REVIEW ARTICLE

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The consequences of Chernobyl accident

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Abstract: *These days marks 30 years since the Chernobyl nuclear accident, followed by massive radioactive contamination of the environment and human in Belarus, Ukraine and Russia, and resulted in many deaths among people who intervened to decrease the effects of the nuclear disaster. The 26 April 1986 nuclear accident contaminated all European countries, but at a much lower level, without highlighted consequences on human health. In special laboratories, the main radionuclides (I-131, Cs-137, Cs-134 and Sr-90) were also analyzed in Romania from environmental samples, food, even human subjects. These radionuclides caused the population to receive a low dose of about 1 mSv in 1986 that is half of the dose of the natural background radiation (2.4 mSv per year). As in all European countries (excluding Ukraine, Belarus and Russia) this dose of about 1 mSv fell rapidly by 1990, reaching levels close to ones before the accident at the nuclear tests.*

Keywords: *nuclear accident, Chernobyl disaster, radionuclide, radioactive contamination, effective dose*

INTRODUCTION

2016 marks 30 years since the major accident in the history of nuclear power plants (active zone melting and thermal explosion) that took place on 26th April 1986 at 4th reactor of Chernobyl Nuclear Power Plant (Ukraine). Emissions of radio nuclides were particularly high and affected many countries in Europe, including our country. The 4 reactors in operation at the time run on natural uranium (U-238) with low-enriched U-235, a high producer of Pu-239 (strategic material for nuclear weapons).

Although this type of reactor was well known by the operating personnel, they conducted an experiment with the turbine running in the inertial mode and lowering reactor's power at 10%, but the return to full power (thousand MW) took only 2 seconds which led to a loss of control and the impossibility of an emergency shutdown of reactor no. 4. The rapid and uncontrolled increase in temperature of the reactor core produced two successive explosions seconds after each other that threw the 1000 tons concrete for protection, as well as large amounts of nuclear fuel with fission products and activation products, along with the burning graphite moderator [1].

Definitions of specific terms

1. Activity (radioactivity) of a radionuclide: the unit of work in the International System (S.I.), is one disintegration per second, or s-1, with the name Becquerel and symbol Bq. Curie - special name for the tolerated unit of the activity of a radionuclide, with the symbol Ci; is 3.7 x 1010 disintegrations per second

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(approximate activity of radon – 222 in equilibrium with one gram of radium – 226) and respectively 3.7 x 1010 Bq.

2. Half-life – the time after which the number of nuclei of a radionuclide is reduced to half by radioactive decay with symbol T1/2, or Tf is used.

The biological half-life – the time required for a biological system to remove half of the nuclei (stable or radioactive) by metabolic processes with symbol Tb. The effective half-life – the time needed to halve the number of radioactive nuclei (activity) by decay and metabolic processes with Tef symbol.

3. Effective dose – weighted sum of equivalent doses from external and internal exposure, performed on all organs (tissues) of the body (the absorbed dose multiplied by the weighting factor of radiation and weighting factor of tissue or organ). In the S.I. unit is J/kg with the name Sievert and symbol Sv.

The effective dose limit for occupationally exposed workers – effective dose limit for people working in environmental radiation is 20 mSv per year. The effective dose limit for the population – effective dose limit for an individual in the population is 1 mSv per year.

CONTAMINATION OF THE ENVIRONMENT

Fission products (Cs-137, Sr-90, Sr-89, I-131, etc.) and activation products (Cs-134, Co-60, Fe-55, Fe-59, etc.) were released in atmosphere and transported by air currents throughout the northern hemisphere. The most affected (radioactive contamination) were Belarus, Ukraine and European Russia; less contaminated air currents reached many other countries in NW Europe (mainly Norway, Sweden, Finland), and to S and S-V Europe, inclusively to Romania.

Rainfall and dry deposition made possible contamination of the environment (soil, surface and biosphere).

Cs-137 was the easiest to detect (beta-emitting and gamma-emitting radiation) and has a great half-life period (Tf or 1/2) of approximately 30 years, for which most of the estimations of environmental and human contamination reported to this radionuclide.

