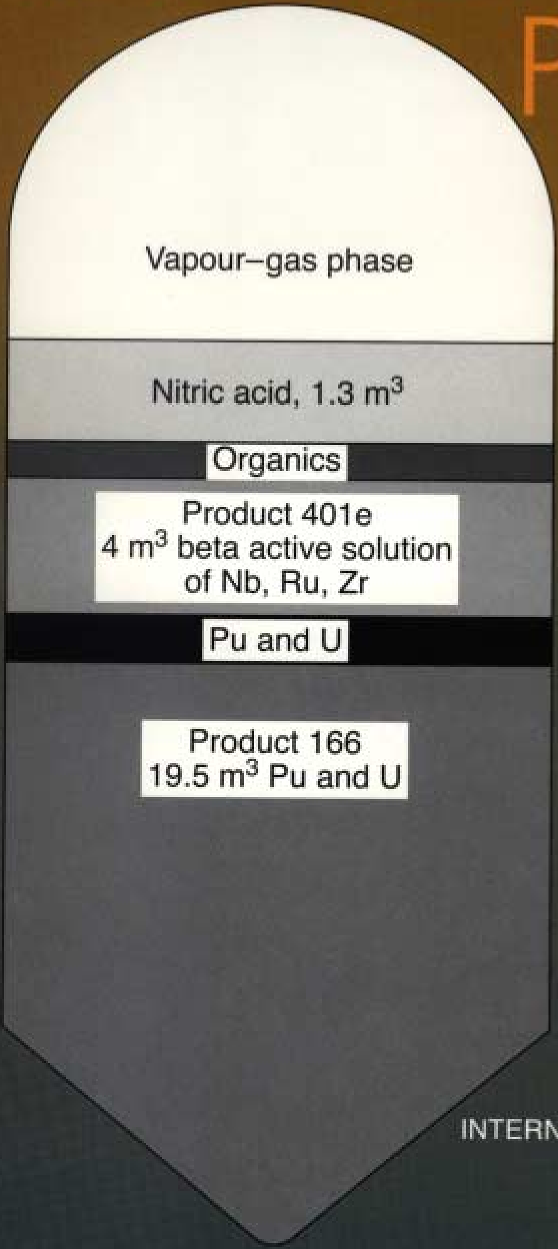
THE RADIOLOGICAL ACCIDENT IN THE REPROCESSING PLANT AT TOMSK



INTERNATIONAL ATOMIC ENERGY AGENCY

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The Agency’s Statute was approved on 23 October 1956 by the Conference on the Statute of the IAEA held at United Nations Headquarters, New York; it entered into force on 29 July 1957. The Headquarters of the Agency are situated in Vienna. Its principal objective is “to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world’’.

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THE RADIOLOGICAL ACCIDENT IN THE REPROCESSING PLANT AT TOMSK

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FOREWORD

A radiological accident occurred on 6 April 1993 at the location then known as Tomsk-7 in the Russian Federation. Very soon after the event the Government of the Russian Federation requested assistance from the IAEA to assess the radiological, health and environmental impacts of the accident. The IAEA used its contacts and resources to assemble a mission. The mission arrived at Tomsk-7 on 15 April, just over a week after the accident. The authorities at the complex, which had until then been a closed city, opened all the facilities to inspection. They gave a comprehensive description of the possible causes and evolving consequences of the accident and made arrangements for the team to visit the neighbourhood to carry out sampling and measurements and to inspect the facility where the accident took place. The team also inspected the environmental monitoring laboratory and whole body counting facilities of the complex.

The mission team was impressed by the technical descriptions provided, but there were a number of matters still needing investigation and resolution. The results of the analyses on samples confirmed the radionuclide composition of the beta/gamma emitters and showed that it was unlikely that there would have been significant amounts of alpha emitters released. This means that the external dose rate will decrease quickly and no further off-site decontamination should be necessary.

There was some discrepancy revealed by the computer simulation between the release estimate provided and the dose rate contours. This was not considered to be serious for an estimate of radiation hazards to the population, which is decided on the basis of measurements in the environment. However, it was regarded that it should, if possible, be clarified.

The IAEA therefore commissioned an in-depth investigation from the Institute of Biophysics of the State Research Center of Russia. The objectives were to confirm the causes of the accident and the sequence of events leading to the explosion and the radioactive release to the environment; to corroborate the early estimates of doses both on- and off-site; and to assess the effectiveness of the countermeasures.

This report contains an explanatory Preamble setting out the findings of the mission together with the detailed findings of the investigation. The IAEA is grateful to the team of Russian scientists who carried out the investigations under the leadership of Academician L. Ilyin.

CONTENTS

PREAMBLE

The IAEA mission

On 6 April 1993 an accident occurred during the reprocessing of spent nuclear fuel at the facility then known as Tomsk-7 in the Russian Federation. Soon after the accident the Government of the Russian Federation contacted the Director General of the IAEA to request assistance in assessing the consequences of the accident.

The IAEA used its contacts and resources to rapidly assemble a mission team which was charged with assessing the radiological health and environmental impacts of the accident. The team arrived in Moscow on 14 April for initial briefing at the Ministry of Atomic Energy and then proceeded to Tomsk in central Siberia, arriving on 15 April, just over a week after the accident.

The mission was immediately admitted to the Tomsk-7 complex, which is located 16 km from Tomsk, a city of about half a million inhabitants. Tomsk-7 is an extremely large complex which includes:

- an inner city with approximately 100 000 inhabitants, most of these workers of the complex and their families;
- several reactors, basically plutonium production facilities, although some also generate heat for Tomsk;
- fuel fabrication facilities;
- uranium enrichment facilities;
- reprocessing facilities;
- radiochemical laboratories;
- support facilities.

The mission was received by the head of the complex and his staff at the headquarters and a comprehensive description of the possible causes and evolving consequences of the accident was provided.

The mission then inspected the facility where the accident had taken place from distance of 20–30 metres. The destruction of the external walls caused by the accident also allowed an overview of the inside.

Recovery operations were under way at the time of the visit. Although the recorded dose rate was not very high (around 30–50 $\mu Sv \cdot h^{-1}$ at 20–30 m) there was a great deal of resuspension and dust caused by the ongoing work. The members of the mission wore protective clothing and used respiratory protection. The mission then inspected the environmental monitoring laboratory and whole body counting facilities of the complex.

The mission subsequently inspected the contaminated area outside the complex fence and took measurements and a few samples of soil, vegetation and snow at the intersection of the nearby route and the approximate axis of the plume. From there the mission visited the only inhabited place that had been under the plume: the hamlet of Georgievka with a population of about 200, located at around 15 km from the complex, and comprising a few tens of frail wooden houses, and a simple, almost empty, grocer’s shop. No crops were being grown at the time of the visit.

After returning from Georgievka, the mission held a summing up session in Tomsk-7 with the authorities of the complex.

Subsequently, the mission returned to Tomsk and had a brief meeting with the local oblast (region) authorities, followed by a large press conference attended by local and Russian media, a few international correspondents and members of the public.

The mission returned to Moscow on 16 April and provided a summary to the authorities at the Ministry of Atomic Energy. The mission left Moscow on 17 April and produced a report for the IAEA Director General on return to Vienna.

Findings of the mission

The accident took place on 6 April 1993 at 12:58. Overpressure occurred in a tank containing uranium nitrate solution and caused gases to burst through the top of the tank, displacing the cover of the containment cell and leading to a forceful explosion. Release of radioactive materials to the local environment took place through the large holes in the side walls and roof of the room and through the side wall of the galley. There was also a release via a ventilation system through a 150 m high stack.

The initial release of radioactive materials caused contamination near the building over an area of 1500 m^2. The wind was blowing towards the damaged side wall of the building at the time, which may have limited the spread of released materials. The localized release was said to be 150 GBq of beta/gamma emitters. The major release occurred through the 150 m stack to the atmosphere until the ventilation flow could be rearranged to curtail the release. The total beta/gamma activity of material released was said to be 1.5 TBq.

The wind was said to be light, and it was snowing at the time of the accident. These factors may have helped to limit the spread of released materials.

Environmental measurements began within 1 hour of the accident and by the time the mission arrived the whole area of contamination had been surveyed by air and ground sampling, and a contour dose rate map had been prepared. The contamination trace extended to the northeast, over mostly forested land. There are about 100 ha of agricultural fields used for producing crops within the trace, and the village of Georgievka. At the village, the dose rate in air was reported to be 0.2–0.4 $\mu Sv \cdot h^{-1}$ with spots of up to 1.8 $\mu Sv \cdot h^{-1}$ and sometimes as high as 30 $\mu Sv \cdot h^{-1}$. Some decontamination had been carried out in the village with the removal of snow and surface soil.

The highest recorded external dose to a worker was 7 mSv and the firemen who extinguished the fire received about 2 mSv. There were no firm data on internal doses. There were no injuries to workers.

Some very preliminary calculations were carried out to check the relationship between the quantity of activity said to have been released and the measured dose rates.

The calculations were carried out for a total release of 1.5 TBq with the nuclide composition provided by the authorities of the complex. The following assumptions were made:

- low wind speed (5 m/s)
- a 30 min release from 150 m stack in weather category D
- a dry deposition velocity of 1×10^{-3} m/s
- snow falling during release (which is assumed to increase deposition by a factor of at least 10).

Under these conditions the peak air concentration occurs at 3 km from the stack. The air concentration at 10 km will be about half that at 3 km assuming no depletion of the plume. Plume depletion would reduce air concentrations by a large amount, but this factor could not be estimated on the basis of the information available at the time of the mission.

The resultant external dose rate at about 3 km is in the range 0.02–0.2 $\mu Sv \cdot h^{-1}$. At 10 km, the best estimate dose rate is 0.01–0.1 $\mu Sv \cdot h^{-1}$, with no allowance for the effect of plume depletion. It should be noted that these are peak dose rates on the plume centre line. The total deposition at about 3 km was estimated to be of the order of 3–30 $GBq \cdot km^{-2}$.

Measurements of three samples collected by the mission were made by the Agency's Laboratories at Seibersdorf. These were one soil sample and two water samples from melted snow, both with visible particulate sediments and grains; filtered water and particulate matter on the filter were also investigated.

Two portions of the soil (about 6 g each) and one 4 mL aliquot each of filtered water were quantitatively assayed for radionuclides. The soil samples contained the beta emitters ^{95}Zr, ^{95}Nb, ^{103}Ru and ^{106}Ru, in approximately the same ratios as reported to the mission.

Very little activity relating to the above nuclides was measured in the water samples and no other radionuclides were detected. The particulate residue on the filter from one water sample was evaluated. A similar pattern to that in the soil was found.

Attempts were made to establish the presence of alpha emitters. Assuming a similar ratio in the activities of the released material to that reported in the inventory, the above samples should have had an alpha activity of about 3 Bq, but this was not detected.

There was no uranium activity detected above the limits that could be assayed instrumentally in the soil and water samples.

Conclusions of the mission

The general impression of the mission was that the technical and radiological picture of the accident presented was relatively coherent and therefore plausible. On this basis the mission advised that:

- it is not to be expected that any clinical deterministic effects of radiation will occur as a result of this accident;
- the radiological impact for stochastic effects should be minor and certainly undetectable by epidemiological methods;
- the exposure to persons off-site should be minimal on the basis of the radiological measurements and an assessment of the consequences.

Although the mission team was satisfied with the technical descriptions, the impression obtained from the radiation protection laboratories was poor: they were badly equipped for a complex of this size. For instance, a few gamma spectrometers, only one alpha spectrometer (with an old analyser) and only two whole body counters (neither equipped with Pu detectors) were registered.

Although, because of the nature of the accident, hot particles would not have been expected to occur, the subsequent fire and the explosion through the stack could have carried any hot particles if they were generated.

No uranium measurement was reported. Although the radiological significance of natural uranium is minor, it would have been helpful to have some contamination values for reference.

The results of the analyses on samples confirmed the radionuclide composition of the beta/gamma emitters and suggested that it was unlikely that there were significant amounts of alpha emitters. This meant that the external dose rate will decrease quickly and the mission concluded that no further off-site decontamination should be necessary.

There remained some discrepancy revealed by the computer simulation between the release estimate provided and the dose rate contours. This was not regarded as serious for the estimate of radiation hazards to the population, which is decided on measurements in the environment. However, the mission recommended that it should, if possible, be clarified.

In order to clarify these matters and to provide full documentation of the radiological consequences the IAEA commissioned a team of Russian scientists to carry out a detailed assessment. The results of this assessment are given in the main body of this report.

1. INTRODUCTION

1.1. BACKGROUND

On 6 April 1993 at 12:58 local time, an accident occurred during the reprocessing of irradiated reactor fuel at the Siberian Chemical Enterprises (SCE) facility at Tomsk-7, situated near the city of Tomsk in the Russian Federation. The accident caused damage to both the reprocessing line and the building and resulted in the release of about 30 TBq of beta and gamma emitting radionuclides and about 6 GBq of ^{239}Pu. The accident corresponded to Level 3 on the International Nuclear Event Scale, namely, a “serious incident” but one in which there was no overexposure to personnel.

Parts of the SCE site and a considerable area of the surrounding countryside to the north of the complex, including the village of Georgievka and part of the trunk road linking Samus with Tomsk, were contaminated with radionuclides. Although the level of contamination was relatively low, considerable effort was expended in decontaminating buildings and land on the SCE site, as well as farm land and areas within the locality of Georgievka. Food was imported for both the local population and animals to avoid consumption of contaminated food. Some of the measures introduced in the surrounding area were not strictly warranted by the level of contamination but were carried out to provide reassurance to the local population and to reduce their concern and stress. Figure 1 gives an impression of the relative size of the contaminated area and its location within the Russian Federation.

