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The causes and consequences of the nuclear disaster at the Mayak Production Association facility in 1957

A Majak Termelési Egyesülés létesítményében 1957-ben történt nukleáris katasztrófa okai és következményei

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Introduction

From the onset of the post-WWII nuclear arms race until 1989, the strict secrecy surrounding the Soviet military-industrial complex prevented credible information from emerging regarding any serious radiological accidents that may have occurred within the Soviet Union.

In this information vacuum, Zhores Medvedev, an exiled Soviet biologist, was the sole individual who, in the 1970s, drew attention to the possibility of a 1957 nuclear disaster in the Urals through scientific inference; according to his hypothesis, an explosion in an underground radioactive waste storage facility had contaminated a vast area.

Although the international community had already become aware of the 1986 Chernobyl events, the details of the 'Kyshtym disaster' remained hidden until the era of Glasnost, when Soviet authorities finally decided to release the relevant data.

In 1989, during an event organized by the IAEA, it became clear to the world that Medvedev was right. There really was a separate and secret nuclear facility in the southern Urals where serial human omissions led to an INES 6 event on 29 September 1957 at Mayak Production Association (PA) near the town of Kyshtym in the Chelyabinsk oblast.

Bevezetés

A második világháborút követő nukleáris fegyverkezési verseny kezdetétől egészen 1989-ig a szovjet katonai-ipari komplexumot övező szigorú titoktartás megakadályozta, hogy hiteles információk kerüljenek napvilágra a Szovjetunióban esetlegesen bekövetkezett (súlyos) radiológiai balesetekről.

Ebben az információs vákuumban egy száműzetésben élő szovjet biológus, Zsoresz Medvegyev volt az egyetlen, aki az 1970-es években tudományos következtetések útján felhívta a figyelmet egy 1957-es uráli nukleáris katasztrófa lehetőségére; feltételezése szerint egy földalatti radioaktívhulladék-tárolóban bekövetkezett robbanás hatalmas területet szennyezett el.

Noha az 1986-os csernobili eseményekről a nemzetközi közösség már korábban tudomást szerzett, a „kistimi katasztrófa" részletei egészen a glasznoszty időszakáig rejtve maradtak, amíg a szovjet hatóságok végül a releváns adatok nyilvánosságra hozatala mellett nem döntöttek.

1989-ben, a Nemzetközi Atomenergia-ügynökség (NAÜ) által szervezett rendezvényen a világ számára világossá vált, hogy Medvegyevnek igaza volt. Valóban létezett egy különálló és titkos nukleáris létesítmény a Déli Urálban, ahol sorozatos emberi mulasztások 1957. szeptember 29-én egy INES 6 besorolású eseményhez vezettek a Majak Termelési Egyesülésnél (Mayak PA), Kistim városa közelében, a Cseljabinszki megyében.

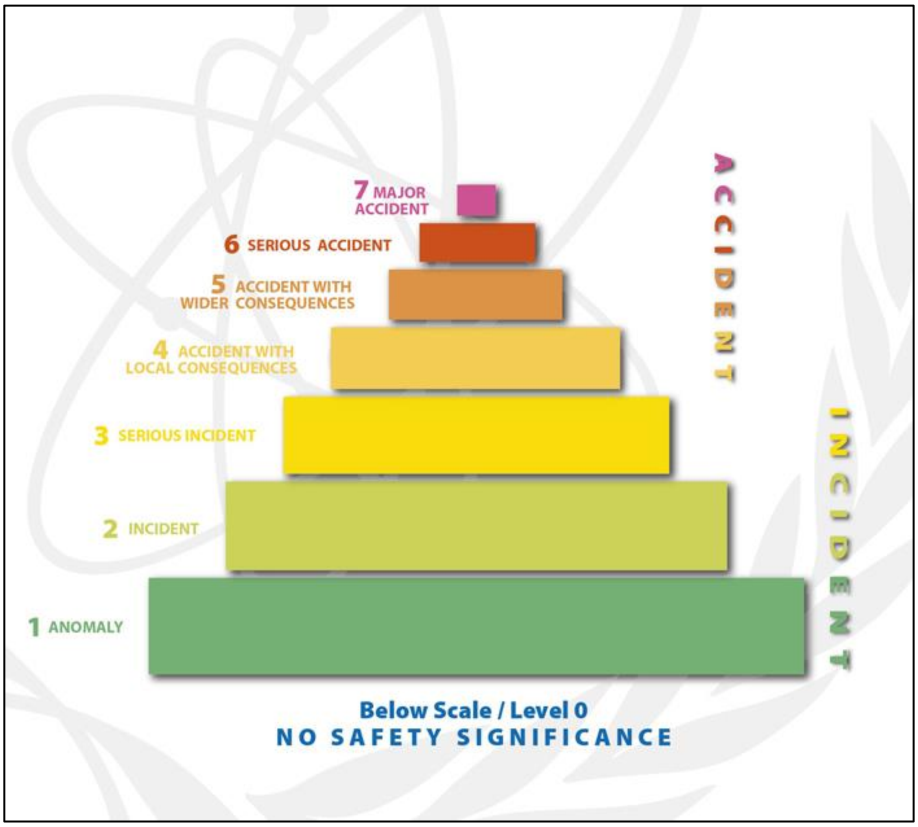
Kulcsszavak: nukleáris katasztrófa, Kysthym, Mayak PA, nukleáris hulladék, szennyeződés, EURT.

