cdot 10^5$	$8.4 \cdot 10^4$
Tc-99m (HM-PAO)	16	35	$3.1 \cdot 10^4$	$1.1 \cdot 10^4$
Tc-99m (MAA)	16	45	$3.4 \cdot 10^4$	$1.5 \cdot 10^4$
Tc-99m (MAG)	95	97	$9.6 \cdot 10^3$	$9.3 \cdot 10^3$
[Normal renal function]				
In-111 (Octreoscan)	29	85	$2.6 \cdot 10^3$	$2.2 \cdot 10^3$
I-123 (DATSCAN)	8	32	$1.8 \cdot 10^4$	$5.7 \cdot 10^3$
Therapeutic procedures				
I-133 (Iodine)	15	68	$8.5 \cdot 10^3$	$5.8 \cdot 10^3$
[Hyperthyroidism therapy, medium uptake]				

$$E_{im} = C_A \times DF_{im} \times O_f \quad (14)$$

where C_A (Bq/m³) is the annual activity concentration of the radionuclide present in air, DF_{im} (Sv/y per Bq/m³) is the effective dose conversion coefficient for immersion (Table XV) [11] and O_f is the occupational factor, which is equal to 0.18 and computed by considering an average working time of 1800 h/y (Table XIV) [11]. However, to evaluate properly the total annual external dose due to the immersion of the workers in the contaminated cloud, the contribution to the skin from the β -emitter nuclei have to be included. The annual effective dose due to inhalation (E_{inh}) of airborne material is computed similarly to Eq. (13), but replacing the annual average radionuclide concentration in air [11].

2. Materials and methods

The evaluation of the total activity released by patients' excreta,

Table 2

Total annual activity intercepted by the hospital, total annual activity non-intercepted by the hospital and total non-intercepted activity released from patients returning to their clinics or home [7].

Radiopharmaceuticals	Excreted activity intercepted by hospital [MBq/y]	Excreted activity non-intercepted by hospital [MBq/y]	Excreted activity released by other clinics [MBq/y]	Excreted activity released outside the hospital [MBq/y]
Diagnostic procedures				
F-18 (FDG)	$6.1 \cdot 10^4$	$2.3 \cdot 10^4$	$5.8 \cdot 10^3$	$1.7 \cdot 10^4$
Tc-99m (HM-PAO)	$4.9 \cdot 10^3$	$5.9 \cdot 10^3$	$1.5 \cdot 10^3$	$4.4 \cdot 10^3$
Tc-99m (MAA)	$5.4 \cdot 10^3$	$9.6 \cdot 10^3$	$2.4 \cdot 10^3$	$7.2 \cdot 10^3$
Tc-99m (MAG)	$9.1 \cdot 10^3$	$1.9 \cdot 10^2$	$0.5 \cdot 10^2$	$1.4 \cdot 10^2$
[Normal renal function]				
In-111 (Octreoscan)	$7.7 \cdot 10^2$	$1.5 \cdot 10^3$	$3.7 \cdot 10^2$	$1.1 \cdot 10^3$
I-123 (DATSCAN)	$1.4 \cdot 10^3$	$4.4 \cdot 10^3$	$1.1 \cdot 10^3$	$3.3 \cdot 10^3$
Therapeutic procedures				
I-133 (Iodine)	$1.3 \cdot 10^3$	$4.5 \cdot 10^3$	$1.1 \cdot 10^3$	$3.4 \cdot 10^3$
[Hyperthyroidism therapy, medium uptake]				

shown in last column of Table 1, has been obtained by the total administered activity for both diagnostic and therapeutic procedures (see third column), considering all the clinical practices performed at the Trieste NM Department during a year. The excreted fraction in the first two hours, which mainly consists in urine, and the total excreted fraction including urine and faeces are reported in the first two columns of the Table 1, respectively [7,8]. The excreted fractions have been evaluated according to biokinetic models reported in reference guidelines [6,15], while for Iodine-131, they have been obtained from the activity curves proposed by Leggett's model [16]. Instead, the first column in Table 2 gives the annual excreted activity intercepted by the hospital, which is stored in decay tanks for 7 weeks, before being released into the sewage system. The total excreted activity non-intercepted by the hospital is given in the second column, and it is the sum of the total non-intercepted excreted activity released into the environment by inpatients (Eq. (2)) and outpatients (Eq. (3)), expressed in the last two columns of Table 2, respectively [7]. These evaluations are in agreement with the diagnostic and therapeutic clinical procedures performed in Trieste NM Department, since an activity of therapeutic I-131 larger than 600 MBq/pt is not administered. For the outpatients we assume that their excreta are discharged in the Trieste sewage system, because clinical procedures are mainly performed for local residents.