Table 1: Surfaces contaminated with Cs-137 in some countries affected by the Chernobyl nuclear accident [2]

Country*)	37-185 (kBq/m²)	185-1480 (kBq/m²)	over 1480 (kBq/m²)
Russia	49800	7800	300
Belarus	29900	14400	2200
Ukraine	37200	4100	600
Sweden	12000	-	-
Finland	11500	-	-
Norway	5200	-	-
Austria	8600	-	-
Bulgaria	4800	-	-
Switzerland	1300	-	-
Greece	1200	-	-
Slovenia	300	-	-
Moldavia	60	-	-

*) In Romania, most of the surface was contaminated with Cs-137 with values below 2 kBq/m². There were large areas contaminated 2-10 kBq/ m² in Oltenia, Banat, N-E Moldova, central and northern Muntenia; here they were found locations with contamination exceeding 10 kBq/ m².

ASPECTS OF RADIATION PROTECTION IN ROMANIA

Monitoring environmental radioactivity and food radioactivity in Romania [1,3] was carried out by:

- 47 Environmental Radioactivity Monitoring Stations (belonging to the former National Council for Water, today 37 stations form the National Network of Environmental Radioactivity Monitoring and belongs to the Ministry of Environment)
- 22 Ionizing Radiation Hygiene Laboratories, of which 4 were from the Institute of Hygiene and Public Health in Bucharest, Iasi, Cluj and Timişoara (Ministry of Health)
- departamental laboratories (Institute of Atomic Physics – IFA Măgurele – Bucharest, Institute of Nuclear Energy Reactors – IRNE Pitești, Ministry of National Defense – MND, etc) (The Laboratory for radiochemistry of the Military Center for Medical Research also had tasks of human and environmental radioactivity monitoring in addition to the experimental research. There was also a laboratory to

measure the radioactive contamination of man (with whole body counter).

In the period immediately after the accident (the night of April 30, 1986 when contaminated air masses came first in the N-E) and in the years after the accident the following analyzes were performed:

- global beta measuring and gamma spectrometry of aerosol filters, total atmospheric deposition, surface and drinking water analysis, soil, wild vegetation and crops analysis, animal products and food menus from various canteens in Bucharest and in the country analysis

- direct measurement of radionuclides incorporated into man (I-131, Cs-137 and Cs-134) with MND and IFA whole body counter

- radiation dose exposure estimation for humans.

Among the measures taken for radiation protection of population in Romania, it is worth mentioning:
- consumer restrictions on certain foods (dairy products contaminated with I-131, Cs-137 and Cs-134) based on the values determined by measuring the radioactivity of food in the most contaminated counties
- forbidding sport events scheduled to take place outdoors on May 2
- administration of stable iodine for children, beginning with 3th May

Recommendations:
- extensive washing of vegetables before consumption
- reduced time spent in the open in the first week after the accident.

Negative aspects concerning the application of radiation protection measures:

- insufficient public information on the accident,
- KI administration started with a two days delay leading to reduced performance at about 50% and the administration was not performed at all children in areas contaminated with I-131.

ENVIRONMENTAL, FOOD AND HUMAN CONTAMINATION IN ROMANIA

After corroborating the results of radioactivity monitoring of the environmental factors, water and food, it was possible to create a map of radioactive fallout in our country in three stages: 1st to 2nd of May, 3rd - 4th of May and 5th to 6th of May respectively. So, the greatest contamination occurred due to the fallout of 3rd to 4th of May, which came from N-E and followed the Eastern and Southern Carpathians, with the southern area being the most contaminated (Figure 1) [4].

In atmospheric aerosols there were readings of a maximum of 103 Bq/m^3 for I-131, respectively 63 Bq/m^3 for Cs-137 at Toaca station in Ceahlău on 1st of May 1986; also readings of 17 Bq/m^3 I-131 and 14 Bq/m^3 for Cs-137 at Fundata station (Braşov county). These peaks declined rapidly in the second half of May and early June 1986, going as low as a 1000 times lower. Regarding the average concentration of Cs-137 in the aerosols, from about 106 Bq.s/m^3 in 1986 fell below 105 in 1987 and in 1991 it went back to the value from before the accident (about 200 Bq.s/m^3) [4,5].

