Radiological Hazards at the Chernobyl Shelter Site

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Abstract. The Shelter of unit 4 of the Chernobyl NPP still remains a dangerous nuclear facility. Inside the Shelter remained about 96 % of the irradiated nuclear fuel inventory of the reactor before the accident, i.e. 180 t of Uranium of total radioactivity 7×10^{17} Bq. The radioactive releases to the environment were estimated to amount 4 %. Because of the radiation exposure the spent fuel inside the Shelter and the radioactive soil and groundwater contaminations at the site have an essential impact on all human activities which are presently under progress e.g. in the framework of the Shelter Implementation Plan. The paper presents an overview over the amount, modifications and local distribution of spent nuclear fuel inside the Chernobyl Shelter and at its surrounding site as well as the associated radiological hazards. The fuel may in particular cause radiations fields with high dose rates. The potential criticality of fuel lava will be estimated. Mobile radioactive dust particles may contribute to inhalation doses when resuspended inside the Shelter or released by air ventilation towards the Shelter site. Furthermore, radioactive dust may be released during accidental situations, e.g. after roof collapse of the Shelter or in case of grass and forest fires within the 30 km zone.

1. Introduction

Eighteen years after the accident of unit 4 of the Chernobyl NPP the Sarcophagus still remains one of the most dangerous nuclear facilities in the world. The ruin of the destroyed unit 4 and its surrounding Sarcophagus together are termed object Shelter, which still comprises about 96 % of the spent nuclear fuel. The radioactive releases to the industrial site around the Chernobyl NPP were estimated to amount 0,5 - 1,0 % of the spent fuel inventory.

To investigate the potential radiological hazards associated with the radioactive fuel containing materials inside the Shelter and the radioactive contamination at the site in more detail GRS on behalf of the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety performed a research program in close co-operation with organizations from Ukraine and Russia [1, 2].

2. Spent nuclear fuel inside the Shelter

2.1. Modifications and local distribution of spent fuel

Presently, the spent nuclear fuel exists in four modifications, i.e. radioactive dust in almost all rooms, but predominantly in the central hall, fuel element fragments, mainly in the central hall, molten fuel lava in the lower rooms and Uranium and Plutonium solutes in water contained in the lower levels.

Table 1. Local distribution of remaining fuel inside the object Shelter.

Modification	Location	Estimated Mass
Fuel Dust	Central Hall + Upper Rooms	30 t
Fragments of Reactor Core	Central Hall	> 21 t
Fragments of Reactor Core	Southern Cooling Pool	14,8 t
Fragments + Lava + Dust	Upper Rooms + Room 305/2	85 ± 25 t
Lava	Rooms Level 3 (incl. 304/3)	10,5 ± 4,5 t
Lava	Rooms Level 2	12,4 ± 6,2 t
Lava	Lower Rooms	10,5 ± 6 t
Water Solutes	Lower Rooms	4 kg in Water

The estimated masses of the modifications of spent nuclear fuel are described in Table 1. The local distribution of spent nuclear fuel inside the Shelter is shown in Figure 1.