1.2. OBJECTIVE

This review of the accident at SCE is intended to bring together in one publication the facts about the accident, to provide as much information as possible about the radiological consequences to the workers at the facility and to the public in the vicinity, and to evaluate the effectiveness of the actions taken in dealing with the accident.

1.3. SCOPE

There has been considerable variation in the way accidents have been reported in easily accessible literature and consequently useful information, from which valuable lessons may be learned, has been lost. This publication is based mainly on information contained in a report commissioned by the IAEA from the Institute of

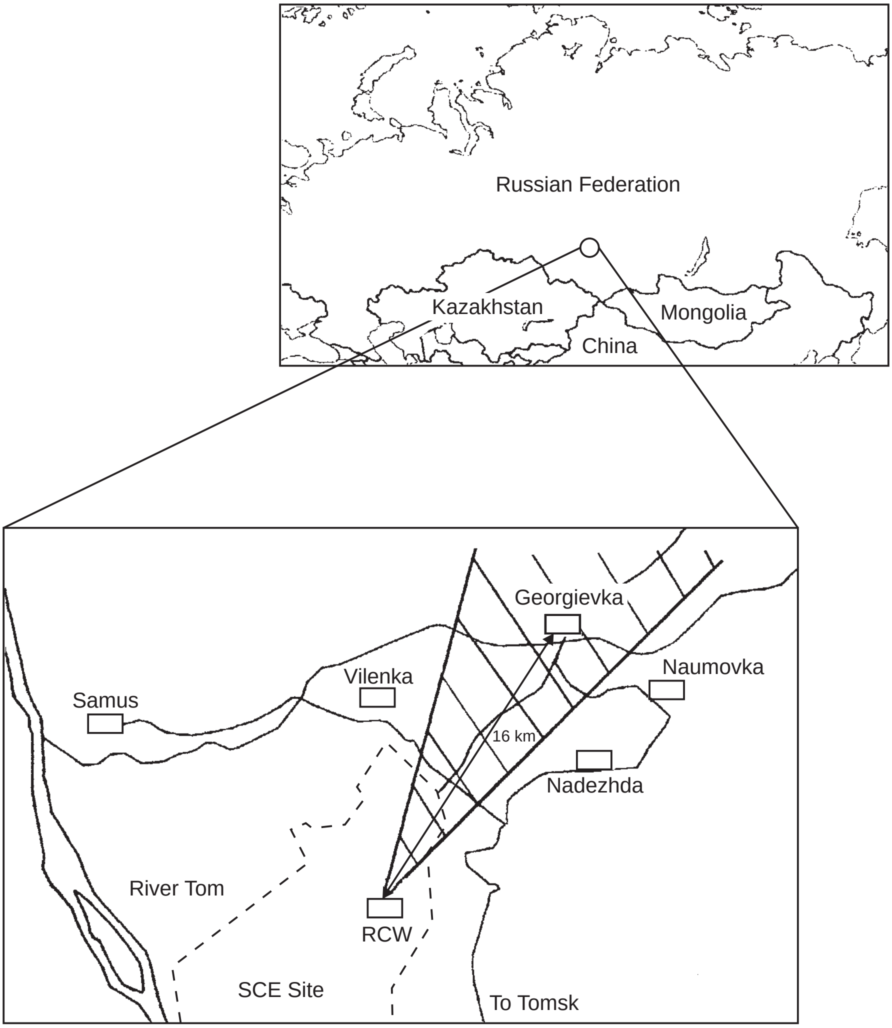


FIG. 1. Plan showing the location of the SCE site with an impression of the relative size of the contaminated area.

Biophysics of the State Research Center of Russia [1]. Additional information has been taken from the internal report of the IAEA team which visited SCE immediately after the accident and from other unpublished sources.

1.4. STRUCTURE

Section 2 gives background information about the local area, the SCE site and its functions, together with a description of the radiological situation at SCE and in the surrounding area prior to the accident. Section 3 describes the reprocessing facility at SCE and the situation in the plant prior to the accident. The chronology of the accident and a description of its likely cause are given in Section 4. The radiological situation resulting from the accident, the actions taken to reduce the effects of the accident, including those to reduce the radiological burden on the local population, as well as the way SCE personnel and the local population were affected by the accident and the effectiveness of the remedial measures introduced are covered in Sections 5–7. Section 8 highlights the main conclusions that can be drawn and ways in which improvements might be made in responding to accidents.

2. BACKGROUND INFORMATION

2.1. SIBERIAN CHEMICAL ENTERPRISES

SCE forms part of the Russian Federation’s nuclear industry and is involved in the large scale production of plutonium and uranium. Construction of the SCE complex started in 1949, with the facilities for producing enriched and strategic (high enriched) uranium coming into operation between 1952 and 1955. Strategic plutonium was initially produced in commercial reactors until the two reprocessing lines in the Radio Chemical Works (RCW), where the accident occurred, came into use in August 1961 and October 1962.

The facilities on the SCE site also include several reactors used for power production and processing strategic plutonium, an isotope separation plant, a sublimation plant for producing uranium oxide–protoxide and hexafluoride, a metallic uranium and plutonium production plant and storage facilities for liquid and solid radioactive wastes.

Since the international agreement on reducing strategic armaments was reached, the role of SCE has changed considerably; the activities on the site have gradually been shifted away from military towards civil applications.

2.2. LOCATION OF THE SCE SITE

The SCE site is located in the Russian Federation about 16 km from the regional capital of Tomsk and covers an area of about 192 km^2 with an area surrounding it of 1560 km^2, designated as the Supervision Zone, in which routine measurements are taken to monitor the environmental impact of nuclear operations at the complex. The countryside around SCE is relatively sparsely populated apart from the regional capital Tomsk and Tomsk-7 (now known as Seversk), which are located south of the SCE site. Tomsk has a population of about 500 000 while Seversk, which houses personnel working at SCE and their families, has a population of over 100 000 people. The rest of the local population live in small villages of a few hundred inhabitants and are generally involved in farming or are retired.

The countryside is slightly undulating with height variations of about 30 m and slopes towards the river Tom in the west. To the east of the region, there is a plateau about 175 m high which has a number of ravines on its western slope with depths of up to 13 m. The river Tom flows to the west of the SCE site with its tributary, the river Samuska, flowing westwards to the north of the site. There is a lake Chernoe (surface area about 1 km^2) on the territory of the SCE complex. The two other rivers in the region are the Talovka and Pesochka, both of which are tributaries of the Samuska. Waste water from SCE is released into a system of channels running in the dry bed of the river Romashka and then into the river Tom near the village of Chernilshchikovo. The map in Fig. 2 shows the position of the SCE site and the Supervision Zone in relation to the main towns and places mentioned in the report.

To the north of SCE the land which was contaminated from the accident is mainly covered with 10–12 m high coniferous trees such as pine, cedar and fir, with some parts utilized for farming. The fauna of the region is fairly diverse, with over fifty species including squirrels, chipmunks, mountain hares, ermines, weasels and elks, the main species of birds being sparrows, grackles and blue rock pigeons.

2.3. LOCAL CLIMATE

The climate in this part of the Russian Federation is harsh, with a short spring lasting through April and May and after the summer an equally short autumn in September and October before the onset of the long winter. Temperatures in the region vary from an average of about –19°C in the winter to 18°C in the summer, with an overall average annual temperature of –0.6°C.

The average annual precipitation in the region is 525 mm, most of this falling during the winter period when there is some precipitation on 60% of the days. For the remainder of the year, this drops to between 11 and 14%. Thirty per cent of the yearly

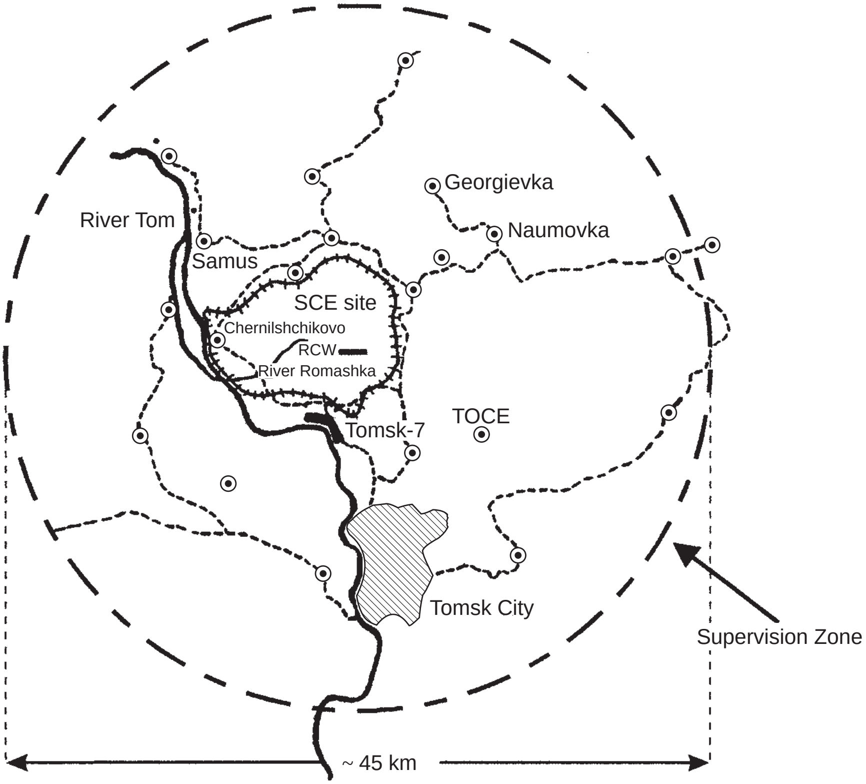


FIG. 2. Map of the SCE site and the Supervision Zone in relation to other locations mentioned in the report.

precipitation falls as snow, which on average lasts for 187 days and reaches its maximum depth of 57 cm in the open and 69 cm in the forest in March. The average monthly wind velocity during the year varies between 2.6 $m\cdot s^{-1}$ and 4.0 $m\cdot s^{-1}$ and for most of the time blows from a southerly direction.

2.4. RADIOLOGICAL PROTECTION AT SCE AND IN THE TOMSK REGION

Radiological protection at SCE and in the surrounding area is the responsibility of both SCE and the Central Medical Sanitary Department (CMSD). CMSD has the responsibility, on behalf of the State authorities in the Russian Federation, for the supervision of radiation safety on the SCE site, within the Supervision Zone and in the Tomsk region. CMSD, through organizations under its control such as the Centre for State Sanitary Epidemiological Supervision (CSSES) and hospitals, also carries out measurements to monitor the radiological situation within the SCE site and the Supervision Zone. The organizations responsible to CMSD and the type of monitoring they carry out are:

CSSES	Supervision of radiation safety at SCE Tomsk-7 and the surrounding area
Hospitals	Measurements of radiation levels using clinical methods Measurements of doses from radionuclides.

The amount of radiation monitoring carried out at SCE is agreed with the State sanitary epidemiological bodies taking into account the radiological situation existing at SCE and in the surrounding area. Radiation monitoring is carried out by departments within SCE and involves monitoring levels within buildings, around operating plant and on land within the site as well as levels associated with releases to the environment and the disposal of solid wastes. The departments within SCE involved with radiological measurements and the type of monitoring they carry out are:

Department of Personnel Protection and Radiation Safety (PPRS)	Radiation monitoring of work places, buildings and surrounding areas Monitoring of external doses to individuals Monitoring of internal doses to individuals
Environmental Protection Department	Monitoring of activity in airborne and liquid releases to the environment and resulting dose rates Monitoring of activity in the area of radioactive waste disposal.

The sources of radioactive contamination within SCE and the materials and items inside and outside of the site monitored by the two organizations are shown in Fig. 3.

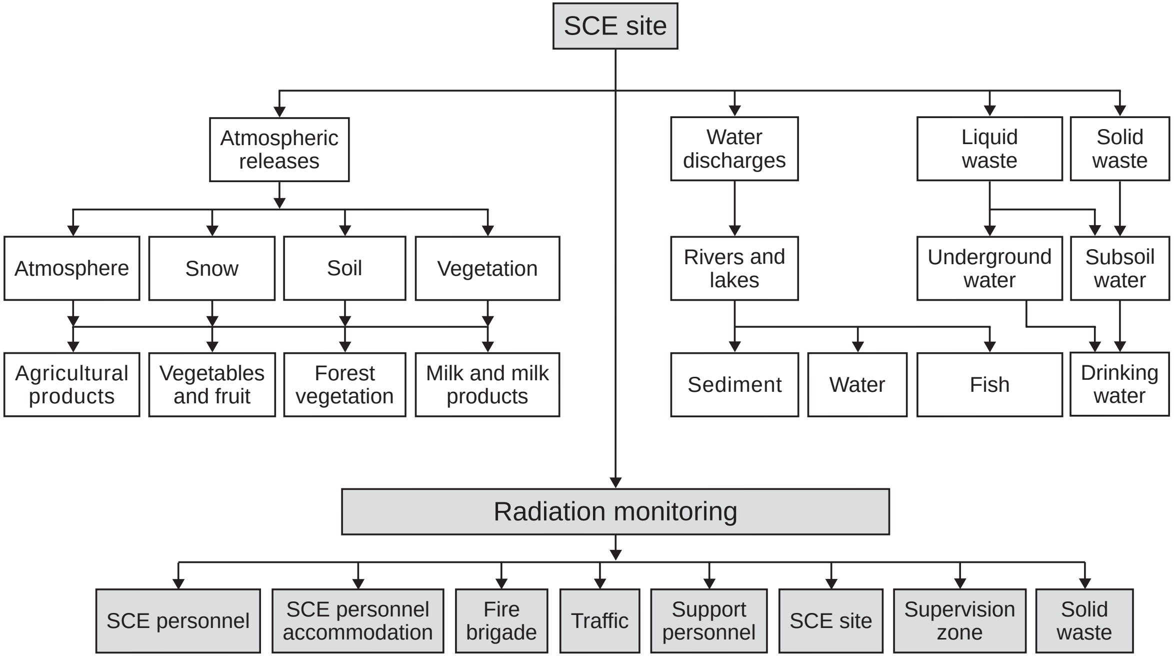


FIG. 3. Sources of radioactive contamination from the SCE site and radiation monitoring activities.