Atmospheric radioactive depositions values were in 1986 over 3 orders of magnitude higher compared to before Chernobyl accident. As late as 1993 the average values of Cs-137 deposition reach 1 order of magnitude over that of 1985 because of wind carrying out the contaminated dust and returning in the form of radioactive fallout.

Average concentrations of Cs-137 in untilled soil samples were of 350 Bq/kg, with peaks in excess of 1000 Bq/kg in the northern county of Gorj. High levels of Cs-137 in untilled soil were recorded at Toaca-Ceahlău, Targu Mures, Gheorghieni and Parâng, with maximum levels of 2050 Bq/kg of dry soil.

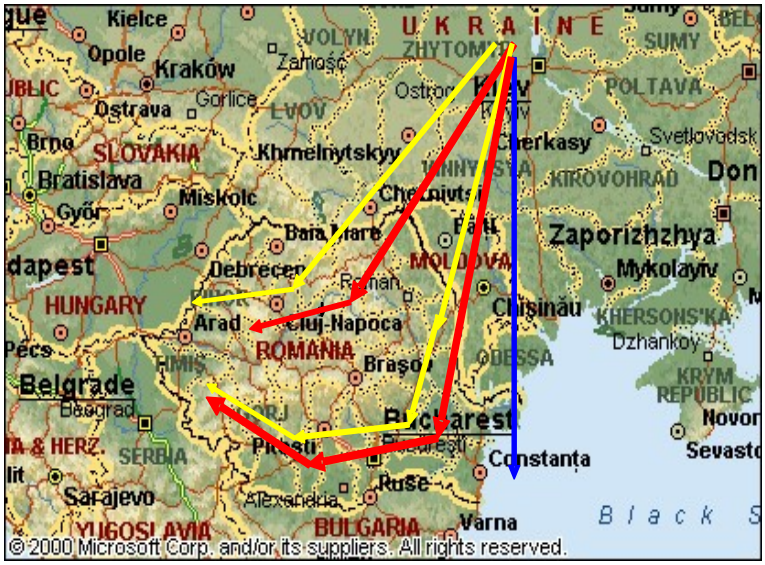
In surface water, high values of Cs-137 were determined 2 or 3 days later than the atmospheric reading, measuring 50 Bq/m^3, with rapid drop below 10 Bq/m^3 in 1987 and 1988, returning to the values from 1985 as late as 1993.

The contamination of wild vegetation was carried out by fine radioactive particle deposition and measuring

average values of Cs-137 as high as 1000 Bq/kg of dry vegetation, with values declining to before the accident in 1990. Contamination of crops by absorbing radionuclides in the soil was quite low, so radionuclide values decreased rapidly in the coming years [3].

The highest level of contamination with I-131 in food was found in ewe`s milk, with values of about 1300 Bq/L or higher, which led to temporary restriction in consumption imposed by the Ministry of Health, for dairy products. Cs-137 values in milk and dairy products were about 500 Bq/kg (Table 2). This radionuclide content in food has decreased since 1990, and since 2000 has reached the 1985 values.

Figure 1: Contamination Romanian territory since May 1, 1986 [4]



Three stages of contamination in Romania: 1 – 2 3 – 4 5 – 6

Table 2: Content of Cs-137 (Bq/L or kg) in drinking water and foods [5, 6]

Food	1986	1987	1988 - 1991	2003
Water	-	0.05	0.002 – 0.009	0.002 – 0.009
Milk	10 - 200	27.92	1.02 – 5.13	0.01 – 0.137
Dairy products	10 - 500	61.98	5.07 – 16.61	-
Meet	50 - 300	47.50	1.31 – 39.25	0.014 – 10.28
Meet products	10 - 727	23.19	1.50 – 19.15	-
Grain products	50 - 100	42.16	1.01 – 12.15	0,251
Fruits and vegetables	7 - 411	46.43	1.89 – 23.39	0.037 – 0.265
Food menu/24 hours	-	23.69	1.50 – 4.49	-

If immediately after accident experts paid particular attention to radionuclides I-131 and Cs-137, easily determined by gamma spectrometry directly from samples, by the end of the year and in following years measurements were performed to determine the content of Sr-90 in water and food. Aerosols contamination levels with Sr-90 were less than 1/10 the levels of Cs-137 so the food contamination with Sr-90 was much lower, generally below 10 Bq/kg or L of product (Table 3).