To evaluate the average radionuclide concentrations into coastal waters, at the receptor position, Eq. (6) has been used: the Trieste sewage plant pipes extend at a water depth of 20 m under the sea and the emission point (y_0) lies at 3 km far from the shoreline [12]. By setting a large value of y_0 , the second factor in Eq. (6) rapidly decreases to zero, then a more conservative evaluation has been carried out assuming this parameter is equal to 100 m. For screening purposes the potential receptor location has been assumed to be at a distance of 1000 m along the shoreline [10].

Regarding the average radionuclide air concentration, the advanced atmospheric screening model has been implemented (see Sec. 1.1.2.). The incinerator plant belongs to Ecoeridania company, it is located in Forlì (Italy): the height of the stack (H) is 49 m, set as the height of the release point [17] and the average wind speed (u) near the incinerator is 2.3 m/s [18]. The radionuclide air concentration has been computed at the receptor downwind distance of 800 m from the incinerator [11].

The total annual external and internal effective doses to workers of both sewage and incinerator plants have been evaluated following the

Table 3

Radionuclide activities present simultaneously, in the Trieste NM Department Radiopharmacy Laboratories.

Radionuclide	Activity [GBq]
Diagnostic procedures	
F-18	10.5
Tc-99m	39.4
I-123	0.2
I-131	0.01
Generator system	
Mo-99	33
Sealed sources	
Cs-137	0.009
Co-57	0.44
Therapeutic procedures	
I-131	0.6

models given in Section 1.2.1 and Section 1.2.2, respectively. In case of external effective dose to sewage workers, a radioactive decay correction (D_i) has been introduced in Eq. (11) in order to take into account the activity reduction of the specific radionuclide i [19]:

$$D_i = \frac{1}{\lambda_i} [1 - e^{-\lambda_i T}] \quad (15)$$

where λ (s^{-1}) is the radionuclide decay constant and T is the number of second in 20 days, which is the average sludge treatment period in the sewage plant [20]. The external irradiation exposure $E_{s,i}$ (Sv/y), for each radionuclide i in sewage sludge, then becomes:

$$E_{s,i} = C'_{sludge,wet} \times D_i \times SF_i \times O_f \quad (16)$$

where the screening factor considered is e_E^{ground} (Sv/s per Bq/m²), the effective dose rate coefficient for ground surface found in Table 4-1 [19].

Finally, an accidental fire event in the Trieste NM Radiopharmacy Laboratories has been simulated by Hotspot software. A pessimistic scenario has been hypothesised: the maximum radionuclide activities for all diagnostic and therapeutic procedures are simultaneously available in the Radiopharmacy Laboratories (see Table 3) and contribute to the source term. Also sealed sources and generator system activity contributions have been included in this term, as they are present in the NM Radiopharmacy Laboratories inventory [13].

Other parameters inserted in the Source Term section are: the physical height of the fire, which has been set to zero; the release radius and the room temperature, set to 1 m and 22° C, respectively. The release radius corresponds to the radius of an equivalent circle that has the same area of the Radiopharmacy Laboratory window. A heat emission rate of $7.6 \cdot 10^5$ cal/s has been assumed, knowing a typical average fire load for a standard hospital room is 230 MJ/m² [21]. However, this value is overestimated, considering that all possible kinds of flammable elements (e.g. furnishings, papers, solvents...) are not allowed in the NM Radiopharmacy Laboratories, and since all materials composition have to be chosen with reference to their resistance to heat and fire [22]. In Meteorology section, two wind speeds have been chosen, the first equal to 3.1 m/s to simulate a mild wind rising from West, while the second is 32 m/s to mimic the strong local wind (called Bora) which blows from East-North-East (ENE). The speed of local wind Bora has been derived from weather forecast data collected on March 26th 2020 [23]. The solar information "sun high in the sky" has been chosen, because it leads to the appropriate stability classification based on our direct observations: extremely unstable (class A) and slightly unstable (class C) [13]. A receptor height of 1.5 m has been set in the Receptor section. Finally, in the Setup section, a fire duration of 30 min has been considered (before

Table 4

Total annual effective dose estimations to representative person, evaluated through advanced screening models, due to the radionuclides discharged into coastal surface water and atmospheric releases.