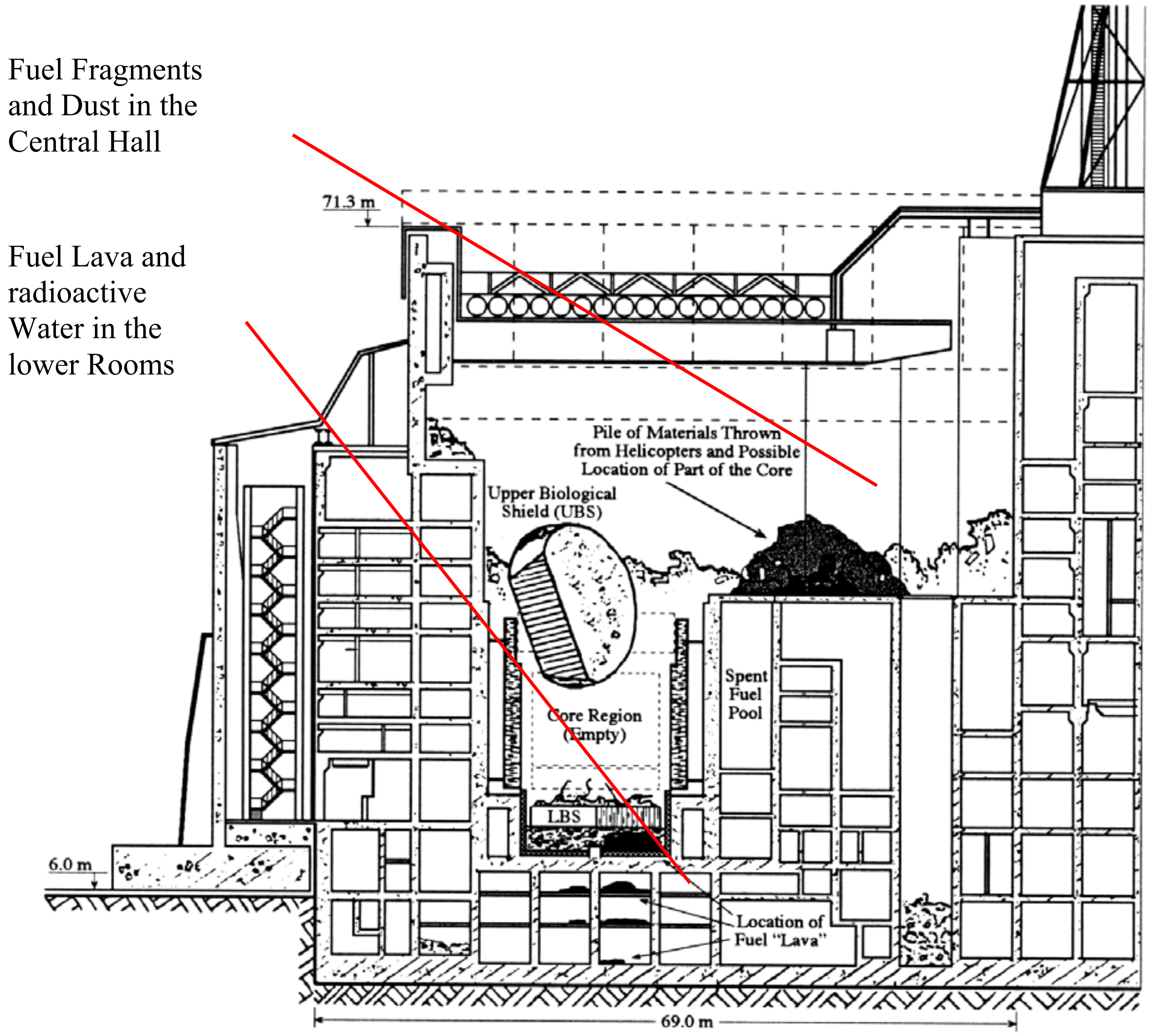

FIG. 1. *Scheme of the cross section West-East of the Chernobyl object Shelter.*

2.2. Criticality of fuel containing materials

To estimate potential hazards related with a criticality event of the fuel lava estimations were made. For the covering case of a material mixture of the black ceramics lava, as e.g. in room 304/3, the infinite neutron multiplication factor k_{inf} was calculated for various water fractions between 0 and 20 wt. % and for fuel contents of 4,5 % and 10 %. The burn up of the fuel and the presence of neutron poison were further input parameters for the calculations [3].

The results are shown in Figure 2, the multiplication factor k_{inf} is clearly below 1,0. The largest values up to 0,72 are reached for the assumed material mixture of black ceramics containing 10 wt. % of fresh fuel and no neutron absorbers as e.g. boron or gadolinium. In summary the calculations showed that the lava with a homogeneously distributed fuel fraction of up to 10 % is not capable of reaching criticality by water moderation.