2.5. RADIOLOGICAL ASSESSMENT CRITERIA IN THE RUSSIAN FEDERATION

In the Russian Federation, the protection criteria for people living in the vicinity of a nuclear plant and exposed to standard operating conditions are based on dose limits [2]. The value used is the maximum value of the average individual equivalent dose in a calendar year for the most-at-risk group (the critical group), such that within a period of 70 years continued exposure of that group at the dose limit would not result in any changes in health that could be detected by up-to-date medical examination techniques. The dose limit specified for the whole body, gonads and red bone marrow is 5 mSv; for muscle, thyroid and other organs, it is 15 mSv; and for skin, bone tissue, hands, forearms, legs and feet, 30 mSv. On the basis of these limits, thresholds have been set that are applicable to permissible dose rate, particle flux density, contamination of skin, clothes and surfaces, activity in the body from inhalation and ingestion and activity concentration in ambient air.

The authorized State bodies can specify the reference values for each of these types of measurements in different radiological situations so that the limits are not exceeded. If conditions occur in which exposure to the public could exceed the dose limits, then provisions must be made to minimize this exposure. For instance, under the criteria established for an accident at a nuclear power plant [3] children and pregnant women would be evacuated if the dose ranged between 20 and 250 mSv and there would be total evacuation of the population for doses in the range between 50 and 500 mSv over a ten day period. Preventive treatment with iodine would be introduced for children and pregnant women with doses to the thyroid between 20 and 250 mSv within 10 days, or for the whole population if the dose is in the range 50 to 500 mSv. Relocation would be carried out when the dose ranges from 50 to 500 mSv within a one year period, dependent upon local conditions. Monitoring of foodstuffs would take place if the expected dose to the whole body of people consuming local food is between 5 and 50 mSv (or from 5 to 500 mSv for separate organs) during the first year.

After the accident at Chernobyl, the general international levels [4] and the derived levels for permissible concentrations of caesium and strontium radionuclides in foodstuffs were specified, together with regulations on the permissible contamination of inhabited areas within specified time periods [5].

2.6. RADIOLOGICAL SITUATION PRIOR TO THE ACCIDENT

2.6.1. Radioactive releases from SCE

As might be expected, the radiological situation at SCE and in the surrounding area has been influenced by the operations carried out on the site over the past decades. These operations have resulted in radioactive effluent being released into the atmosphere and liquid waste being discharged along the dry river bed of the Romashka, which eventually finds its way into the river Tom.

Measures have been taken over the past twenty years to gradually reduce the levels of radioactive material released into the environment from SCE. Since 1993, the releases have been below the permissible threshold values. These measures have included the upgrading of water drainage and sewage plants, the underground burial of liquid waste, the closure of reactors and the closure of some production lines.

2.6.2. Ground contamination

Although releases in waste water and to the atmosphere have been reduced in recent years, soil contamination to the north of SCE with the long lived radionuclides ^{137}Cs and ^{90}Sr significantly exceeded the total radioactive fallout levels typical for this latitude of the northern hemisphere [6, 7]. The contamination levels are shown in Fig. 4 as a function of distance in a northerly direction from SCE. The average values in the villages are about 1.0 kBq·m^{-2} and 0.15 kB·m^{-2} for ^{137}Cs and ^{90}Sr respectively. The distributions of contamination due to these two radionuclides in Georgievka, the village most affected by the accident, are shown in Fig. 5.

Between 1989 and 1992, the average concentrations of ^{137}Cs and ^{90}Sr were less than 0.58 Bq·L^{-1} and 0.26 Bq·L^{-1} respectively in milk from the villages in the Supervision Zone, and less than 0.33 Bq·kg^{-1} and 0.097 Bq·kg^{-1} in potatoes. These values are similar to those found in other regions of Siberia during this period.

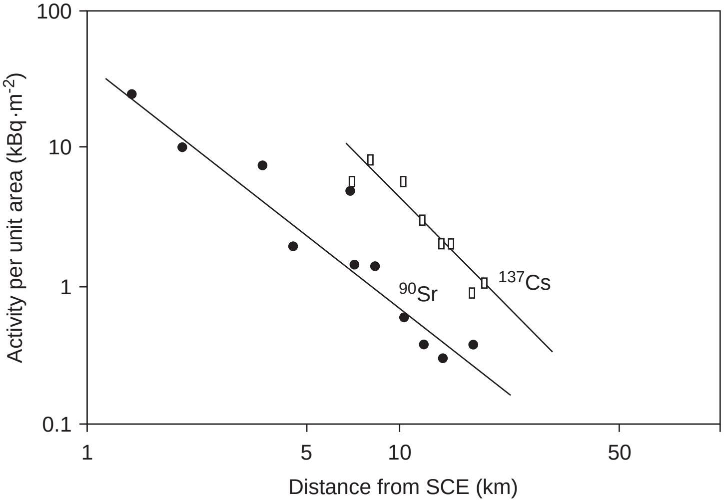
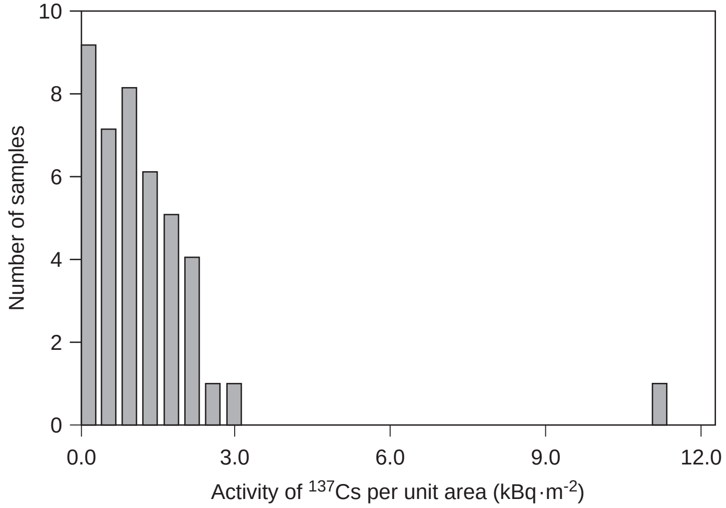


FIG. 4. Soil contamination in 1993 due to ^{137}Cs and ^{90}Sr as a function of distance to the north of SCE.



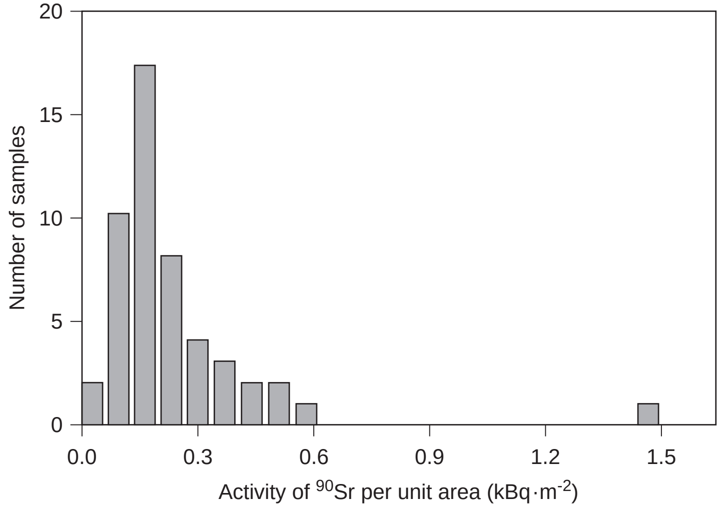


FIG. 5. Distribution of the contamination at Georgievka due to ^{137}*Cs and* ^{90}*Sr.*

Additional information on ^{137}Cs and ^{90}Sr activity in produce from the Supervision Zone is given in Table I.

There were some local ‘hot’ spots outside of SCE due to contamination of the soil with ^{239}Pu [8]. However, there were insufficient data available to make any detailed estimates of the degree of this contamination. Some idea of the levels can be gathered from measurements which were made in 1992 in the villages within the Supervision Zone. These showed a maximum activity concentration of ^{239}Pu of 0.029 Bq·kg^{-1} in grass and a maximum activity per unit area of 0.2 Bq·m^{-2} over snow.

TABLE I. ACTIVITY IN GRASS, MILK AND POTATOES PRODUCED IN THE SUPERVISION ZONE BETWEEN 1989 AND 1992

		Activity parameters					
	Radio-nuclide	Grass		Milk		Potatoes	
	q	N	P	N	q	N	
1989	Cs-137	2.0	11	0.15	10	0.15	7
	Sr-90	1.4	11	0.027	10	0.038	7
1990	Cs-137			0.030	8	0.05	9
	Sr-90			0.015	8	0.042	9
1991	Cs-137	1.0	10	0.059	9	0.05	5
	Sr-90	0.9	10	0.024	11	0.024	5
1992	Cs-137	0.31	7	0.033	8	≤0.037	7
	Sr-90	1.8	7	0.027	7	0.057	7

Note: N is the number of samples;
q is the mean activity concentration in grass and potatoes ($Bq \cdot kg^{-1}$);
P is the mean activity concentration in milk ($Bq \cdot L^{-1}$).

2.6.3. Atmospheric contamination

The average annual activity concentration of the major long lived radionuclides ^{137}Cs and ^{90}Sr in the atmosphere varied between 0.037×10^{-4} and 0.19×10^{-4} $Bq \cdot m^{-3}$ and between 0.015×10^{-4} and 0.26×10^{-4} $Bq \cdot m^{-3}$, respectively. The activity concentration of ^{95}Nb was below 7.4×10^{-6} $Bq \cdot m^{-3}$ while those for other radionuclides such as ^{103}Ru, ^{106}Ru, ^{144}Ce, ^{131}I and ^{95}Zr were below the detection thresholds of the instruments used to carry out the measurements (these ranged from 1.0×10^{-6} $Bq \cdot m^{-3}$ for ^{103}Ru to 1.1×10^{-2} $Bq \cdot m^{-3}$ for ^{131}I). These figures are similar to those measured in later years and are generally below the permissible values adopted by the Russian Federation [2] for these populations.

Overall, these figures, together with a measured external dose rate in the villages of between 0.08 and 0.16 $\mu Gy \cdot h^{-1}$, show that the radiological situation in the Supervision Zone prior to the accident was stable and did not exceed the radiation standards [5] laid down by the Russian Federation.

3. FUEL REPROCESSING AT THE RADIOCHEMICAL WORKS

3.1. THE REPROCESSING FACILITY

Reprocessing of uranium and plutonium is carried out in Building 201 of the Radiochemical Works (RCW) at SCE. The reprocessing procedure starts with the loading of irradiated standard uranium blocks into the plant and their dissolution in concentrated nitric acid. The resulting solution is then transferred to another vessel where it is prepared for extraction by adjusting the acidity and temperature. This may in some cases involve the addition of material that has already been through part of the reprocessing cycle. Compressed air is used to ensure mixing of the liquids so that separating out does not occur; this is essential if an energetic reaction between the nitric acid and the solvent is to be avoided. After this preparation stage, the solution is passed along the reprocessing line for solvent extraction using tributylphosphate (TBP) in a light hydrocarbon dissolver. The selective transfer of uranium and plutonium to the TBP occurs in a series of mixer–settlers, with the fission products, such as caesium and strontium, remaining in the aqueous solution. The two liquids are then allowed to separate, with the organic solvent passing on for further processing to separate the uranium and plutonium from each other.

This method of extraction has some disadvantages. TBP decomposes to form dibutylphosphate (DBP), monobutylphosphate (MBP) and phosphoric acid when exposed to nitric acid and ionizing radiation. The resulting products form colloidal suspensions in the organic phase and decrease the efficiency of the purification process and, together with stable emulsions in aqueous solution, form sediments at the phase boundary. These products are removed from the extractant by soda-alkali washing after each cycle so that the solution can be reused. About 3–4 mg of DBP per litre of extractant is left behind after washing and a point is eventually reached when the decomposition products accumulate to such an extent that the resulting decrease in efficiency requires the organic solution to be removed for recovery or storage. A flow diagram showing the steps used in the reprocessing procedure is given in Fig. 6.