Radionuclides	Coastal waters	Atmospheric releases
	Total Annual Effective dose [$\mu\text{Sv/y}$]	
Diagnostic procedures		
F-18	$1.5 \cdot 10^{-5}$	$<10^{-10}$
Tc-99m	$2.1 \cdot 10^{-5}$	$<10^{-10}$
In-111	$1.6 \cdot 10^{-4}$	$1.9 \cdot 10^{-8}$
I-123	$1.1 \cdot 10^{-5}$	$<10^{-10}$
Therapeutic procedures		
I-131	$5 \cdot 10^{-3}$	$1.4 \cdot 10^{-4}$

Table 5

Total annual effective dose evaluations for sewage and incinerator plant workers, for radionuclides employed in diagnostic and therapeutic clinical procedures in the Trieste NM Department.

Workers	Sewage	Incinerator
External exposure [$\mu\text{Sv/y}$]	$E_{s,i}$ 3.8	$E_{in/skin}$ $1.4 \cdot 10^{-9}$
Internal exposure [$\mu\text{Sv/y}$]	E_{res} $8.9 \cdot 10^{-5}$	E_{inh} $5.8 \cdot 10^{-8}$

the intervention of fire-fighting teams) and a breathing rate value of $2.66 \cdot 10^{-4} \text{ m}^3/\text{s}$, which corresponds to the average adult inhalation rate, have been set [11,13].

3. Results

Regarding the impact of liquid waste disposed of directly by the Trieste hospital, by using the simplest screening model [10] we have estimated a total annual effective dose of $6.4 \mu\text{Sv/y}$ to representative person at the discharge point, so the exemption limit is widely respected [4]; it leads to a negligible value of $5.6 \cdot 10^{-3} \mu\text{Sv/y}$ by applying the decay correction present in Eq. (15).

Furthermore, the total annual effective doses to representative person, resulting from the analysis of the radioactive waste releases into the surface waters and in the atmosphere, have been evaluated through advanced screening models and they are reported in Table 4.

The effective dose assessment has also been performed for the workers involved in the maintenance of sewage and incineration plants, who receive a total annual effective dose of $3.8 \mu\text{Sv/y}$ and of $5.9 \cdot 10^{-8} \mu\text{Sv/y}$, respectively (see Table 5).

Regarding the accidental fire event, the Hotspot software returns the TEDE (Total Effective Dose Equivalent – Sv) plots, this parameter includes the effective dose equivalent for external irradiation due to the cloud submersion and the internal effective dose equivalent due to inhalation, at several downwind distances from the source [13]. The maximum TEDE value is $3.8 \cdot 10^{-8} \text{ Sv}$, reached at distance of 0.2 km for mild wind (see Fig. 6) with stability class A; while for strong Bora wind and stability class C the maximum TEDE value is $4.1 \cdot 10^{-7} \text{ Sv}$ at 0.044