Radionuclides Cs-137, Cs-134 and Sr-90, a little transferable from soil to plant, however they were detected many years after the accident; radioactive

contents fell sharply in 1987 and then steadily, currently reaching in most foods well below 1 Bq/kg, hard to detect even with radiochemical analysis. There still are very low values for Cs-137 (units Bq/kg) in berries, mushrooms and wild venison.

Table 3: Content of Sr-90 (Bq/L or kg) in drinking water and foods [5, 6]

Food	1987	1988 - 1991	2003
Water	0.04	0.003 – 0.010	0.001 – 0.066
Milk	0.43	0.14 – 0.33	0.068 – 0.930
Dairy products	0.75	0.19 – 0.76	-
Meet	0.46	0.10 – 0.24	0.087 – 0.690
Meet products	0,62	0.09 – 0.20	-
Grain products	0.70	0.25 – 0.76	0.135 – 0.730
Fruits and vegetables	0.97	0.10 – 0.98	0.047 – 1.060
Food menu/24 hours	2.30	0.19 – 0.23	-

Assessment of human internal contamination with radionuclides I-131, Cs-137, Cs-134 and Sr-90 (Table 4) was performed both directly for the first three radionuclides (measuring radionuclides from humans) and by estimating the contamination based on the values of radioactive content determined in drinking water, food, and in real or hypothetical food menu (Table 2).

Table 4: Content of Cs-137, Cs-134 and Sr-90 in the human body (direct measurement/ estimation from ingestion of food) in Romania [6]

Radionuclide		1986	1987	1988	1989	1990	1991	1992	1993
Cs-137	measurement	1000 - 2000	2000 - 2500	800 - 1700	500 - 1100	300 - 500	< 300	< 300	< 300
	estimation	1538 - 20383	2335 - 12774	415 - 673	106 - 198	82 - 150	80 - 140	60 - 119	19 - 38
Cs-134	estimation	686 - 8703	729 - 4894	94 - 153	18 - 33	10 - 18	5 - 10	1 - 3	-
Sr-90	estimation	30 - 100	18 - 57	12 - 38	12 - 34	11 - 32	10 - 30	9 - 28	8 - 25

After about 80 days I-131 disappeared from humans and food through physical decay (if 10 Tf pass, it is considered that radionuclide decreases in values too difficult to determine; Tf for I-131 is 8.1 days). In terms of I-131 content found in thyroid, it presents very different values to a few thousand Bq only in May and June, depending on the level of contamination of the studied area and the food consumed. These rates were still much lower compared to human radioactivity/radiation dose received in the case of thyroid scintigraphy (tens - hundreds of kBq) [1,6].

For humans, Cs-137 + Cs-134, from about 2500 Bq in 1986 the values have gradually decreased to a point where after four years they went below 300 Bq. The loss of activity of the two radionuclides in humans was attributed to their reduction in food and to metabolic processes in the human body (Tb for the two radionuclides is 100-150 days) or by disintegration for Cs-134 (Tf = 2.05 years); so that after 1990 the Cs-137 values fell below the detection limit of the equipment used for the direct measurement. Sr-90 contamination for humans was much lower, estimated values below 100 Bq (radionuclide emits only beta radiation that can only be detected in small biological samples and the low contamination of foods did not allowed measuring this radionuclide in humans) [1,6].