3.2. INSTALLATION AD-6102/2

Building 201 contains two reprocessing lines with the plant situated in equipment rooms and the vessels located in a series of cells below ground level with 2 m thick concrete walls and a concrete roof; one such line is shown diagrammatically in Fig. 7. The accident took place in the southern branch of the facility in Installation

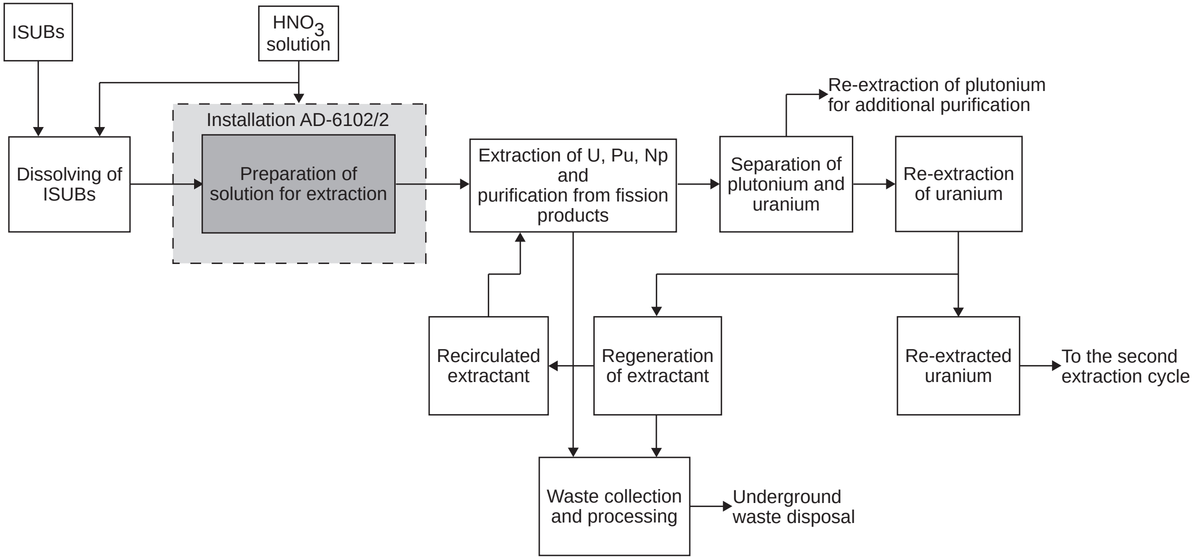


FIG. 6. *Flow diagram showing the steps in the reprocessing procedure (ISUB — irradiated standard uranium block).*

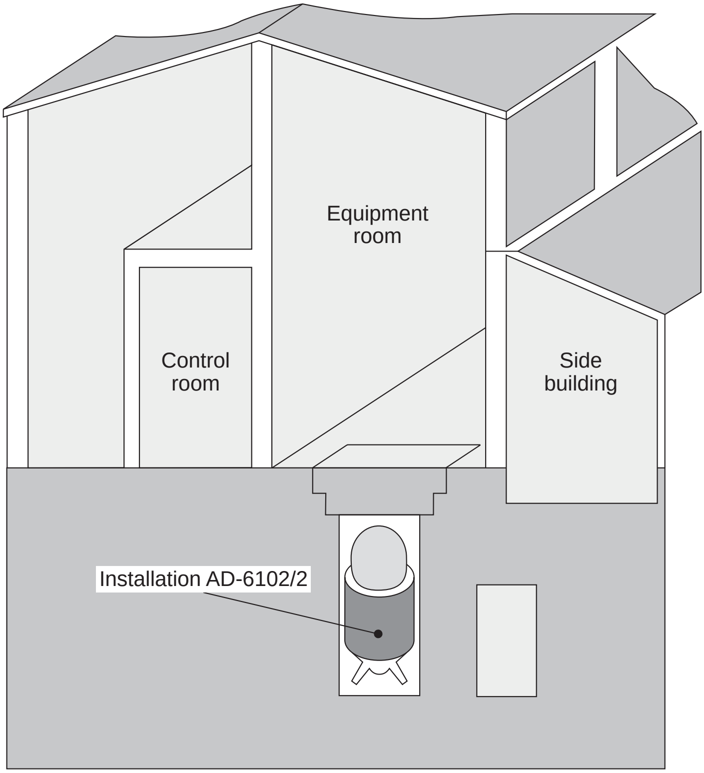


FIG. 7. Schematic diagram of Installation AD-6102/2 in relation to other parts of Building 201.

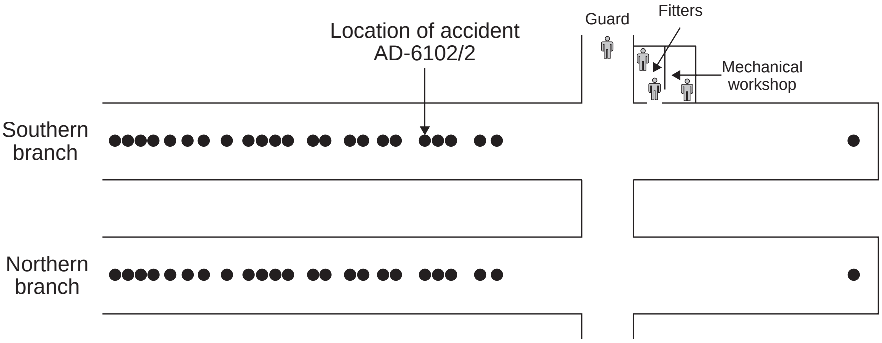


FIG. 8. Location of Installation AD-6102/2 in Building 201 at the RCW, where the accident occurred.

AD-6102/2, a vessel used to prepare the solution prior to reprocessing. Figure 8 shows the position of this installation relative to the other vessels in Building 201, together with the location of personnel who were in the building at the time of the accident. Installation AD-6102/2 comprised a stainless steel vessel with a volume of 34 m^3 incorporating a steam heating and cooling sleeve, and was fitted with a number of sensors for process control. These sensors included two level indicators, a thermometer, a 'PIT OPEN' warning device, a pressure transducer, a flow rate transducer for bubbling control and radiometric control sensors.

4. THE ACCIDENT AND ITS CAUSE

4.1. CONTENTS OF INSTALLATION AD-6102/2 AT THE TIME OF THE ACCIDENT

At the time of the accident, the contents of Installation AD-6102/2 had been prepared for reprocessing by adjusting the temperature of the solutions to between 45 and 50°C and correcting the acidity to give a value of 90 $g \cdot L^{-1}$. A set of routine measures were normally undertaken to ensure that safety was not compromised during the preparation stage. These included checking the specification of the nitric acid, and monitoring organic deposits that had accumulated in the aqueous solution settlers and periodically removing them. Compressed air (flow rate 50 $m^3 \cdot h^{-1}$) was passed through the solution to ensure a uniform temperature and concentration of nitric acid and air was continuously bubbled through the solution (flow rate greater than 20 $m^3 \cdot h^{-1}$) to dilute the gaseous products.

When the accident occurred, the vessel contained the following solutions:

- Product 401e — cooled nitric acid solution which had been prepared containing uranium and plutonium, ready for the second cycle of extraction. This component is a mixture of high level (Product 903v) and low level (Product 422n) radioactive waste from the first extraction cycle which also contains organic materials;
- Product 166 — uranium concentrate that had already been through one extraction cycle and which had been loaded into the installation in two batches;
- Product 2z — concentrated nitric acid.

These solutions contained a total of 449 g of plutonium and 8757 kg of uranium which, assuming specific activities of 2.3 $TBq \cdot kg^{-1}$ and 12.4 $MBq \cdot kg^{-1}$ for the two elements, corresponds to total activities of 1.0 TBq and 0.11 TBq,

TABLE II. CHARACTERISTICS OF THE SOLUTIONS IN AD-6102/2

	Vol. (m^3)	Mass concentration					Relative gamma activity (%)				Beta activity ($Bq \cdot L^{-1}$)	Organics
		Pu ($mg \cdot L^{-1}$)	U ($g \cdot L^{-1}$)	HNO_3 ($g \cdot L^{-1}$)	Th ($mg \cdot L^{-1}$)	Np ($mg \cdot L^{-1}$)	Cs	Ru	Zr	Nbs		
401e	4	16.6	37.4	94.5	35.5	62	2	25	16	57	4.8×10^9	+
166	19.5	19.6	441	30	—	—	—	27	43	30	4.1×10^7	—
2z	1.5	—	—	896	—	—	—	—	—	—	—	—

respectively. The total beta activity was 0.02 PBq, a figure obtained from measurements made on the products as they were introduced into the installation. Further details on the characteristics of these solutions are given in Table II [9, 10].

4.2. CHRONOLOGY OF THE ACCIDENT

The accident occurred at 12:58 on 6 April 1993. The procedures carried out during the immediately preceding days had a bearing on the accident and its causes so they are described here. On 1 April, Installation AD-6102/2 was completely emptied. The facility was then recharged and the solutions prepared as described in the following sequence of events:

1–6 April	41 m^3 of Product 903v and 74 m^3 of Product 422n were prepared for extraction as Product 401e.
6 April	Two batches of Product 166 with a total volume of 19.5 m^3 were added to the 4 m^3 residual volume of Product 401e.
05:30	First batch of Product 166 (12 m^3) added.
09:30	Second batch of Product 166 (7.5 m^3) added.
10:30	1.5 m^3 of HNO_3 (concentration 14.2 $mol \cdot L^{-1}$) were added to prepare for extraction.
12:00	Data from pressure transducer showed that the pressure within the installation was starting to rise.
12:40	Start of shift change. Staff on the new shift noticed red smoke coming out of the vent tube near Building 201 although none of the processes involved the release of nitrogen oxides.

12:50 Operators informed the engineer-in-charge that a pressure rise was occurring. The pressure was found to have reached 2.0 atm and was still rising. The engineer ordered depressurization of Installation AD-6102/2 through the processing lines of the adjacent plant. However, this operation did not reduce the pressure significantly.

12:55 Pressure was continuing to increase and had reached 5.0 atm.

12:58 Installation AD-6102/2 ruptured and several seconds later there was an explosion. Flames were observed on the roof of the building.

Directly following the accident, the radiation monitoring warning system was activated, and personnel donned breathing apparatus (Lepestok type) stored near their places of work. All the people in Building 201 were gathered together in a safe area and informed about the situation. Those not involved in urgent operations were ordered to evacuate the RCW compound. The immediate response to the accident was rapid and effective. The fire brigade arrived within two minutes of the accident and extinguished the fires on the roof and in the equipment room within ten minutes. No injuries were sustained by any of the personnel in the building or by the firemen who came to the scene.

The high levels of radiation dose rates and contamination combined with unsafe structural conditions within the building made it impossible to gain direct access to the site of the accident. However, it could be seen from a distance that a considerable amount of damage had been sustained both by the cell and by the equipment room above. The slabs covering the cell had been displaced and the ceiling of the equipment room had been partially destroyed and had fallen across the cell. Blackening and blistering on the walls showed that the explosion had affected several metres to the left and right of the cell housing Installation AD-6102/2. Some of the windows had been blown out and some side panels had been dislodged, including those at the end of the room farthest away from the explosion. Power for lighting and instrumentation had been cut and the heating system had been destroyed. Photograph 1 gives a view of Building 201 showing clearly the holes in the side walls caused by the explosion.

A visual examination of the cell containing the vessel was impossible, and therefore no immediate assessment could be made as to how much solution had escaped or how badly Installation AD-6102/2 had been damaged.

4.3. CAUSE OF THE ACCIDENT

The cause of the accident was most likely a lack of the compressed air needed to ensure that the solutions were thoroughly mixed. According to the chief operator, compressed air was being used to mix the solutions; however, sensor measurements indicated that most probably none was being introduced into the vessel. Whether this

Photo 1. View of Building 201 after the accident.

absence of compressed air was due to operator error or plant failure is not clear, but investigators considered the former to be the more likely. However, what is apparent is that at the time the nitric acid was being introduced to adjust the acidity, there was not enough air to cause the necessary mixing of the solutions. Under these circumstances the solutions could have settled out into different layers as shown in Fig. 9, allowing the oxidation and nitration of the organic layer by the nitric acid. This ‘red oil reaction’ is a well known phenomenon when these types of solvent are used in extraction processes. It would seem most likely that the reactions occurred with the more concentrated nitric acid solution in the upper layer. This assumption is supported to some degree by the lack of noticeable pressure rise until approximately one hour and a half after the nitric acid solution had been introduced into the vessel.

As the oxidation of organic substances by nitric acid is autocatalytic, the rate of gas release would have increased and, because the reaction is also exothermic, would have been accompanied by a rise in temperature. Eventually, some two hours and a half after the introduction of the nitric acid, a point was reached when the amount of gas generated was more than could be vented through the stack, and attempts were made to depressurize the vessel via adjacent installations. These were unsuccessful and the pressure continued to rise until it reached about 5 atm. Within a few minutes, the pressure rose very rapidly to about 18 atm and the vessel ruptured.