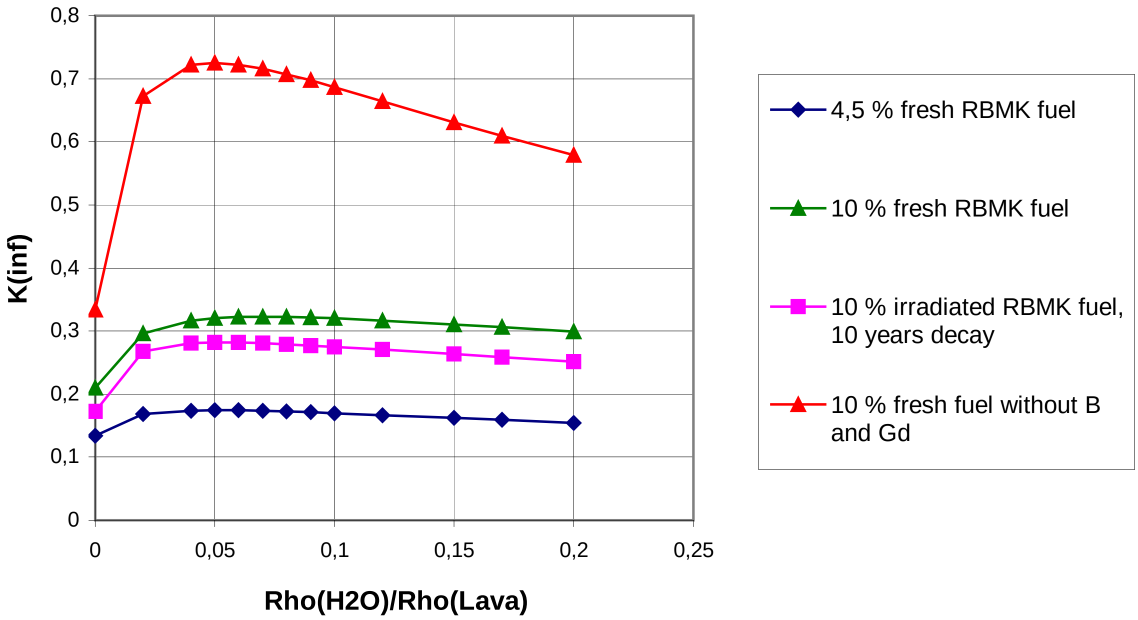

FIG. 2. *Neutron multiplication factor k_{inf} for fuel lava in room 304/3 versus water contents.*

Investigating the potential criticality of fuel assemblies in the lower rooms the probability of a hypothetical self sustaining chain reactions would be rather low [3]. Even supposing most pessimistic assumptions the potential consequences, i.e. limited short term release of volatile nuclides and direct radiation, would be screened by the building walls, so that serious radiation exposures to the workers at the site are not to be expected.

2.3. Fuel dust resuspension

The non-fixed radioactive surface contamination inside the Shelter on average ranges from about 10^5 to 10^7 Bq/m^2, which is approximately 6 % of the total surface activity density, i.e. more than 90 % are closely bound to the surface. The total amount of non-fixed fuel dust is several tons [4].

The present radioactive composition shows a higher content of Cs 137 by 30 % and a lower content of Sr 90 by 40 % compared to that at the moment of the accident accounting for the radioactive decay. The mean resuspension coefficient of 10^{-4} m^{-1} caused by walking of personnel under the roofing is smaller by about one order of magnitude compared to other rooms. This is mainly due to the periodic operation of the dust suppression system.

More than 50 % of the fuel dust particles are in the respirable range with aerodynamic equivalent diameters (AED) less than 10 µm (see Figure 3), i.e. they potentially may contribute to inhalation doses. The dust contamination under the roofing of the Shelter varies very slowly with time due to dust transport from lower rooms caused by natural air ventilation.

2.4. Accidental fuel dust release

The release of radioactive dust in case of a potential roof collapse may cause severe radiation exposures to the workers at the site. The doses due to inhalation and ground shine exceed significantly the annual limits of occupationally exposed persons, i.e. by more than one order of magnitude [5]. However, the exposure drops down with increasing distance, so that at distances of several thousand meters the dose values are very low, e.g. there will be no consequences outside the 30 km zone.