Keywords: nuclear disaster, Kysthym, Mayak PA, nuclear waste, contamination, EURT.

Prologue

As a result of the accident, a total of 740 PBq (~20 MCi) of radioactive material was released by a chemical explosion. Approximately 90% of this radioactive content settled in the immediate vicinity, affecting an area of around 20,000 km², home to approximately 270,000 people. The remaining 10%, about 74 PBq (~2 MCi) of radionuclides, was transported into the atmosphere to a height of 1 km, shaping a plume consisting primarily of ^{90}Sr and ^{137}Cs. This plume spread beyond the Mayak PA site to form the East Urals Radioactive Trace (EURT). [1, p. 1.] [2, p. 1.] [3, p. 1.]

In the history of mankind at that time, this level-6 accident on the INES scale was the largest in terms of quantity of radioactivity released. To date, only the two level-7 events have exceeded it in magnitude: the Chernobyl disaster, with 5,200 PBq (~140,5 MCi), and the Fukushima accident, with 770 PBq (~20,8 MCi).



Picture 1. The INES Scale

(Source: International Atomic Energy Agency)

But before all, let's go back in time, because the roots of the disaster go far beyond what happened in 1957. The event was the result of a series of actions that demonstrate a high degree of complete irresponsibility. Twelve years prior to the disaster, during the conflict between the US and Japan, many people died as the US detonated atomic bombs in Nagasaki and Hiroshima. The USSR leader, Josef Stalin understood that the era of traditional warfare was over and realised the USSR's nuclear program lagged significantly behind of the US's and needed to be accelerated. Stalin's comment in the presence of his closest associates and the scientific director of the Soviet Union's nuclear arms project, Igor Kurchatov, reveals his unease: "A single demand of you, comrades. Provide us with atomic weapons in the shortest possible time. You know that Hiroshima has shaken the whole world. The balance has been destroyed. Provide the bomb – it will remove a great danger from us." Stalin was promised the Soviet Union's nuclear weapon would be ready within a maximum of five years. So it's happened.[1] Firstly, a secret location was needed. A mountainous region in the Urals around 1800 km from Moscow was chosen, and very soon the first-ever plutonium plant was created and named Mayak (officially Tšeljabinsk-65). Around 40,000 inmates all over from the Soviet Union (mainly from GULAG and war camps) were forced into carrying out its construction. The Mayak PA facilities operated under the Soviet P-Plan, which had a single priority: rapid and large-scale production of ^{239}Pu for nuclear weapons. Soon after, water from the Lake Karachay and Techa River was used to cool the six reactors of the facility and because cold war tensions were raised this whole investment was done in a hurry and in the utmost secrecy. [2, p. 1.] [4, p. 4.]

This military pressure led the operators to ignore safety protocols. Since the plant began producing plutonium almost immediately, the Mayak PA facility nevertheless became the pearl of the nuclear armament of the USSR at its time, despite the safety concerns.

A classified study – presumably an internally commissioned investigation (*thought of the authors) – conducted in 1951 revealed that 124,000 people who lived along the Techa river had been seriously exposed to radiation. This exposure was a direct consequence of the intentional release of approximately 78 million m^3 of medium- and high-level liquid radioactive waste from the Mayak facility into the nearby river system between 1948 and 1956. The total activity of the discharged waste reached approximately 106 PBq (~2,86 MCi).[2] [4, pp. 9-10.]

Due to the report the discharge of radioactive wastes into the Techa river was *practically eliminated* by introducing a cascade of reservoirs and bypass canals.[3] [5, p. 2.]