The resulting shock wave was sufficiently intense to raise and displace the concrete slabs forming the roof of the cell as well as cause damage to the equipment room

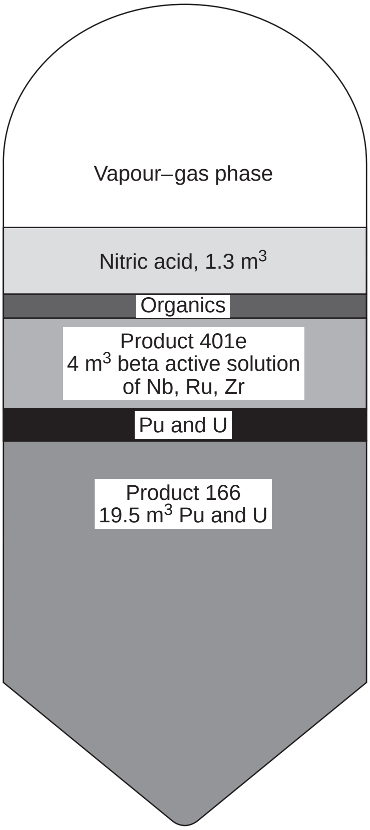


FIG. 9. Assumed layering of the solutions in Installation AD-6102/2 at the time of the accident.

above. Some of the organic material was released in the form of steam and small droplets and some was probably oxidized to form gaseous products. A localized explosion of this inflammable cloud then occurred either as a result of a spark or because of the prevailing high temperature of about 450°C.

An estimation of how much organic solution was in the vessel and whether enough of it was available to produce a sufficient amount of gas to rupture the vessel has proved difficult. Experimental data on two-phase systems utilizing the irradiated extractant, uranyl nitrate, in organic phase and nitric acid (concentration 10–12 mol) in aqueous phase indicate that gas would have been released at the temperature prevailing in the vessel. However, without a knowledge of the quantity of organic material present, no reliable predictions can be made of the resultant pressure rise. Calculations have shown that in order to generate the pressure of 18.0–20.0 atm [11] needed to rupture the vessel, the oxidation of 35–40 L of the organic phase by nitric acid would have been required had the vessel been closed, and 3–5 times this amount had the gas been vented.

5. RADIOLOGICAL SITUATION AFTER THE ACCIDENT

5.1. INITIAL ASSESSMENT OF THE SITUATION

The main release of radioactive material to the environment took place through the large holes in the side walls and roof of Building 201. Some material was also released via the 150 m high vent tube, although the amount from this source is difficult to assess as the measuring equipment was incapable of coping with the high velocity at which the gas escaped. The release occurred while a steady southwesterly wind was blowing with a velocity of between 8 and 13 $m \cdot s^{-1}$, and consequently contamination was spread in a northeasterly direction towards relatively sparsely populated areas and away from the city of Tomsk and the town of Tomsk-7. Outside of the SCE site, the contaminated area consisted mainly of forest with about 100 ha of agricultural land used for crops. The main populated area directly affected by the fallout from the accident was the village of Georgievka, with a population of about 200. Fallout from the release was deposited onto a snow covered landscape with more snow falling during the afternoon on the day of the accident. The region experienced further intermittent snowfalls until the middle of May, by which time the snow had completely melted. During the release, the temperature was between –2.0 and –3.8°C, with between 67 and 80% humidity.

Immediately after the accident, seven survey teams from Tomsk-7 and ten from the Tomsk Region started making environmental measurements in the vicinity of SCE. These surveys were carried out using plans that had previously been drawn up to cope with emergency situations. Measurements were made of external dose rates and alpha and beta activity concentrations. Samples were also gathered for subsequent laboratory analysis.

More widespread monitoring was carried out using ground and aircraft based weather stations belonging to the Tomsk branch of the Hydrometeorological Service of the Russian Federation. Radiation dose rates were measured in 23 places and the radioactive fallout at 13; the atmospheric activity concentration was measured at the village of Kolpashevo. This service, together with those in the adjacent regions of Novosibirsk, Kemerovo and Krasnoyarsk, took measurements every hour so that any changes in the situation could be rapidly assessed. All information was passed to the

Commission on Emergencies of the Tomsk-7 and Tomsk regions, which continually assessed the situation and formulated appropriate responses so that the effects of the release could be localized and limited as much as possible. The rapid and effective actions taken in response to the accident meant that by the end of the first day it had been established that:

- The spread of radioactive material into the environment extended 8 km to the perimeter fence and a further 20 km beyond in a northeasterly direction;
- The effects of the accident were confined to the northeastern part of the Tomsk Region with no measurable contamination in adjacent areas;
- The contaminated area to the northeast of SCE had been surveyed and the 0.6 and 0.15 $\mu Gy \cdot h^{-1}$ dose rate contours defined;
- The contamination levels indicated that no urgent protective measures were needed in Georgievka;
- A 3 km length of the main road between Tomsk and Samus had been contaminated and required immediate action to restrict access and for decontamination.

5.2. EXTENT AND CHARACTERISTICS OF THE CONTAMINATION

Within a few days of the accident, the Hydrometeorological Service of the Russian Federation had verified the extent of the contaminated area using aircraft and ground gamma dose rate surveys along accessible routes at distances of from 7 to 25 km from RCW. The data obtained from these surveys were used to compile detailed maps of the contamination levels over the affected region. The maps showing data gathered on 12 and 13 April are given in Figs 10 and 11. The first was compiled using both aerial and ground surveys [12], while the second was taken from a ground survey along preset routes [10]. These surveys confirmed that the radioactive contamination extended to the northeast of SCE. They further showed that at a distance of about 7 km from the RCW there was a noticeable deflection of the contaminated area to the east, with another deflection northwards near Georgievka.

In two places there were areas of about 1 km^2 within which the external dose rate was considerably higher than elsewhere. The first was to the southwest of Nadezhda, where the external dose rate exceeded 1 $\mu Gy \cdot h^{-1}$, and the second to the north of Georgievka, where it was above 0.5 $\mu Gy \cdot h^{-1}$. There were also several local spots elsewhere in the contaminated area of between 100 and 160 m^2 where the external dose rate and beta flux density were between 5 and 7 times higher than the average values [11], and occasionally places with external dose rates up to 30 $\mu Gy \cdot h^{-1}$.

Another set of soil samples was taken on 6 May so that a general assessment could be made of the situation on the SCE site. These measurements showed that the

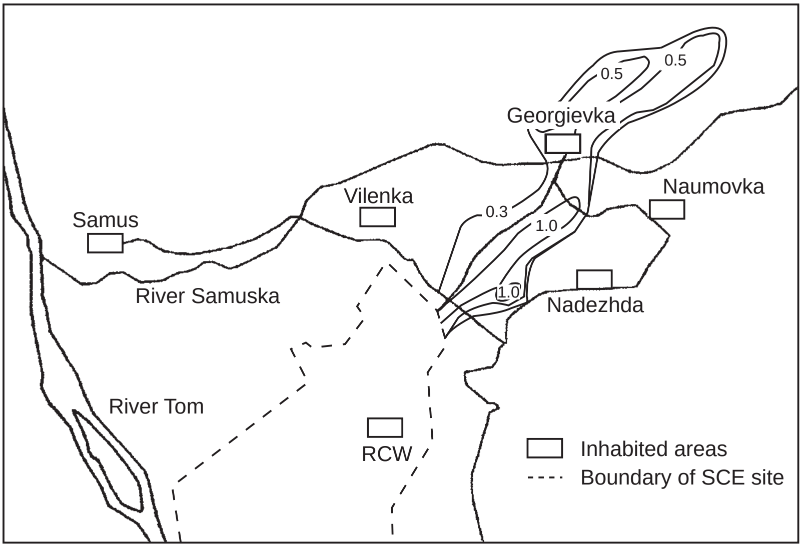


FIG. 10. Contaminated area showing external gamma dose rate contours derived from data taken on 12 and 13 April 1993: the numbers against the contours show the dose rate in μGy·h^{-1}.

total beta and gamma activity in these areas was 4.3 TBq, including 0.04 TBq of ^{103}Ru, 0.92 TBq of ^{106}Ru, 0.80 TBq of ^{95}Zr and 2.54 TBq of ^{95}Nb [13, 14]. Overall there was an area of 89 km^2 outside of SCE where the external dose rate exceeded 0.15 μGy·h^{-1} and, as shown in Fig. 12, there were two distinct maxima in the deposited activity (ground contamination) and external dose rate across the contaminated area (at right angles to the direction of the release) at distances of up to 12 km from the RCW. These can be explained if the releases originating from the roof and the walls of the RCW are combined and the wind directions at different heights (ground level 190 degrees and at 100–200 m height 210 degrees) are taken into account.

The area of land affected by the contamination fell rapidly with time as would have been expected from the half-lives of the radionuclides present, with the dose rates decreasing to a negligible level by the beginning of 1994. Table III shows how the area of land with an external dose rate falling within specified values decreased with time following the accident.

Variations in beta flux density on the soil surface were found to be substantially non-uniform, even over distances of less than 1 m. This can be explained by the presence of hot particles. Figure 13 shows changes in the ratio of beta flux density on the ground to external dose rate at a height of 1 m with time for the six month period after the accident. The average density distribution of the beta flux can be satisfactorily approximated using a log-normal distribution with a geometric standard deviation.

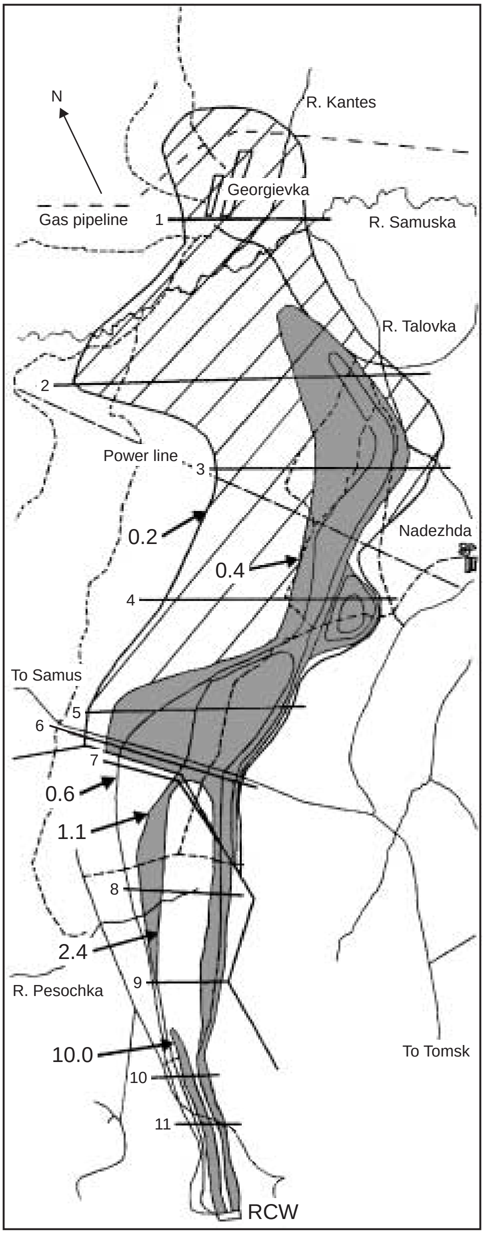


FIG. 11. Contaminated area showing external gamma dose rate contours derived from data taken on 13 April 1993. The numbers against the contours show the values in μGy·h^{-1}. The other numbers (1–11) indicate the survey routes.

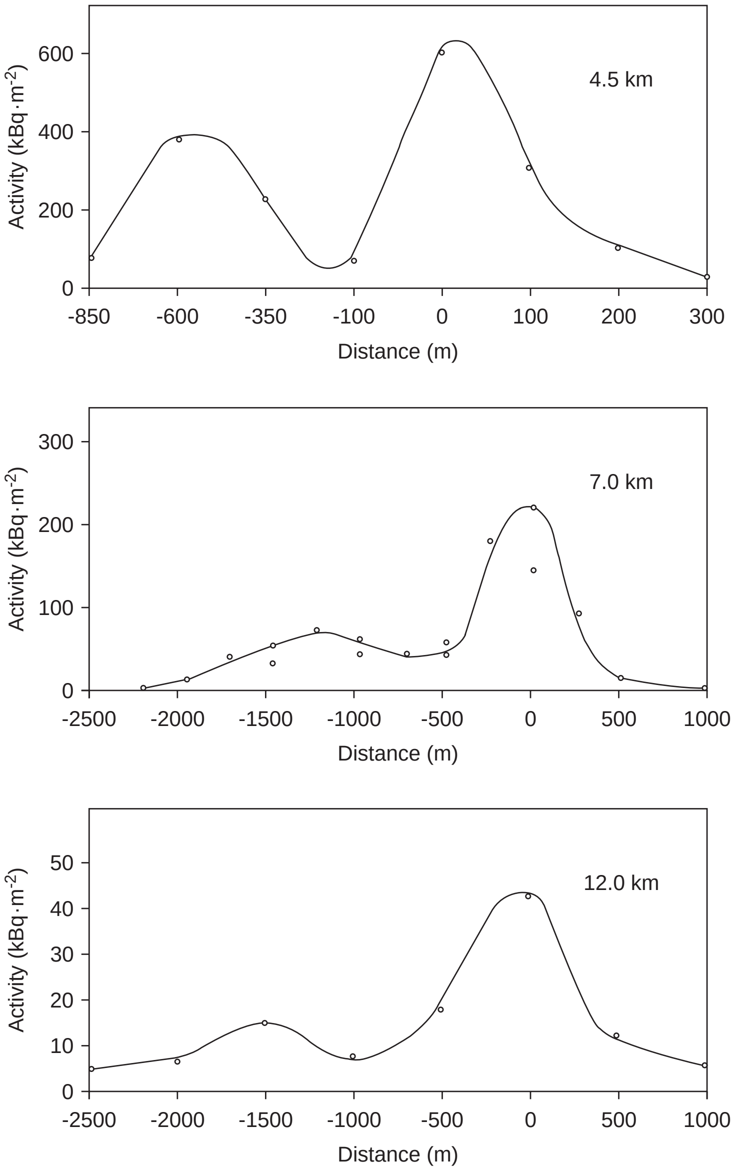


FIG. 12. Ground contamination due to ^{106}Ru across the path of the fallout at different distances from the RCW.