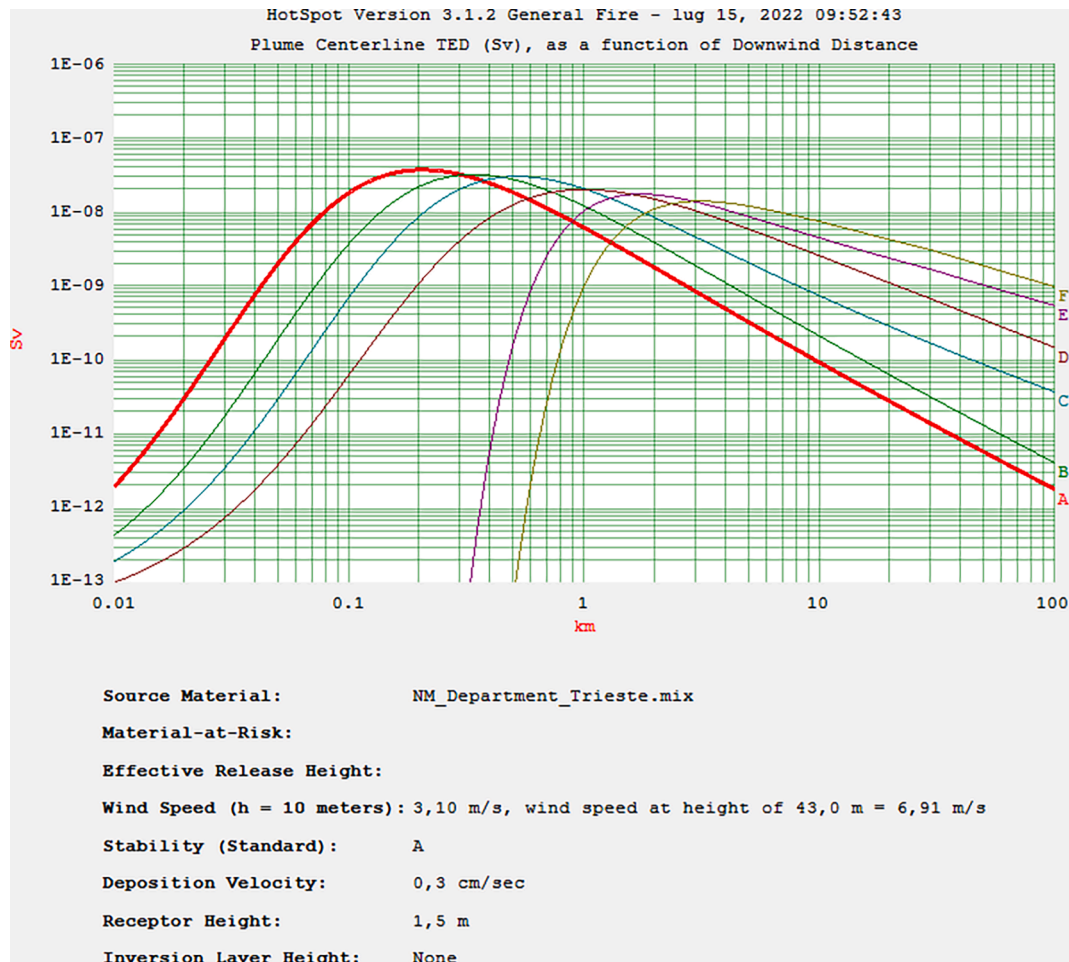


Fig. 6. HotSpot TEDE plots performed for the scenario with a mild wind from West, as a function of downwind receptor position.