High-level waste was diverted to Lake Karachay—a landlocked lake south of Mayak—and, to a lesser extent, into reservoirs specifically excavated for this purpose. Between 1951 and 1967, radionuclides with a staggering total activity of approximately 44,400 PBq (~1,2 billion Ci) were discharged into Lake Karachay[4]. Meanwhile, medium- and low-level waste continued to be released into the Techa River, but the upper reaches of the river were eventually dammed to confine the pollution to a restricted area. [4, p. 10.]

The releases of radioactive waste into the Techa River resulted in external and internal exposures of the members of a cohort of about 30,000 persons who lived at some time in downstream settlements. The estimation of the doses received by the Mayak workers has also received considerable attention. During the early years of operation, from 1948 until the mid-1950s, the Mayak workers were exposed to relatively high exposures due to external irradiation and plutonium intakes. [1, pp. 3-4.]

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[1] The first soviet nuclear weapon was detonated in 1949. [2, p. 1.]

[2] This was the most important waste reprocessing and plutonium production facility in the history of the Soviet Union. [4, p. 9.]

[3] Before this was accomplished a large part of the floodplain and the bottom of the river were contaminated. [5, p. 2.]

[4] Making the lake to become one of the most polluted places on the planet. [4, p. 10.]

Picture 2. The Mayak PA facility and its southern territory nowadays

(Source: Google Earth)

About the disaster

The most dangerous environmental problem in the Mayak PA facilities was the early system of radioactive wastes produced in large quantities. [1, p. 3.]

Not only the Techa river and Lake Karachay were used for storage, but several metal tanks were installed too, for this reason.

By 1953, large amounts of liquid high-level radioactive waste from the radiochemical facility were placed into these stainless-steel tanks, which were mounted on a concrete base, 8,2 m underground. Each full tank contained 70–80 tons of radioactive wastes, mainly in the form of nitrate compounds. The tanks were water-cooled and equipped with temperature and liquid-level measurement devices. The accident involved waste which was from the sodium uranyl acetate process used by the early Soviet nuclear industry to recover plutonium from irradiated fuel – the idea was to dissolve the fuel in nitric acid, alter the oxidation state of the plutonium, and then add acetic acid and base.[5] This would convert the uranium and plutonium into a solid acetate salt. The heat generated by the radioactive decay of the high-level nuclear waste stored in the tanks was removed by a water-cooling system. However, the maintenance of the cooling systems was presumably inadequate.

[5] The acetate process was a special process which was never used in the West. [2, p. 1.]

In September 1957, as a result of a failure of the temperature-control system of tank #14 – which was full at the time, so it contained 70-80 tonnes of highly radioactive waste –, cooling-water delivery became insufficient and radioactive decay caused an increase in temperature followed by complete evaporation of the water, leaving behind a radioactive mixture of ammonium nitrate and acetates with the heat of 330 °C–350 °C. [2, pp. 1-2.] [3, p. 3.]

Exothermic processes begin in mixtures of sodium nitrate and solid organic materials at a high temperature, about 360-400 °C. This is because organic matter interacts with oxygen; a decomposition product of sodium nitrate, rather than with this compound itself. Pure sodium nitrate breaks down into nitrite and oxygen at 380 °C. The sodium nitrite that forms as a result is stable. Mixtures weighing around 100 mg consisting of 30% sodium acetate and 70% sodium nitrate by weight, and 10% sodium acetate and 90% sodium nitrate (with molar ratios of 1:3,74 and 1:14,6 respectively) were subjected to derivatographic analysis[6]. After removal of water (around 10% weight loss in the first case and 5% in the second) at temperatures of 385 °C and 370 °C respectively, an intensive exothermic process (with 620 kJ/kg heat release) coupled with a weight loss of 15% begins in the first case, and a relatively slow exothermic process (with 83 kJ/kg heat release) coupled with a weight loss of 2,1% begins in the second. Considering the data of derivatographic analysis, the processes that actually occur when storage mixtures undergo heating, and the fact that boiled-down highly radioactive wastes are a stoichiometric mixture or one with excess oxidizer, the most probable equation for the reaction between the mixture's components would be:

$$CH_3COONa + 0{,}5H_2O + xNaNO_3 = 2CO_2 + 1{,}5H_2O + 0{,}5Na_2O + xNaNO_2$$

with *release* of 150,4 kcal (630 kJ) *of heat*.