TABLE III. VARIATION OF CONTAMINATED AREA WITH TIME FOR DIFFERENT VALUES OF EXTERNAL DOSE RATE

External dose rate ($\mu Gy \cdot h^{-1}$)	Contaminated area (km^2)			
	13 May 1993	15 July 1993	12 Oct. 1993	15 Jan. 1994
0.20–0.40	23.0	20.0	10.7	0.0
0.40–0.60	5.0	6.3	2.2	0.0
0.60–1.10	3.0	1.6	0.2	0.0
over 1.10	2.0	0.6	0.0	0.0

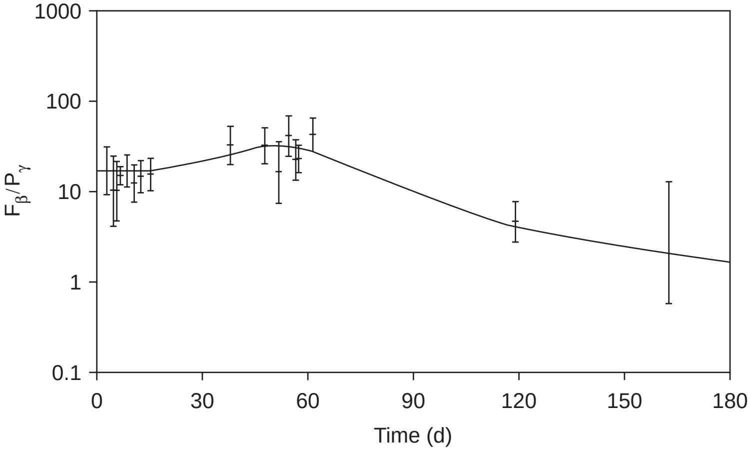


FIG. 13. Ratio of beta flux density on the ground to exposure rate at a height of 1 m, as a function of time after the accident.

5.3. RADIONUCLIDE COMPOSITION AND CHARACTERISTICS

During the six months following the accident, over 300 snow and soil samples were analysed to determine the radionuclide composition of the contamination [10, 12–16]. Gamma spectroscopy showed the presence of ^{103}Ru, ^{106}Ru, ^{95}Zr, ^{95}Nb and

TABLE IV. COMPOSITION AND HALF-LIVES OF RADIONUCLIDES IN THE FALLOUT FROM THE ACCIDENT

	Zr-95	Nb-95	Ru-103	Ru-106	Sb-125	Ce-141	Ce-144	Pu-239
% composition in fallout	20.4	44.0	1.4	31.4	0.4	1.5	0.9	0.01
Half-life	65 d	35 d	40 d	1 a	2 a	33 d	284 d	2.4×10^4 a

traces of ^{125}Sb, ^{141}Ce and ^{144}Ce in the snow samples. The alpha emitters ^{239}Pu, ^{234}U and ^{238}U were also detected, with about two thirds of the associated activity coming from ^{239}Pu and ^{240}Pu. Analysis of the suspended and soluble fractions of snow showed that more than 80% of the activity occurred in the suspended fraction [12]. The comparison between plutonium levels in snow and soil samples taken at varying depths showed that only 10–15% of the total activity present resulted from the accident, with the remainder attributable to long term operations at SCE [17].

The radionuclide composition of the contamination resulting from the accident did not vary substantially as the distance from the RCW increased, apart from that for ^{239}Pu, whose contribution to the total activity was higher nearer the release point. The percentage of the different radionuclides in the contaminated area resulting from the accident and the half-lives involved are given in Table IV. The composition of gamma and beta emitting radionuclides in the hot particles [16] that were extracted from soil samples did not differ significantly from that shown in Table IV.

In the year following the accident, more than 95% of the external dose rate and beta flux density were due to the release of ^{95}Nb, ^{95}Zr and ^{106}Ru, while in the second and subsequent years ^{106}Ru was dominant.

No direct measurements of aerosol size were carried out during the course of the release and deposition of the radioactive material. Nevertheless, the range of aerosol size under resuspension conditions and the solubility were investigated after the accident. It was concluded that the distribution of the beta/gamma activity with particle size could be approximated by a log-normal function with average values for aerodynamic median activity diameter (AMAD) of 20 ± 5.7 μm and for geometric standard deviations of 4.4 ± 1.6 μm. The estimated deposition velocity for all beta–gamma emitting radionuclides as well as for 65% of the ^{239}Pu varied between 0.15 and 0.2 $m \cdot s^{-1}$, while the remaining activity from the ^{239}Pu was associated with larger particles whose deposition velocity was estimated to be between 0.3 and 0.5 $m \cdot s^{-1}$ [12].

Migration of the radioactive particles was determined by dialysis in a Ringer solution using four samples collected in September 1993 from the vertical and horizontal surfaces of Building 201. The results of these tests showed that the aerosols from the release consisted mainly of the insoluble oxides of the radionuclides.

5.4. RADIOACTIVE CONTAMINATION OF THE ENVIRONMENT

5.4.1. Atmospheric contamination

Two fixed sampling posts, one at SCE and the other at Naumovka, were situated in the path of the activity released from the accident. Only ^{95}Nb could be measured in air sampled between 6 April and 8 April 1993 as the concentrations of the other radionuclides were below the detection threshold of the instruments. The activity concentration of ^{95}Nb measured on the SCE site rose from 1.5×10^{-4} Bq·m^{-3} before the accident to 1.5×10^{-3} Bq·m^{-3} immediately thereafter. By 19 April, the concentration of ^{95}Nb in the air had also fallen to below the detection threshold in both locations, and consequently the sampling posts were returned to their normal daily sampling procedures.

During May 1993, air was sampled and analysed from the contaminated area near the main road from Tomsk to Samus and at the village of Georgievka, 7 km and 16 km away from the RCW, respectively. These measurements enabled an assessment to be made of the atmospheric contamination caused by resuspension due to the wind [15]. The average total activity concentration in the most contaminated area of the Tomsk–Samus trunk road was 0.16 Bq·m^{-3}, of which 3.7×10^{-4} Bq·m^{-3} was due to ^{239}Pu. At Georgievka, apart from ^{239}Pu with an average concentration of 3×10^{-5} Bq·m^{-3}, the radionuclides were below the threshold of the detectors. The resuspension coefficient due to the wind estimated from these data was 2×10^{-7} m^{-1}, which is in good agreement with the results obtained at Chernobyl a few weeks after the accident there [18].

5.4.2. Surface water contamination

Water samples (volume 0.5–3 L) were taken from the Pesochka, Samuska and Tom rivers and analysed using gamma spectrometry and by separation using filters and ion exchange units [10]. Measurements of contamination levels made between 10 April and 12 May on Samuska and Pesochka river samples were below 3.0×10^{4} Bq·m^{-3}, the minimum detectable level of the equipment.

The variation in total beta activity concentration in water samples measured at the SCE outflow into the Tom river showed an immediate increase after the accident, with a return to normal values by 18 April. A smaller rise did occur, however, towards the end of the month. Measurements carried out in the vicinity of Chernilshchikovo were less clear. There was no substantial rise directly after the accident, although one

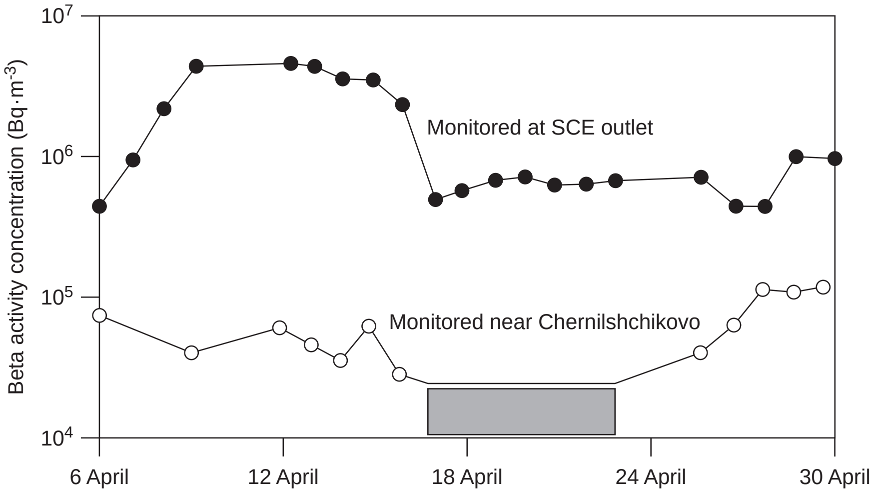


FIG. 14. Total beta activity concentration measured in water from the Tom river during April 1993. The shaded area indicates a beta activity below 2×10^4 Bq·m^{-3} from 17 to 23 April.

was registered towards the end of April. This mirrors the results of the SCE outflow, as does the clear drop in activity below the detector threshold from 18 April. The results obtained from these measurements are shown in Fig. 14.

Gamma spectrometry measurements were made over two 14 day periods during April 1993 to determine the activity of individual radionuclides in water from the Tom river. The results from water sampled at the SCE outflow into the Tom all showed a substantial drop from the first to the second period, apart from ^{144}Ce, which remained below the detection limit. The measurements at Chernilshchikovo are again less straightforward, with rises in the activity of some radionuclides between the two periods, even though a decrease in ^{106}Ru activity was observed.

5.4.3. Contamination of forested areas

The contamination of the forested areas with radionuclides released from the accident [10] was, as might be expected, of the same composition as that deposited onto the ground. If the relative areas of forest and phytomass specific to the region are taken into consideration, then an estimated 25–30% of the activity from the fallout was deposited onto the forest canopy.

5.5. ASSESSMENT OF TOTAL ACTIVITY RELEASED

Two methods of estimating the amount of radioactive material released during the accident were considered. The first was a comparison of the quantity of alpha and beta emitting radionuclides in Installation AD-6102/2 before and after the accident. According to the technical documentation issued after the enquiry [9], immediately prior to the accident the installation contained 449 ± 120 g of plutonium and 8757 ± 286 kg of uranium. In the subsequent cleanup operations, 577 ± 117 g of plutonium and 8707 ± 350 kg of uranium were collected from the installation and the cell in which it was located. From these figures, it can be seen that not all of the material recovered during the cleanup could have been released from the vessel during the accident. The discrepancy could be explained by assuming that some of the material recovered after the accident originated in previous extraction cycles. Moreover, the estimates of the amount of plutonium and uranium deposited in the contaminated area were also somewhat higher than the amounts in Installation AD-6102/2 prior to the incident.

Because of these discrepancies, a second method was used, based on extrapolations derived from the levels of contamination measured in and around SCE. Two models were used: the first assumed that the migration and fallout processes associated with the release could be described by a Gaussian model with a release period of 15 min [13], and the second, by a Gaussian model with instant release [17], the methodology for which is described in Ref. [19].

The first model incorporated measurements of the radionuclide content taken from 11 snow samples, while the second model used measurements from 120 snow and soil samples taken from 16 profiles across the area. The release was represented

TABLE V. ESTIMATED ACTIVITY (TBq) RELEASED DURING THE ACCIDENT

	Model 1	Model 2
Ru-106	11.1	7.9
Ru-103	0.37	0.34
Nb-95	17.4	11.2
Zr-95	7.8	5.1
Ce-141	—	0.37
Ce-144	—	0.24
Sb-125	—	0.10
Pu-239	7.4×10^{-3}	5.2×10^{-3}
Total	36.7	25.3

as originating in two places: the first through breaches in the walls at a height of 15–30 m, which accounted for 50–60% of the activity released, the second coming from the roof at a height of 100–150 m. Table V gives estimates of the amounts of different radionuclides derived from these two models.

The two models give fairly similar results, with an average value for the total activity of all material released of about 30 TBq. These figures show that a substantially higher amount of activity was released than the early estimates of about 0.15 TBq of beta/gamma emitters.

5.6. ORGANIZATION OF RESPONSES TO THE ACCIDENT

During the first 24 hours following the accident, the response was organized by SCE personnel working in conjunction with the regional authorities and using existing emergency procedures. After this initial response a joint committee headed by E.I. Mikerin was set up by the Ministry for Nuclear Energy on 7 April to examine the causes of the accident and to formulate measures to limit its effects. This committee worked at SCE from 8 to 17 April 1993 and announced its findings [9] at a press conference held on 20 April. In parallel, a commission led by V.A. Vladimirov was established to comply with the State requirements in an emergency situation. This commission was charged with controlling and co-ordinating activities in the area outside of the SCE site [20]. Set up on 6 April, the commission worked in the area from to 13 April 1993. Additional information was also made available in 1993 on the radiological situation outside of the SCE site and on aspects of radiation safety [13, 21].

The Government of the Russian Federation also asked the IAEA to provide assistance in assessing the radiological, health and environmental impacts associated with the accident. Consequently a mission team from the IAEA visited the area on 15 and 16 April 1993.

6. SCE SITE

6.1. RADIOLOGICAL SITUATION ON THE SCE SITE

The damage caused to Installation AD-6102/2 resulted in contamination not only to Building 201 in which it was situated but also to the surrounding buildings and land within the SCE site. Figures 15 and 16 illustrate the surface contamination levels and dose rates around the RCW buildings, and clearly point to the source of the contamination.