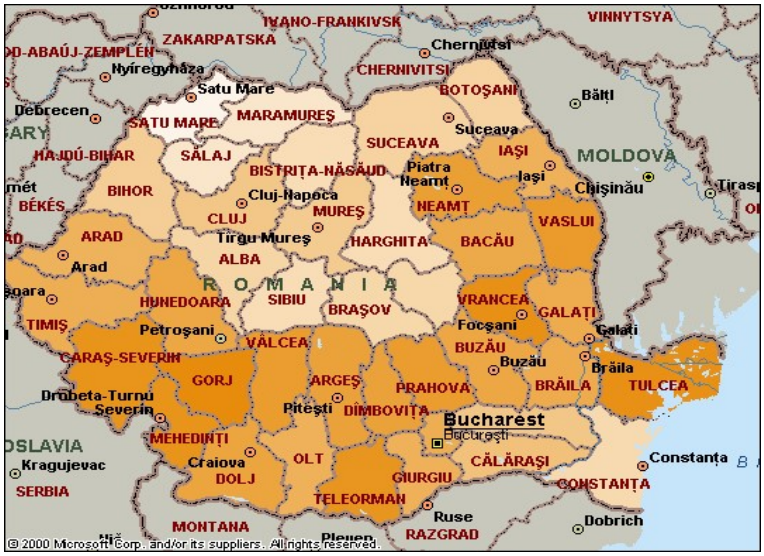
ESTIMATION OF THE EXPOSURE DOSE FOR THE POPULATION OF ROMANIA

Immediately after the accident, Oncescu and Galeriu (IFA Bucharest – Măgurele) have calculated the exposure dose due to radioactive contamination of the

population in our country which calculated to be about 1 mSv for the first year after the accident. Values are similar to those published by WHO (World's Health Organization) and IAEA (International Atomic Energy Agency) for other European countries (Finland: 0.44 mSv, Germany: 0.5 to 1.1 mSv, Italy: 0.61 mSv, Poland: 0.95 mSv, Switzerland: 1 3 mSv etc.) [1].

The subsequent calculation of the effective dose received by man from radionuclides determined in air, water and food for the most contaminated areas in Romania, except the contribution of I-131, resulted in average values close to 1 mSv in the first year after the accident, with a greater fall in 1988 (the greatest contribution to contamination was from Cs-137 and Cs-134 in food). Between 1990 and 2000 and now, the annual effective dose for humans fell below 50 µSv, values over 40 times lower than the dose received by humans from background radiation [4].

Figure 2: Exposure assessment of Romania's population – dose reconstruction by food based on Cs-137 concentration in atmospheric deposition [4, 5]. Minimum exposure dose of 0.2 mSv in Satu Mare County, maximum exposure dose of 2.1 mSv in Gorj County.



Doses of radiation exposure of the population in Romania after the nuclear accident vary by an order of magnitude between 0.2 and 2.1 mSv in the first year (Figure 2), based on contaminated air masses movement (Figure 1) as well as wet and dry deposition in our country. Thus, there were areas (counties) with quite small exposure doses, less than 0.5 mSv such as Satu Mare, Salaj, Maramures, Sibiu, Brasov, Harghita, while in other counties exposure doses were even over 1 mSv such as: Caras-Severin, Gorj, Mehedinți, Tulcea, Neamt, Vrancea, Teleorman.

The average dose received by most of the European countries of about 1 mSv is incomparably lower than that of more than 10 mSv received by population in heavily radioactive contaminated areas of Belarus, Ukraine and Russia. This dose of about 1 mSv in the first year after the accident is below the natural background exposure (irradiation) had a low radiological significance on health.

Natural background radiation exposure (cosmic radiation, earth radiation given by natural radionuclides present in the environment, food and humans) is about 2.4 mSv per year for the entire planet, with the exception of areas with high natural background radiation (even more than 20 mSv per year in some areas of India, Brazil, Congo, Sweden) due to the massive presence of natural radionuclides [1].

Thus, the additional exposure dose received by most of the population of Europe in 1986 was about half of the natural background exposure, which is a quite low dose, closely to effective dose limit (of 1 mSv per year) supported by legislation for an individual of the population. To be mentioned that the effective dose limit allowed for workers exposed for professional

reasons (who work with ionizing radiation in the environment) is 20 mSv per year.

Given the levels of radioactive contamination of the environment in Romania, much lower in comparison with Ukraine, Belarus and Russia, the exposure doses received by our population were relatively low (0.2 to 2.1 mSv in 1986) well below those that could produce significant biological effects on human health. Moreover, studies carried out by the hygiene institutes of Romania did not reveal an increased incidence of congenital malformations in children born between 01.10.1986 and 31.12.1987 compared with the reference group (those born before 1986) [3].