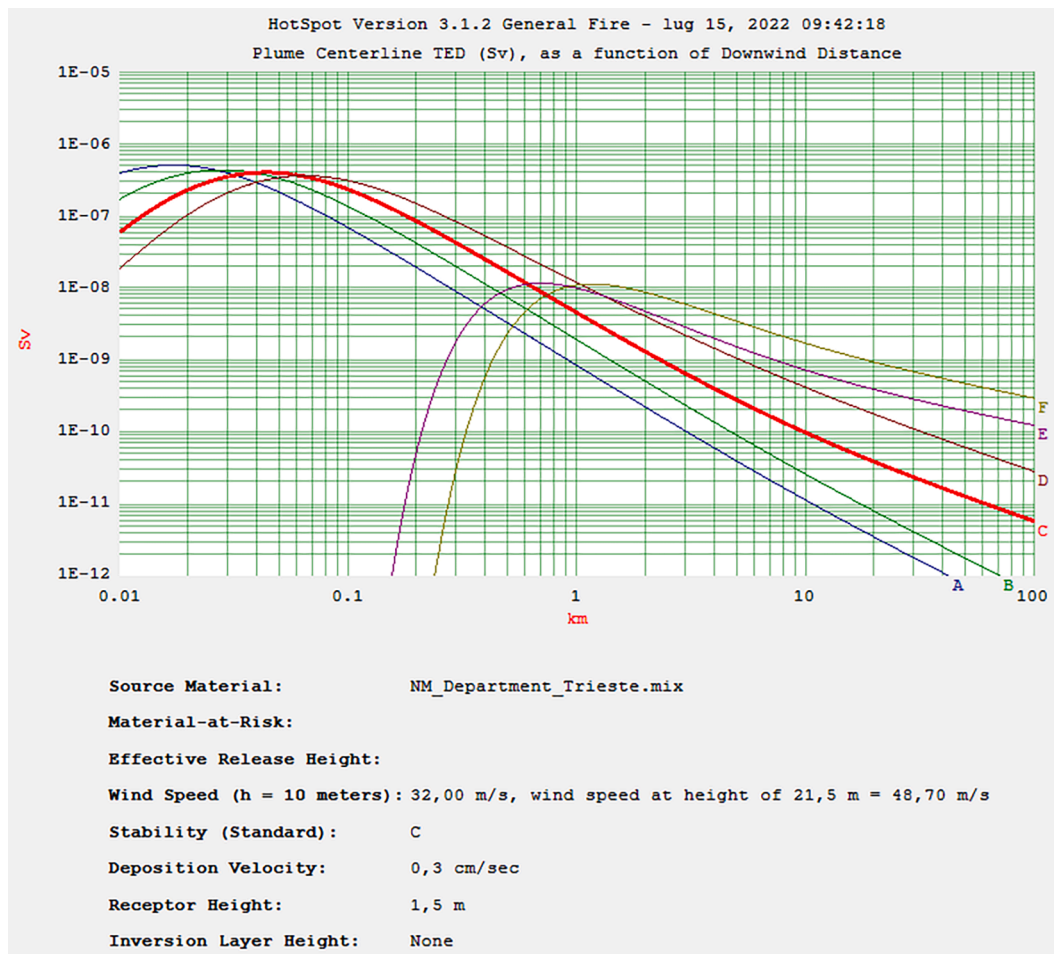


Fig. 7. HotSpot TEDE plots performed for the scenario with a local strong Bora wind from ENE, as a function of downwind receptor position.

km from the source term (see Fig. 7). Also the curves obtained with other atmospheric stability classes (e.g. E and D) have been included in both plots.

4. Discussion

The consequences of radionuclides discharge into the environment, resulting from the management of liquid and solid waste produced by Trieste NM Department clinical procedures, have been investigated through advanced screening models. The models' formalism is based on realistic assumptions, resulting in detailed total annual effective dose estimations for individuals and workers exposed to discharged radioactivity [24]. The resulting annual effective external irradiation, for the sewage workers, demonstrates that the presence of ^{131}I in the sludge is the main source of exposure, while the inhalation risk is negligible [20]. The workers at the incineration plant are subject to the risk of external and internal irradiation due to the presence of airborne radionuclides, for which minimal annual effective dose contributions were found [25]. The same assessment approach has been extended to individuals of the public, for coastal waters and atmospheric releases, and the resulting annual effective dose estimates are consistent with other assessment methods [26,27]. Even though the advanced models give reliable results, an in-depth study to evaluate the accuracy of annual dose exposure calculations is suggested, performing an analysis on data uncertainties [28]. In addition a comparison with experimental measurements is advised: this study could be performed with the support of environmental protection agencies.

The second part of this work is focused on the evaluation of the

environmental impact due to a general fire accident in Radiopharmacy Laboratories. In a fire scenario, decision-makers need to implement countermeasures to minimise the radiation risks for the population, so they need quick information about the local contamination distribution of the dispersed radioactivity. In this context, the 3D Gaussian plume model provided by HotSpot software offers a good compromise between quality of information and computational effort [29,30]. Different atmospheric stability classes (A-F) have been simulated (see Figs. 6 and 7), even those associated with high stability conditions, which lead to the worst radiological consequences (e.g. D and F) [13]. However, the stability classes that cause less atmospheric dispersion are not typical weather conditions of the Trieste local area.

5. Conclusions

Evaluation of circumstances expected to present the highest level of exposure in terms of internal and external contamination has been carried out: workers involved in management of the radioactive sludge in a sewage treatment system and the ones who deal with contaminated incinerated solid waste in an incinerator plant; a representative person located along the coast, or in an area close to the incinerator and at a certain distance from possible hazardous fire event involving radioactive releases. The resulting total annual effective doses from radionuclides discharged into the environment, due to both NM authorized practice and accidental fire event, are in compliance with safety standards issued by the regulations established by Directives [2,4].

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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