6.1.1. Gamma radiation

Measurements taken one hour and a half after the accident showed that the gamma radiation dose rates were between 48.6 and 209 $mGy \cdot h^{-1}$ close to the point of the accident and between 201 and 360 $mGy \cdot h^{-1}$ on the roof of the building. On the road to the north of Building 201 and on adjacent grassed areas they reached 10.8 $mGy \cdot h^{-1}$. As expected, because of the wind direction, these values were considerably higher than the 0.54 $mGy \cdot h^{-1}$ measured on the road to the south of the building. In places at the perimeter fence around the RCW the dose rates were up to 21.6 $mGy \cdot h^{-1}$, while farther away the levels dropped from 180 $\mu Gy \cdot h^{-1}$ down to 2.9 $\mu Gy \cdot h^{-1}$ at a distance of 7 km.

6.1.2. Beta contamination

Measurements showed that surface beta contamination near Installation AD-6102/2 exceeded 50 000 $counts \cdot cm^{-2} \cdot min^{-1}$ in places. No direct measurements were made of radionuclide concentrations in the atmosphere at the time of the accident but indirect estimates and those taken two hours after the explosion showed beta activity from aerosols of up to 100 $Bq \cdot L^{-1}$ near Installation AD-6102/2, but less than 10 $Bq \cdot L^{-1}$ in other locations [9]. Beta activity levels measured in Building 201 during the removal of building debris were about 800 $Bq \cdot L^{-1}$ where people were working on the roof, but below 1.6 $Bq \cdot L^{-1}$ in the rooms, 0.6 $Bq \cdot L^{-1}$ in passageways and 1.4 $Bq \cdot L^{-1}$ in the area surrounding the building.

6.1.3. Alpha contamination

The measured levels of alpha contamination in Building 201 were less than 5 $counts \cdot cm^{-2} \cdot min^{-1}$, no more than the values recorded prior to the accident, and were within the permissible limits for the continuous occupation of industrial premises [2].

6.2. ALLEVIATING THE EFFECTS OF THE ACCIDENT ON THE SCE SITE

A set of programmes was drawn up and implemented by the staff at SCE to deal with the consequences of the accident. In the implementation of these programmes the protection of personnel was considered to be of paramount importance and the procedures stipulated in The Basic Sanitary Regulations for Handling Radioactive Substances and Other Ionizing Radiation Sources [2] were followed. An assessment of the radiological situation indicated that the cleanup operations could be carried out without exposing staff to radiation doses above 50 mSv [2], the annual dose limit specified for normal working conditions. Regular dosimetric monitoring of personnel

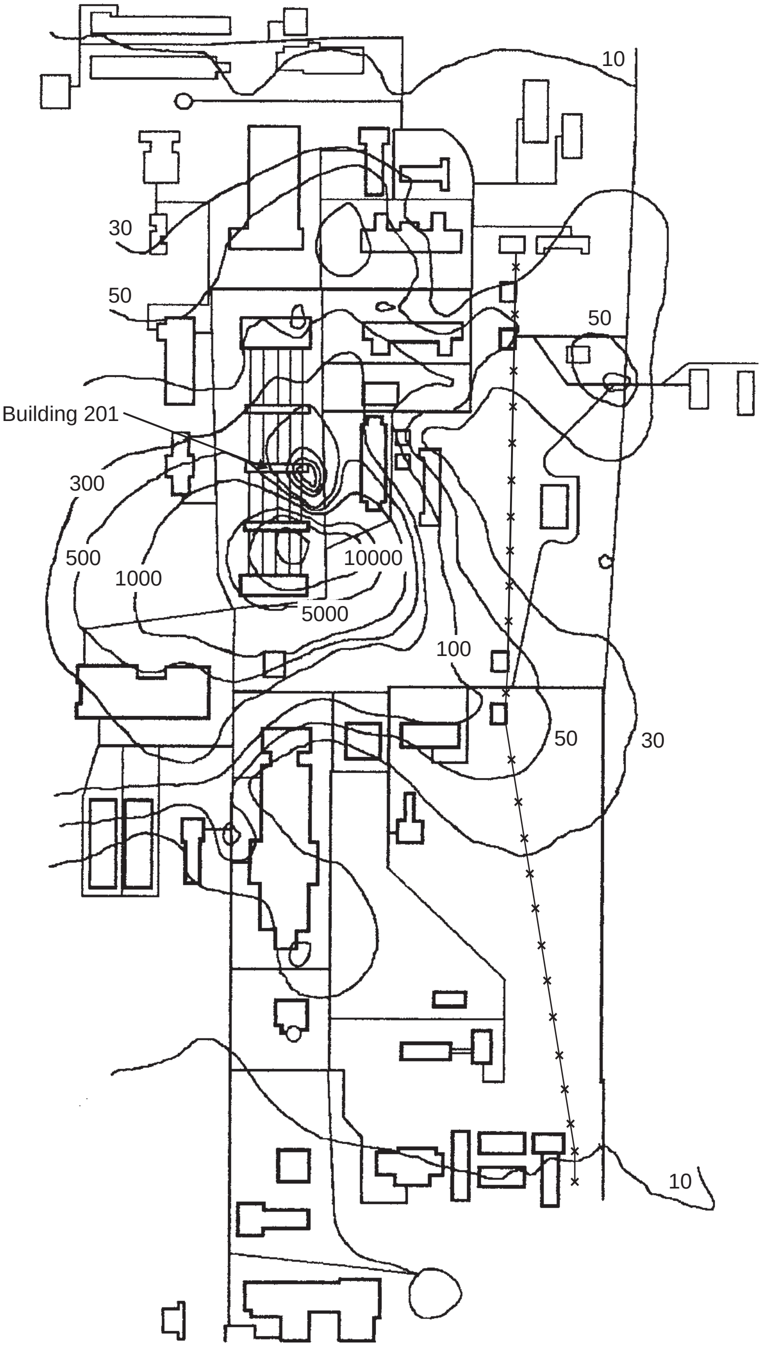


FIG. 15. *Surface contamination at SCE on 6 April 1993 (counts·cm^{-2}·min^{-1}).*

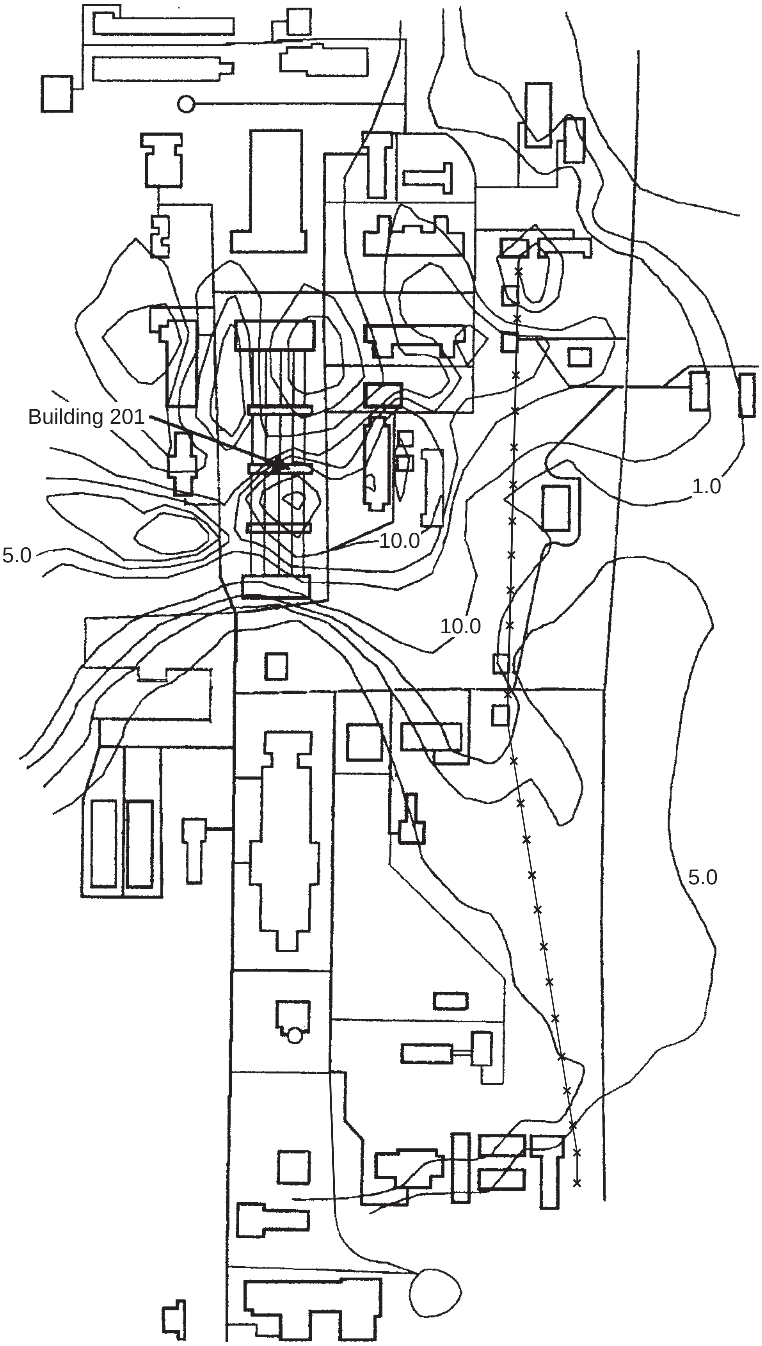


FIG. 16. External dose rates ($\mu Gy \cdot h^{-1}$) at SCE on 6 April 1993.

TABLE VI. MEASURES INTRODUCED TO ENSURE RADIATION SAFETY AT THE RCW

	Time-frame
Fencing off contaminated areas and evacuating personnel	Immediately after explosion
Radiological monitoring of personnel involved in the accident	6 April 1993
Checking position of people at the time of explosion	6 April 1993
Monitoring and decontamination by washing: — personnel — fire-fighting equipment	6 April 1993
Examination of personnel using whole body counters	6–7 April 1993, then regularly
Checking radiation and emergency warning systems	6–7 April 1993
Assessment of local radiological situation	After explosion on 6–7 April 1993, then daily
Checking power supplies and control systems in the affected area	6–7 April 1993
Drawing up plans for decontamination of rooms, equipment, roof, etc.	7 April 1993
Analysis of gas release filters in Building 205	Twice daily
Monitoring surrounding area, trunk roads and vehicles	Regularly
Radiation monitoring of rain water and special sewage systems	Regularly

and estimates of incorporated activity were carried out to ensure that personnel were not exposed to radiation doses above those specified by the State sanitary inspection services.

All cleanup operations were carried out using permission to work procedures appropriate for a serious radiological situation, with the documentation for each task specifying location, appropriate safety measures, safety equipment and clothing to be used, the team members and a responsible person. The protective clothing and apparatus used were dependent upon location, type of operation and climatic conditions.

Three main programmes were rapidly introduced to limit as much as possible the spread of radioactive contamination and to ensure that dose levels to staff were reduced to a minimum. The objective of the first programme, approved on 6 April, was to clean up the accident area to help reduce as much as possible the probability of spreading further contamination. This programme included the removal of all processing liquids so that the equipment could be made safe and washed down. An optical system was used to inspect the damage to Installation AD-6102/2 and to help determine the sequence of events which led to its destruction.

The second programme was set up to ensure the safety of personnel working at the RCW during the cleanup operations and the restoration of the damaged buildings. This programme was also approved on 6 April and involved the series of measures listed in Table VI.

Some of these measures were specifically introduced to monitor the radiological situation with time: the daily assessment of the local radiological situation; the monitoring of the surrounding area and trunk roads; regular examinations of personnel using whole body counters; and the monitoring of surface contamination on vehicles and roads. In addition, the outflows from the contaminated sewage and rainwater systems were monitored, the gas cleaning filters were analysed and machinery, power supply equipment and instruments were checked regularly. The dosimetry and

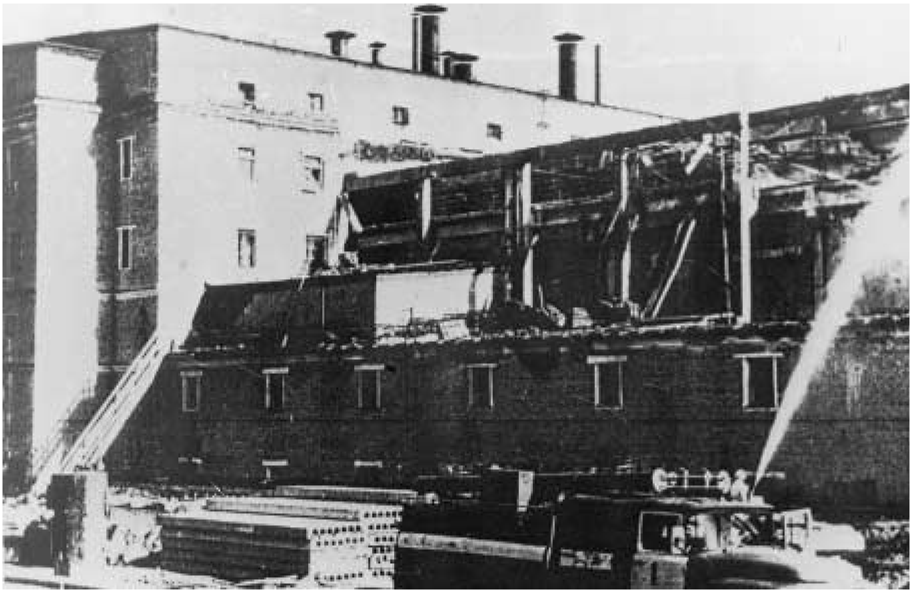


Photo 2. Spray coating of surfaces.

emergency systems in the accident zone were also tested, as well as the processing and internal communications equipment.