The results of calculating the parameters of explosion show that at the molar ratio of sodium acetate and nitrate characteristic of highly radioactive wastes and at a boiled- down salt weight of 30 tonnes, the equivalent charge is *2,4-4,1 tonnes of TNT*. The power of such a charge is sufficient to generate a pressure of up to 10 MPa in the container, and to eject its contents to a height of 1 km. [6, pp. 3-5.]

With this power of aproxomietly tonnes of TNT, on 29 September 1957 at 4:20 pm local time the tank #14 exploded. The lid of the tank, approximately 160 tonnes of concrete, was blown free. At the time of the explosion the activity of the wastes contained in the tank was about 740 PBq (~20 MCi). About 90% of the total activity settled in the immediate vicinity of the explosion site (within distances less than 5 km), primarily in the form of coarse particles. The explosion gave rise to a radioactive plume which dispersed into the atmosphere to a height of 1 km, so about 10% (74 PBq (~2 MCi)) of the total activity was dispersed by the wind (at that time with the direction of north-northeast and with wind velocity of 5–10 m/s) and caused the East Urals Radioactive Trace (EURT) along the path of the plume. The estimates of radionuclide composition of the release used for reconstruction of doses in the EURT area were essentially $^{90}Sr + ^{90}Y$ (5,4%), $^{95}Zr + ^{95}Nb$ (24,8%), $^{106}Ru + ^{106}Rh$ (3,7 %), $^{144}Ce + ^{144}Pr$ (65,8%), $^{137}Cs + ^{137m}Ba$ (0,35%), ^{239}Pu (0,002%) and with traces of ^{89}Sr, ^{147}Pm and ^{155}Eu. [2, p. 2.] [3, pp. 3-4.]

Consequences for people and environment

The workers at Ozyorsk and the Mayak plant did not immediately notice the polluted streets, canteens, shops, schools, and kindergartens.

[6] Derivatographic analysis is a *complex thermal analysis technique* that simultaneously records changes in a sample's mass (TG), the rate of mass change (DTG), and its enthalpy changes (DTA) as temperature is programmed. This method provides simultaneous information on thermal decomposition, oxidation, and other physicochemical processes, allowing for the simultaneous characterization of a material's thermal properties.

In the first hours after the explosion, radioactive substances were brought into the city on the wheels of cars and buses, as well as on the clothes and shoes of industrial workers. However, after the blast at the facilities of the chemical plant, dosimetrists noted a sharp increase in the background radiation. Over the next 10-11 hours the radioactive cloud drifted northeast to a distance of 300-350 km, causing widespread contamination. The contamination, consisting predominately of ^{137}Cs and ^{90}Sr, was spread over an area of 800 – 20,000 km^2 depending on what contamination level is considered significant. A contamination density of 74 kBq/m^2 (~2 Ci/km^2) of ^{90}Sr was established as the intervention level for the evacuation of the population.[7] At the time of the accident, 63% of the area was used for agricultural purposes, 20% was forested and 23 rural communities existed within the region. [2, p. 2.]

Residents in the EURT zone underwent complete sanitization with their personal clothes being changed. Houses and outbuildings in these settlements were destroyed, private farm livestock were slaughtered and buried in situ. [3, p. 5.]

In the most severely affected area, close to the boundary of the industrial site, the initial ^{90}Sr deposition density reached 150 MBq/m^2 (~4,054 Ci/km^2). Countermasures to protect the population were applied in areas with a ^{90}Sr level greater than 74 kBq/m^2 (~2 Ci/km^2). The territory contaminated with ^{90}Sr levels in the range from 3,7 to 74 kBq/m^2 (~0,1 to 2 Ci/km^2) had an area of 15,000 km^2 and a population of 260,000. [1, p. 2.]

It was not until a week after the explosion that evacuation began. Even then, no reason for the evacuations was given. The evacuations were carried out over a period of nearly two years. [2, p. 2.]

Within 7 to 10 days following the accident, 600 residents were evacuated from the settlements in the most severely affected areas, and about 10,000 people were evacuated during the 18 months following the accident. The average effective dose received by the most exposed group prior to evacuation was 520 mSv (52 rem), including a contribution of 170 mSv (17 rem) from external irradiation. Among the 10,730 evacuees, the average effective dose was 120 mSv (12 rem). Among the 260,000 non-evacuees, the effective doses were much smaller, with an average of 5 mSv (0,5 rem). [1, p. 2.]