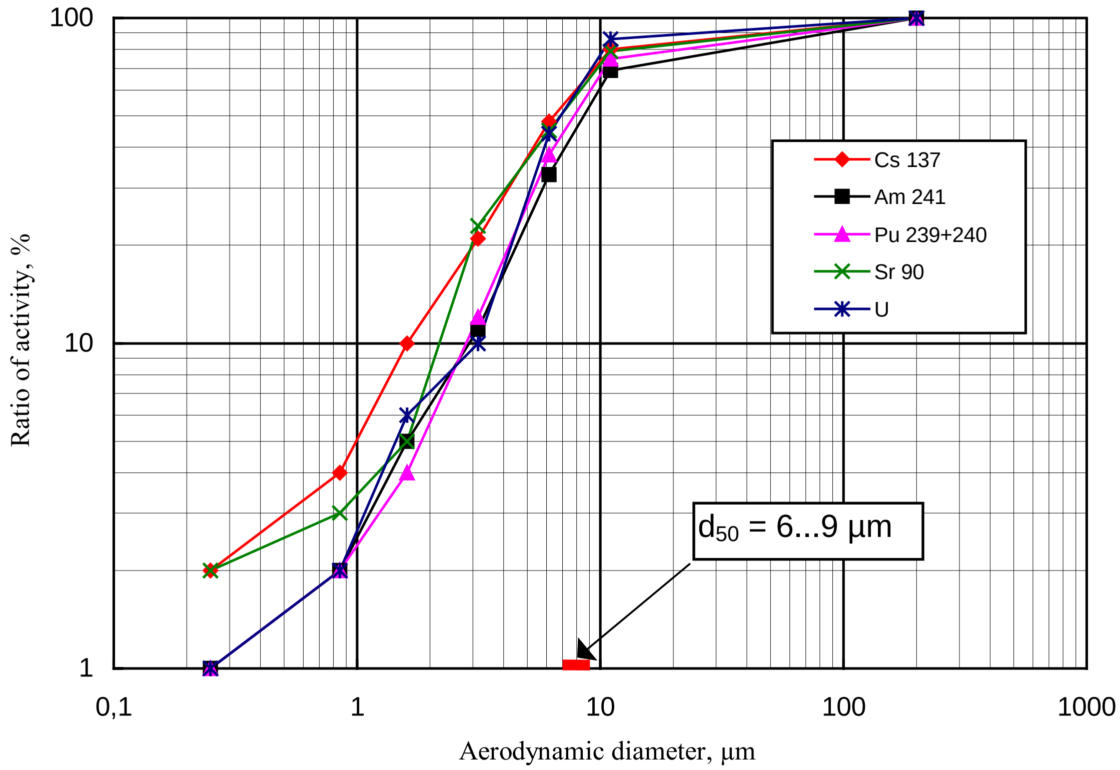

FIG. 3. *Cumulative activity distribution depending on the AED of the fuel dust particles.*

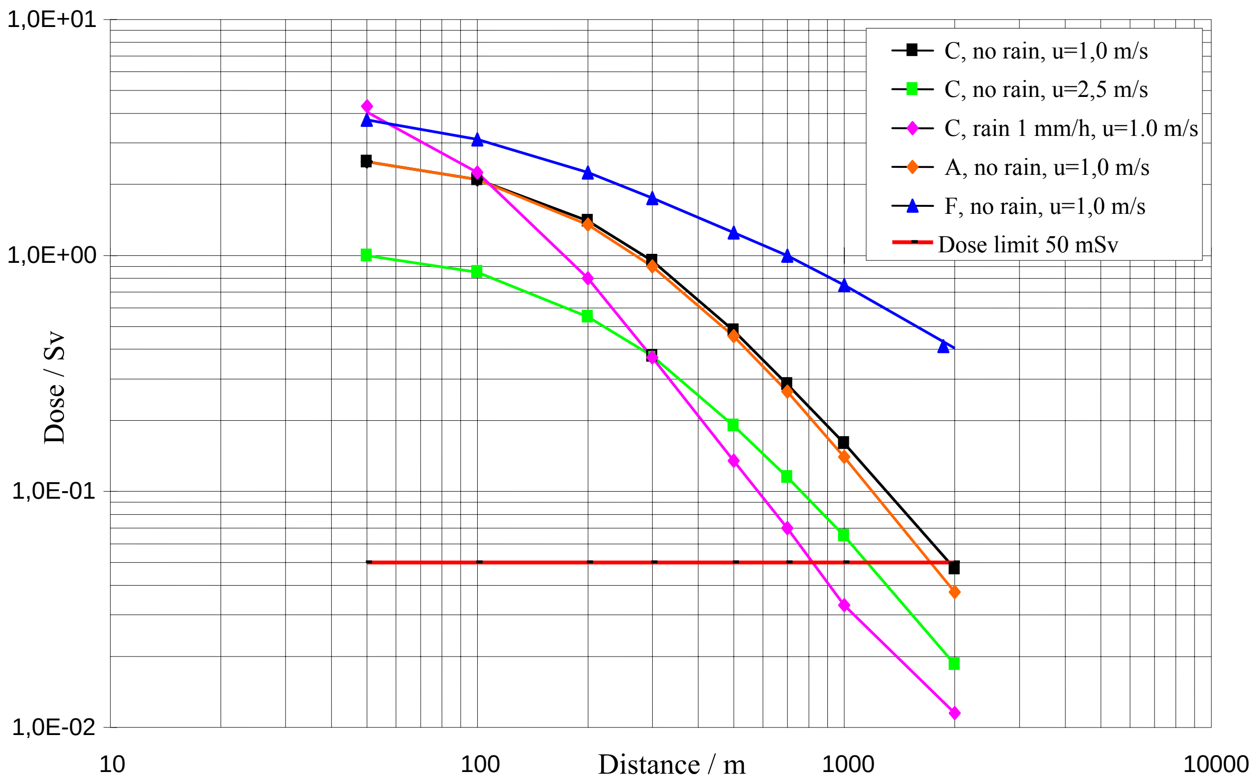

FIG. 4. *Effective dose by inhalation versus distance.*

Figure 4 shows the results for the inhalation doses. The radiation exposure for the most likely diffusion category C decreases only slowly from 50 m to about 200 m. For greater distances a more rapid decrease is obtained. For the wind speed of 2,53 m/s at 10 m height the inhalation doses in the vicinity of 50 m amount to about 1 Sv.

At distances above 1100 m the effective dose decreases below the dose limit of 50 mSv/y for occupationally exposed workers. Assuming a wind speed of 1,0 m/s the doses are increasing by a factor of 2,5 . Hence, the radiological consequences become more severe for lower wind speeds. A comparison of the results for the categories A, C and F is also shown in Figure 4.

In the vicinity up to 100 m the maximum values are obtained for the categories A and F. The most rapid decrease with distance is observed for category A. Rain has no significant influence on the inhalation dose.