Exposure doses and biological effects post-Chernobyl [2]

Average exposure doses received by the affected people in Ukraine following the nuclear accident were distributed as follows:

- 100 mSv, about 240 000 people participating in decommissioning the damaged reactor
- 30 mSv, about 116 000 people evacuated,
- 10 mSv, tens of thousands of people that continued living in contaminated areas, in the first years after the accident.

It is estimated that the maximum exposure dose can be even with an order of magnitude higher in some areas with massive radioactive contamination from the three countries Belarus, Russia and Ukraine.

In other European countries, the maximum dose was about 1 mSv in the first year after the accident, with a progressive decrease in the coming years. The dose is well below the natural background exposure (irradiation) has a low radiological significance.

Another 200,000 workers who received doses of 0.01 to 0.5 Sv were at increased risk of developing late effects, including cancer that could put their lives in danger.

Of the 600 workers that participated directly in the decommissioning, 134 received doses of 0.7 and 13.4 Sv and develop radiation sickness (ARS – Acute radiation syndrome). Of these, 30 died shortly after the accident [2].

In areas heavily contaminated in the three countries, measures taken to limit radiation exposure have changed the lives of millions of people (returning to homeland, modification of eating habits, restrictions and job changing) to damage health conditions including psychiatric problems.

Thyroid cancer was given particular attention, about 1800 cases for exposed children, which greatly exceeds estimates in the 1986. The cases of leukemia (latency 2-10 years) weren't significantly higher in staff directly involved in decommissioning. The greatest increase in cases of thyroid cancer for children has been reported in the Gomel region of Belarus (near Chernobyl) [7].

In the most contaminated areas of Russia, Belarus and Ukraine there are still values of Cs-137 and Sr-90 easily detectable in water and food; thus, in the Bryansk region (Russia), Cs-137 had values of 90 kBq/kg in predatory fish meat, high value for humans too, up to 50 kBq, which led to estimation of doses ranging up to 1.8 mSv in 1996. These values are well above those detected in Romania immediately after the accident [2].

Ever since 1987, a special monitoring program of about 7 million people affected by the accident has begun: liquidators of consequences of the accident (1986 - 1987), evacuated population in 1986 and established in other areas of the former USSR, residents of areas heavily contaminated with Cs -137, Sr-90 and Pu-239, descendants of the irradiated persons (liquidators, people evacuated), people contaminated with I-131, aged 0 to 18 years during the accident [7].

Epidemiological studies have revealed: an increase in the number of people with psychological problems, number of suicides and overall violent deaths among liquidators and evacuated population due to insufficient information on the effects of ionizing radiation, social dislocation and diminishing quality of life. Only complete epidemiological studies will halt the trend of attribution of increasing incidence of all cancers exclusively to the effects of the nuclear disaster, especially in areas heavily radioactive contaminated [8].

CONCLUSIONS FOR CONSEQUENCES OF THE CHERNOBYL ACCIDENT IN ROMANIA

1. The level of radioactive contamination of the environment in Romania after the nuclear accident in 1986 was relatively similar to that of other central and eastern European states; 10 kBq/m^2 at ground level, with few areas over this value.

2. The main radionuclide contaminants, I-131, Cs-137, Cs-134, even Sr-90 from deposition and aerosols immediately after the accident passed quickly in plants and animals. I-131 showed values close to 1 kBq/kg, Cs-137 and Cs-134 values of several hundred Bq/kg, whereas the Sr-90 was below 10 Bq/kg.

3. Radionuclides Cs-137, Cs-134 and Sr-90 transfer difficult from soil to plants trough absorption, were still detectable in food many years after the accident; radioactive contents fell sharply in 1987 and then steadily, reaching below 1 Bq/kg between 1990 and 2003 in most foods. At the same time, there were somewhat higher values detected in berries, mushrooms and venison.

4. In humans, Cs-137 from 1000 to 2000 Bq gradually decreased, so in 1990 reached about 300 Bq. The annual effective dose decreased from about 1 mSv in the first year after the accident, to below 50 µSv between 1990 and 2000, respectively below 10 µSv between 2000 and 2010.

5. Besides the three heavily radioactive contaminated states (Belarus, Ukraine and eastern Russia), other contaminated European countries reported no biological effects on the population after the accident.

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