The actual radiological consequences for local inhabitants from the disaster is difficult to estimate. This is because their overall exposure is made up of that from the disaster itself, and that from the enormous quantities of radioactive material dumped into the Techa river and Lake Karachay. The populations living along the Techa River were chronically exposed to radiation, both externally and internally. Villagers were exposed via many different pathways, of which potable water from the Techa River was one of the most significant. External irradiation from the Techa River bottom sediments and shoreline was also an important factor. The radionuclides believed to contribute most to the dose commitment are ^{90}Sr and ^{137}Cs. Studies have been carried out in an attempt to determine the overall health effects of residents in the Techa river area and the EURT. [2, pp. 2-3.]

Individual doses were calculated for 21,427 members of the EURTC[8] based on their residence histories. It should be noted that 1,431 members of the cohort were exposed both in the EURT area and from the contaminated Techa River (which was taken into account). Maximum values of dose for the whole EURTC reached 0,6 Gy (60 rad) for stomach and 1.9 Gy (190 rad) for bone marrow. The cohort-average values of dose were low: 28 mGy (2,8 rad) for stomach and 78 mGy (7,8 rad) for bone marrow. The average contribution of external exposure to the total absorbed dose was: 83% for stomach, and 35% for bone marrow. Stomach dose was used for the analysis of solid cancers as a group.

[7] This delineated an area of approximately 1000 km^2 that became known as the EURT [2, p. 2].
[8] East Urals Radioactive Trace Cohort.

The dose to the stomach was similar to absorbed doses to the lung and other soft tissues other than intestines. Doses to bone marrow were dominated by bone-seeking ^{90}Sr (contribution >97%). Doses to extra-skeletal tissues were significantly less so, and mainly due to intakes of ^{144}Ce (contribution 60%–70%). Taking into account the fact that children are more sensitive to the effects of ionizing radiation, special attention was paid to the assessment of their health status. Over the period 1958–1960, 952 children aged under 14 were examined in the course of visiting medical examinations. Children from age of 5–9 years at the time of the accident formed the main part of the examined group. Increased infectious disease incidence was observed in the group with the highest exposure dose. Among diseases of the endocrine system, nutritional deficiencies and metabolic disorders rachitis or its residual effects were most often diagnosed. Among diseases of the nervous system and sense organs mainly conjunctivitis, blepharitis and otitis were registered.

Mortality rates, including infant mortality, were assessed over the period 1958–1989 in offspring of the population that was not resettled, but continued living on the EURT territories with low deposition density. The infant mortality rate (per 1,000 person years) for the offspring of the population residing on the territories with ^{90}Sr deposition between 3,7 and 37 kBq/m^2 (0,1–1 Ci/km^2) was 52,4, for the offspring of the population residing on the territory with ^{90}Sr deposition less than 3,7 kBq/m^2 (0,1 Ci/km^2), the rate was 55,7, compared to 57,2 for the offspring of the unexposed control population. The infant mortality structure did not differ radically from that in offspring of unexposed persons. Most often babies died of pneumonia. Another common cause of death was intestinal infectious diseases (for example, dysentery). Rather a large percentage of deaths was of perinatal diseases due to immaturity of the fetus and occurrence of a hypoxic state. No significant increase in mortality rateswas observed in the course of the mortality analysis among persons exposed in utero.

Solid cancer mortality risk among 14,589 residents of the EURT covering the period 1957–1987 was conducted 30 years after the accident. The EURT cohort included people born before the accident, both resettled and those who continued living on the contaminated territories of the Chelyabinsk Oblast. Analysis was performed using both external and internal controls. The external control group, 19,375 persons in number, was formed from the population residing on non-contaminated territories of the same administrative raions of the Chelyabinsk Oblast as the exposed population, and was comparable to the main group in terms of sex, age, and ethnicity. EURTC members subjected to chronic radiation exposure – with external gamma radiation doses in the range of 0,3–43 mGy (30–4,300 mrad) and absorbed doses to the red bone marrow ranging from 6 to 2,100 mGy (06–210 rad) – exhibited a statistically significant increase in solid cancer mortality compared to the external control group. However, no statistically significant dose dependence of solid cancer mortality risk was found. Leukemia mortality rates over a 30-year period after the accident did not differ from those in the group of unexposed people. [3, pp. 9-13.]