3. Radiological situation at the Shelter site

3.1. Soil contamination with spent fuel

The radioactive releases to the industrial site of 500 m radius around the Chernobyl NPP during the first ten days after the accident were estimated to amount 0,5 - 1,0 % of the fuel inventory. After the accident the site was cleaned and decontaminated. Afterwards the ground surface was covered with layers of concrete, sand and gravel. The remaining spent fuel at the Chernobyl Shelter site was estimated on the basis of manual dose rate measurements at ground level and helicopter gamma scanning. Figure 5 shows the assessed distribution of remaining spent fuel [6]. A total amount of about 600 kg with an accuracy of 30 - 50 % resulted.

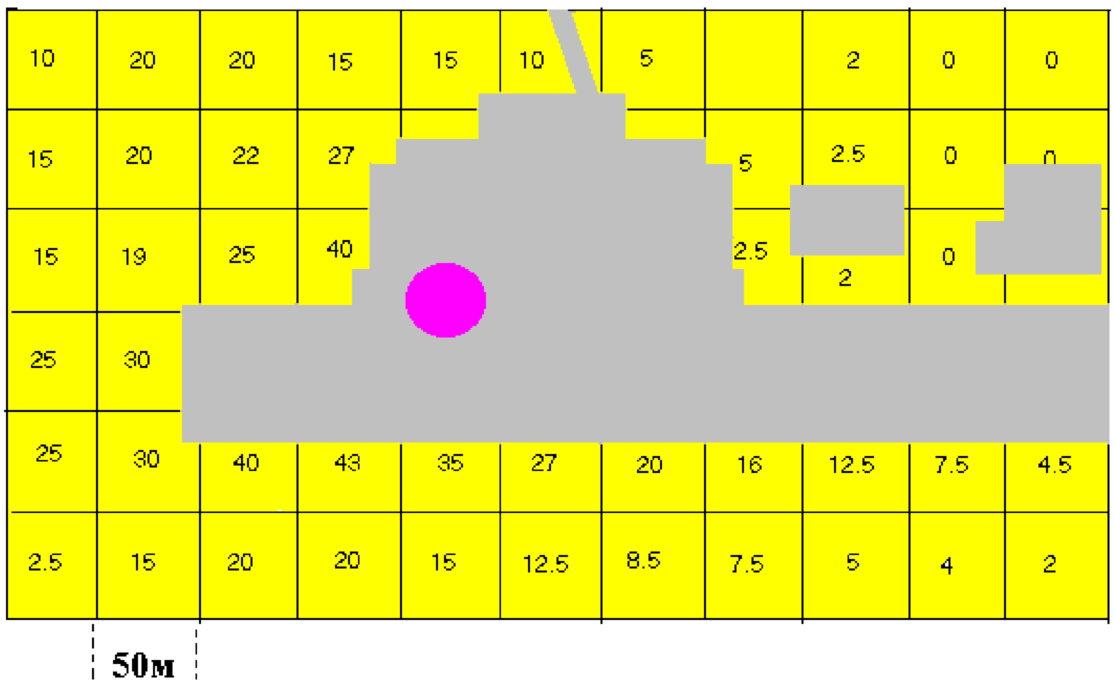

FIG. 5. *Distribution of spent fuel fallout at the Shelter site (in kg per 50 x 50 m^2).*

3.2. Radiation exposure at the Shelter site

In Figure 6 a view from top to the Shelter site is plotted. Along with the reactor building the deaerator and the machinery hall are shown. At the site the radiation exposure rate in 1 m height is drawn using a color spectrum. Far from the Shelter the exposure is below 10 mR/h. Also indicated are aspiration units to collect airborne radioactive aerosols as well as bore holes to investigate the ground water.

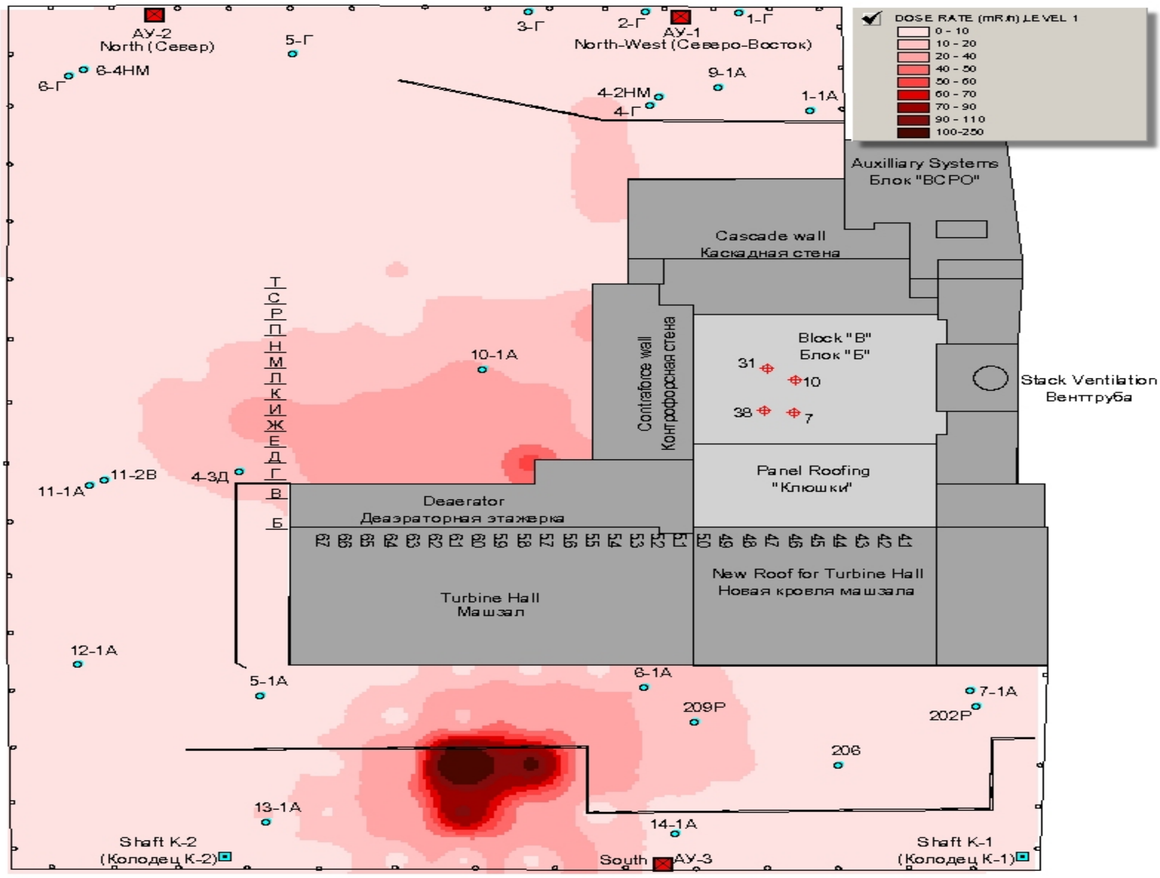

FIG. 6. *Dose rate 1 m above ground at the Chernobyl object Shelter site in 2002, aspiration units AU-1 to AU-3 for aerosol sampling (red), bore holes for ground water inspection (blue).*

3.3. Radioactivity concentration in air

Monitoring of surface air layer contamination on the Shelter site is performed by three aspiration units located at distances of 60…100 m away from Shelter to North, North-West, South directions (see Figure 6). Air is drawn through the textile filters with dimensions about 90 x 140 cm^2, exposure time being of 15 days. The radio nuclides content deposited at the filters is measured in the laboratory.

Radiochemical analysis proved that for radiation protection purposes contents of Pu and Sr 90 may be recalculated from activities of Am 241 and Cs 137assuming fuel nuclides composition in the aerosols.

Averaged over exposure time air contamination at the site is defined as the ratio of nuclide activity at the filter and air volume drawn through it. The averaged radionuclide content in the air on Shelter site is presented in Table 2. Results obtained from end of 1998 to spring 2000 have been used. The reference levels 11,1 Bq/m^3 for beta emitters and 0,02 Bq/m^3 for alpha emitters are allowed for air contamination at the site by the Chernobyl NPP (excluding radon and its progeny).

Table 2. Average radionuclide content in the air of Shelter site for end of 1998 to spring 2000, Bq/m^3.

Aspiration unit	Cs 137	Sr 90	Am 241	Pu 238+239+240
AU-1	$1{,}8 \cdot 10^{-3}$	$6{,}9 \cdot 10^{-4}$	$2{,}6 \cdot 10^{-5}$	$3{,}3 \cdot 10^{-5}$
AU-2	$2{,}7 \cdot 10^{-3}$	$1{,}0 \cdot 10^{-3}$	$3{,}8 \cdot 10^{-5}$	$4{,}8 \cdot 10^{-5}$
AU-3	$9{,}5 \cdot 10^{-3}$	$3{,}6 \cdot 10^{-3}$	$1{,}6 \cdot 10^{-4}$	$2{,}1 \cdot 10^{-4}$

Statistical uncertainty of the results presented is characterized by factor 2. Increased values of air contamination to the south of the site (AU-3) are caused by predominant wind direction (north-west).

The main contribution to the air contamination is due to Shelter aerosol release, dust resuspention from the ground surface gives about 30 % of contribution to total air contamination. Their was no significant variation over the last years.