The cancer incidence structure of EURTC members corresponds to the cancer mortality structure; the most frequent cancer sites are lung cancer and stomach cancer (18,7% and 18%, respectively). The percentage of lung cancer in men is rather high and exceeds 32%. The percentage of breast cancer in total cancer incidence is significantly higher than that in mortality (as not all the cases lead to death) and makes up 7%. In the cancer incidence structure of females, the most frequent were cancer of the reproductive organs, 25,7%. Cancer of stomach (16,8%) and cancer of intestine, colon, liver and other digestive organs rank next to reproductive organs. Breast cancers were also quite frequent, 13,5%. As for hematological malignancies, over the period 1957–2009 there were 76 incidence cases among EURT cohort members: 31 lymphomas, 8 myelomas, and 37 leukemias (including 12 chronic lymphatic leukemias). [3, p. 18.]

Cancer sites (ICD-10 codes)	Male		Female		Total	
	cancer number	%	cancer number	%	cancer number	%
(C00-C14) Lip, oral cavity, throat	60	8.5	18	2.5	78	5.5
(C15) Oesophagus	45	6.4	45	6.3	90	6.3
(C16) Stomach	135	19.1	121	16.8	256	18.0
(C18) Colon	23	3.3	32	4.4	55	3.9
(C17, C19-C26) Other sites within the digestive organs	66	9.3	89	12.4	155	10.9
(C33-C34) Trachea, bronchus, lung	229	32.4	38	5.3	267	18.7
(C30-C32, C37-C39) Other organs of respiratory tract	26	3.7	3	0.4	29	2.0
(C40-C41) Bones, articular cartilage	1	0.1	2	0.3	3	0.2
(C43) Melanoma	7	1.0	6	0.8	13	0.9
(C45-C49) Connective tissue	7	1.0	3	0.4	10	0.7
(C50) Breast	2	0.3	97	13.5	99	6.9
(C53-C54) Corpus uteri and unspecified sites	0	0.0	53	7.4	53	3.7
(C51, C52, C55-C58) Other female genital organs	0	0.0	132	18.3	132	9.3
(C60-C63) Male genital organs	26	3.7	0	0.0	26	1.8
(C64-C68) Bladder and other urinary organs	39	5.5	18	2.5	57	4.0
(C73) Thyroid	2	0.3	20	2.8	22	1.5
(C69-C72, C74-C80) Other not specified sites and brain tumor D43	38	5.4	43	6.0	81	5.7
(C00-C43, C45-80) Total solid, including brain tumor D43	706	100.0	720	100.0	1426	100.0

Table 1. Cancer incidence structure in EURTC members by gender and sites [3, table 7.]

Conclusions

At least about 5,000 people working at Mayak were continuously exposed to annual radiation doses exceeding 1 Sv (100 rem). Furthermore, hundreds of employees received annual doses reaching as high as 4 Sv (400 rem). Occupational exposure peaked between 1948 and 1958, a period during which radioactive contamination resulted in nearly 2,000 documented cases of radiation sickness (specifically Chronic Radiation Sickness). [4, p. 21.]

According to a research the number of sick-cases which led to cancer is 1,426 (as we can see it in the upper table) and only 27 of them could be associated with accidental radiation exposure of the EURT population [3, p. 20.], whilst another scientific work states that radioactive radiation caused 300 to 600 lethal cancer cases among Mayak employees. [4, p. 21.]

In recent decades, many events have occurred that have forever inscribed themselves in the history of mankind. [8, p. 6.] So was the Kysthym. Although this accident was a tragic event on many levels with serious consequences for both the population and the environment, the accident, as can be seen from the above, served as an important impetus for a number of initiatives which form a significant part of emergency response planning today.

An example of this is the use of dose or contamination intervention levels which are used to decide on actions such as sheltering or evacuation, and decontamination/remediation of affected areas following an accident. And also a simple physicochemical experiment provides a possibility for modeling an extreme reaction causing release of radionuclides from a storage facility, and to determine the energy characteristics of this reaction in the particular conditions under which it proceeds. By writing a plausible scenario of an accident at a radiochemical plant based on an analysis of indirect data and the energy characteristics of dangerous phenomena occurring as an accident develops, we can also pose and solve the reverse problem; establishing the possible consequences of an accident before it occurs, and in the ideal case, before a dangerous facility is placed into operation. In other words: the design of a radiochemical plant (of its individual parts) must consider both predictable and unpredictable accidents, as is done with nuclear power stations. [4, p. 29.] [6, p. 5.]

It can also be stated that the prevention, management and response to incidents involving radioactive material are based on similar principles as those for chemical accidents involving hazardous materials [9] [10]. Monitoring the adverse effects of chemical, biological, radiological, and nuclear (CBRN) incidents is an important factor in hazardous material response [11].

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