3.4. Groundwater contamination

The groundwater contamination was determined in special observation well located north, west and south around the Shelter (see Figure 6). The measurements were focused on the radiological relevant nuclides Sr 90 and Cs 137 [7]. The results are depicted in Figure 7.

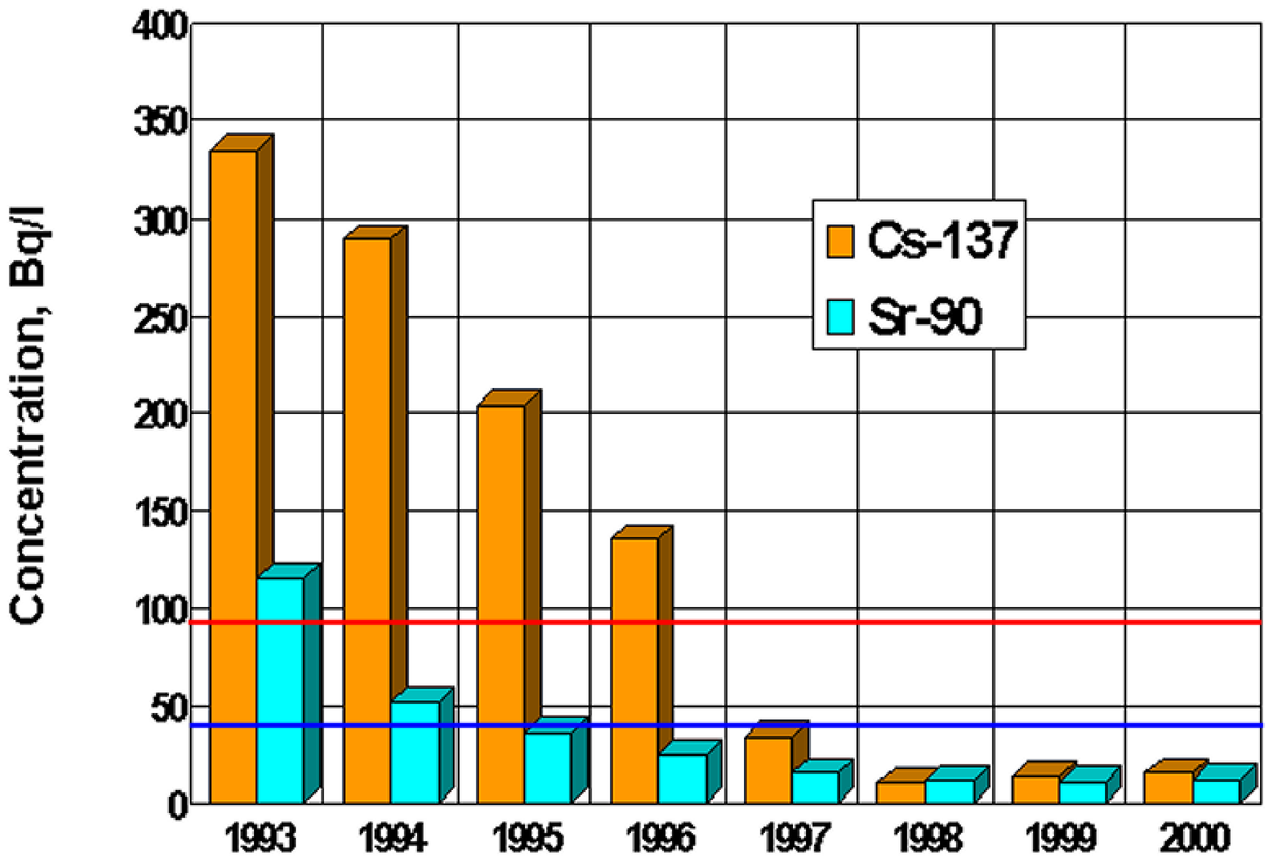

FIG. 7. *Annual groundwater concentrations of Sr 90 and Cs 137, averaged values for wells G1 to G6 at the flow exit of the Shelter site (red line indicates the permissible level of 96 Bq/l for Cs 137, blue line indicates the permissible level of 45 Bq/l for Sr 90).*

The groundwater concentrations values of Sr 90 and Cs 137 show a significant decrease since 1993. Presently, mean values, e. g. for the wells at the northern cascade wall of the Shelter at the flow exit towards the Pripyat river of 12 Bq/l for Sr 90 and of 15 Bq/l for Cs 137, are observed. These averaged values are below the concentration limits for drinking water of Ukraine. However, significant seasonal and local variations as well as different behavior of both nuclides were found.

Obviously, the groundwater contamination is mainly caused by the original contamination layer, which is now covered by new layers of different materials up to several meters height. Up to now there is no distinct evidence of pathways and hence of radioactivity releases from inside of the destroyed reactor building of unit 4 of contributing to the groundwater contamination at the site.

3. Dust resuspension due to grass and forest fires

In the 30 km zone surrounding the Shelter any use of land by agriculture is prohibited. Thus, dry grass and wood leads e.g. in spring and autumn periodically to grass and forest fires. Therefore, investigations were carried out to estimate potential contributions to the radiation exposure as a consequence of grass and forest fires far from the fire front. Figure 8 shows calculated results for inhalation and ground shine doses of different exposure time up to one year, presuming average usual weather conditions at the Chernobyl site as well as a resuspension of 5 % of the ground contamination. The fire front of 1000 m length was assumed to move with a cross velocity of 1 m/s over a time of 10 hours and with a thermal release of 400 kW/m^2.

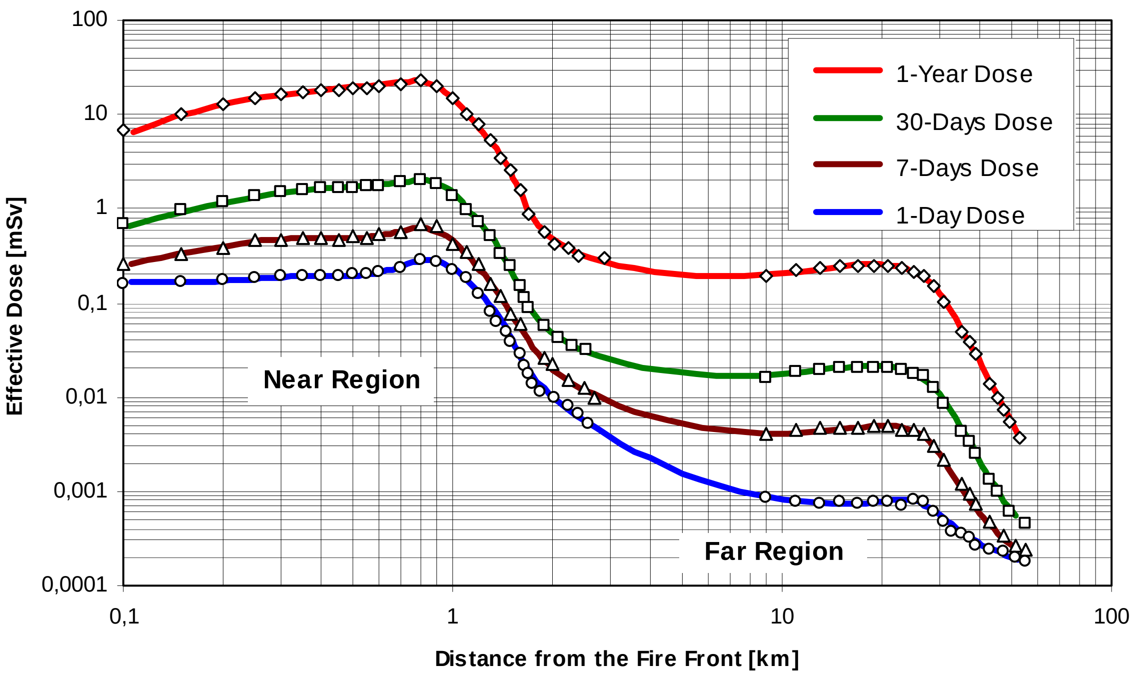

FIG. 8. *Effective dose adult inhalation + ground shine versus distance.*

Due to the air heat up smaller particles are transported higher and into farer regions whereas bigger settle down more quickly. That is why in the near region the values of radiation exposure reach their maximum. After most of the bigger particles in the near region have been settling down at e. g. 2 km, the decrease of the curves in the area between the near and the far regions is smaller due to the relatively long airborne phase of smaller particles up to about 20 km. After that distance the bigger particles have completely been settling and also the smaller particles begin to settle down and hence the exposure drops quickly.

The curves show that periodic fires can contribute even at far regions up to 20 km to the radiation exposure in the order of some mSv when the exposure lasts for a long time.

4. Summary and conclusions

The spent nuclear fuel of the destroyed reactor of unit 4 of the Chernobyl NPP exists now in four modifications, i.e. radioactive dust, fuel element fragments, molten fuel containing lava and Uranium and Plutonium solutes in water. Once no population is living in the 30 km zone the radiological hazards to the population outside are rather low even under accidental conditions, e.g. in case of dust release after roof collapse or dust resuspension after grass and forest fires.

For the workers at the NPP site accidental fuel dust release represents the biggest potential hazard whereas the radiation exposure at the site due to ground and air contamination in most places is low. A criticality event of fuel lava inside the Shelter is very unlikely and the potential radiological consequences would be limited to the inside. Soil and groundwater contaminations however have to be considered when digging new basements for the new Shelter 2 presently under construction in the frame of the Shelter Implementation Plan.

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