The objective of the set of measures introduced in the third programme, which was approved on 7 April, was to clean up and restore the buildings in order to reduce the chances of additional contamination and permit the eventual restarting of the reprocessing line.

Work started with the collection and removal of the damaged parts of the building structure for burial at the solid waste disposal site. Contaminated rooms were washed down and protective liquid glass coatings were used to cover surfaces so that recontamination by dust particles was reduced (this practice was discontinued later on to make decontamination of surfaces easier); this operation is shown in Photograph 2.

Photo 3. The area around the installation after restoration.

Photo 4. View of Building 201 after restoration.

The roads and pathways around the building were decontaminated, snow was cleared from the roof and surrounding areas and then melted for discharge into the contaminated sewage system.

Until the holes in the walls and roof of Building 201 were repaired they continued to be a source of contamination in and around the RCW area, especially on the roads and footpaths, and required additional monitoring and decontamination.

Once decontamination had been completed, the buildings were surveyed, plans were drawn up for restoration work and repairs started. The building restoration work was completed by the middle of 1994. Photograph 3 shows the area around Installation AD-6102/2 after restoration and Photograph 4 shows Building 201 after the completion of repairs.

6.3. EFFECTIVENESS OF THE CLEANUP OPERATIONS

6.3.1. Buildings: gamma radiation

By the middle of May, the building structure had been stabilized, the roof washed down, lead shielding in the accident area removed, contaminated snow cleared and the surrounding area decontaminated. Measurements of gamma dose rates were then made at different locations, providing the values shown in Table VII.

6.3.2. Buildings: surface contamination

Daily checks on the radiological situation showed that the measures taken resulted in a reduction by a factor of between 3 and 25 in the levels of surface contamination in and around Installation AD-6102/2 and Building 201. In September 1993, after Building 201 had been repaired, measurements of the contamination on internal surfaces in the equipment room were carried out. The results from these measurements, showing the activity levels for different radionuclides in two locations, are provided in Table VIII.

TABLE VII. EXTERNAL DOSE RATES FROM GAMMA RADIATION IN DIFFERENT LOCATIONS

	Dose rate	Reduction factor
Accident area	15.1 $mGy\cdot h^{-1}$	16
Upper roof	14.4 $mGy\cdot h^{-1}$	25
South road near Building 201	180 $\mu Gy\cdot h^{-1}$	3
North road and adjacent areas	2.1 $mGy\cdot h^{-1}$	5
North towards perimeter fence	4.5 $mGy\cdot h^{-1}$	5

TABLE VIII. SPECTROMETRIC DATA FROM SAMPLES TAKEN AT RCW IN SEPTEMBER 1993

Sampling location	Number of samples	Activity per unit area ($Bq\cdot cm^{-2}$)			
		Sb-125	Ru-106	Nb-95	Zr-95
High ventilated corridor	5	124	6 800	960	440
Smears from high ventilated cable passages	3	204	40 400	5 200	2 120

6.3.3. Buildings: alpha contamination

Measurements taken in Building 201 using 100 cm^2 samples showed that the alpha activity on each sample was down to between 4.7 and 17 Bq. Table IX gives the percentage activity of various alpha emitting radionuclides on internal surfaces.

6.3.4. Ground contamination

After the accident the contamination of melted snow and rain water was monitored daily at three locations within the SCE site. These measurements showed that in rain water the beta contamination did not exceed 30 Bq·L^{-1} and the alpha contamination was less than 0.08 Bq·L^{-1}, while the beta contamination in melted snow was less than 3 Bq·L^{-1}.

After the snow had finally melted on 8 May, a map of beta/gamma ground contamination was compiled using measurements from 680 points taken over 32 km^2 of the industrial area at distances of up to 8 km from Building 201. A comparison of the maximum levels from these measurements and those from measurements taken on 11 April shows a reduction of 20%. The measurements taken on water from melted snow showed that the permissible levels specified in the Radiation Safety Standards [2] were not exceeded.

6.3.5. Waste burial

The fall in external radiation dose rates at the radioactive waste burial disposal site, as might be expected, was determined principally by the natural decay of the radionuclides present.

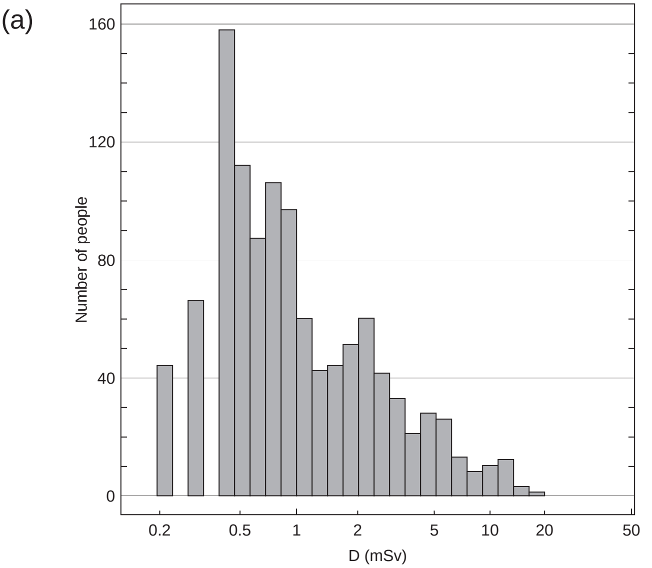
6.4. DOSES TO SCE PERSONNEL

At SCE, a total of 1946 individuals were exposed to radiation as a result of the accident and its aftermath. There were 160 persons inside Building 201 at the time of the accident: 125 technical personnel from the RCW, 29 from the construction and

TABLE IX. RELATIVE ALPHA RADIONUCLIDE CONTENT ON INTERNAL SURFACES IN BUILDING 201

	Pu-239	Pu-238	U-234	U-238
Percentage activity	70.3	1.3	14.8	13.6

(a)



(b)

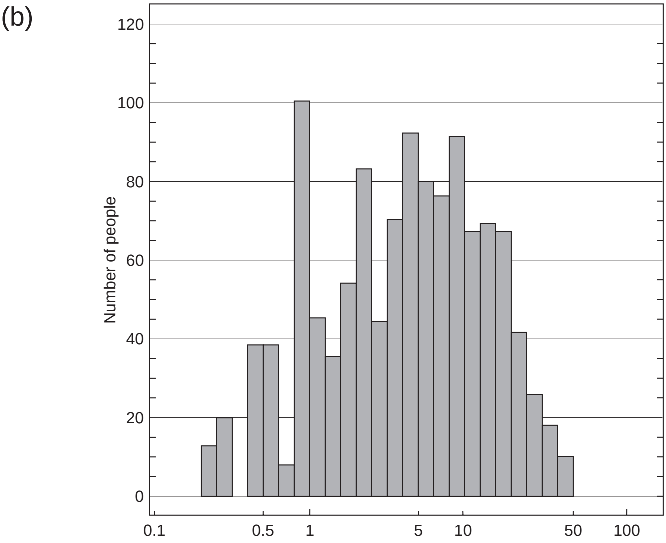


FIG. 17. (a) Distribution of gamma doses for RCW personnel measured in 1992; (b) distribution of gamma doses for personnel from RCW and other organizations involved in the cleanup operations, January to August 1993.

engineering department of SCE and six armed guards. Three of the people working for the construction and engineering department and one armed guard were in the immediate vicinity of the installation when the accident occurred; their positions at the time of the accident are shown in Fig. 8. The remainder were in rooms adjacent to the equipment room and at a substantial distance from where the explosion occurred. All of these people were wearing standard sets of working clothes including cotton underwear, overalls, cap and footwear.

The 20 firemen who arrived a few minutes after the accident were also exposed to radiation during the ten minutes it took to extinguish the fires and while coping with the emergency in general.

The largest group of people exposed to radiation were the 1920 people who were involved in the cleanup operations from 6 April until 1 August 1993. This group included 1185 technical staff from the RCW, 139 persons from the SCE machinery repair works, 388 personnel from other SCE departments and 208 persons from other organizations.

6.4.1. External doses from gamma radiation

Radiation monitoring of personnel was carried out using established procedures and equipment. Monitoring showed that only six of the people who were in the building at the time of the accident received doses above the 0.2 mSv threshold of the dosimeters used, these individual doses ranging from 0.2 to 0.5 mSv.

Fourteen of the twenty firemen exposed to radiation received doses above the 1 mSv sensitivity threshold of the IKS-A thermoluminescent dosimeters, their individual doses ranging from 1 to 7 mSv, with an average value of 4 mSv.

Analysis of the gamma radiation doses received by personnel during the cleanup operation showed that the collective external dose for the 1920 persons was 8.91 man·Sv (for RCW personnel, this dose was 5.85 man·Sv) giving an average individual dose of 4.64 mSv. The distribution of individual doses received by RCW personnel in 1992 is shown in Fig. 17(a) while the distribution in Fig. 17(b) shows the doses received by RCW personnel and others involved in the cleanup operation during the first eight months of 1993. A comparison of the two histograms shows the clear increase in dose levels due to the accident and the following cleanup operations. The number of personnel working in different SCE departments who received doses falling within different ranges is shown in Table X, from which it can be seen that the dose limit of 50 $mSv \cdot a^{-1}$ was not exceeded.

6.4.2. External doses from beta radiation

Experience of the cleanup operations after the accident at Chernobyl showed that the effect of external beta radiation can be significant [22]. However, beta

TABLE X. EXTERNAL DOSES TO SCE PERSONNEL DURING CLEANUP

	Number of personnel			
	<15 mSv	15–25 mSv	25–40 mSv	40–50 mSv
RCW	1287	99	34	8
Other departments	74	11	—	—
Machinery repair works	109	1	—	—
Other works	198	14	2	2

TABLE XI. RATIO OF BETA TO GAMMA DOSE RATES FOR 7 APRIL 1993

	Facial skin	Eye	Testes
RCW production area	5.7	1.1	0.7
Roof of Building 201	15	3.0	1.6
Equipment room	21	4.0	2.1
Passageway	27	2.9	1.6

radiation dosimeters have not been used at nuclear installations within the Russian Federation, including SCE, either before or after the Chernobyl disaster. External exposure to beta radiation was therefore estimated using calculations [22] based on a point isotropic source. In this case, the absorption function was modified as appropriate for a tissue equivalent medium with a heterogeneous density, rather than one with unit density [22]. Table XI gives values for the ratio of beta to gamma dose rate calculated for the face, eyes and testes of individuals working in four areas during the cleanup operations, on the assumption that there was no penetration of radionuclides into the body. In the calculations, the skin density for the face was assumed to be 7 $mg \cdot cm^{-2}$ at a height of 1.5 m, 300 $mg \cdot cm^{-2}$ at 1.0 m for the testes and 500 $mg \cdot cm^{-2}$ for the eyes at 1.5 m. The relative radionuclide content was taken as: ^{95}Nb — 42%; ^{95}Zr — 26%; ^{103}Ru — 1%; and ^{106}Ru — 31%. The values in Table XI can be contrasted with those obtained at Chernobyl one day after the accident. There, the ratio calculated for exposed areas of skin using this methodology went up to 30.

Although gamma radiation from ^{106}Ru in combination with its daughter radionuclide ^{106}Rh contributed only 9% of the total gamma dose, these two radionuclides were the major source of the exposure to facial skin, eyes and testes due to beta radiation. As ^{106}Ru has the longest half-life of all the gamma emitters released in the accident, the value of the beta/gamma ratio increased with time to a maximum of 150 for facial skin. This value assumes there was no penetration of radionuclides into the skin.

The data available on dose distribution within an adult body from radionuclides in an infinite extended source [23] were used to calculate the distribution of equivalent doses for human organs and tissues. The difference between the maximum and minimum absorbed dose from the gamma radiation was estimated to be 24%, a value comparable to the error in the monitoring instruments.

Results from calculations indicate that the contribution of beta radiation to the total external effective dose amounted to some 23% in the equipment room, 9% in the production area and 20% on the roof and in the corridors of Building 201.

6.4.3. Internal doses from incorporated gamma and beta emitting radionuclides

During the period 6 April to 16 August 1993, 732 individuals were examined using whole body counters to determine the radionuclide concentration in their body. The persons examined included 296 RCW workers (168 of these were examined between two and four times), 251 people working in other SCE departments and 185 firemen and armed guards. The minimum detectable activities (MDA) of the whole body counters used were 1.11 kBq for ^{106}Ru and ^{103}Ru, 1.48 kBq for ^{95}Zr and 0.74 kBq for ^{95}Nb, with a detection error of ±30%.

Only 15 of the RCW workers had radionuclide concentrations in their bodies above the MDA. The data for the seven people with the highest concentrations are provided in Table XII and represented graphically in Fig. 18. These figures indicate clearly that ^{106}Ru is the most significant radionuclide from the internal radiation point of view. In all cases, however, the values are below the threshold value of 22.2 kBq specified for chronic intake [24].

In estimating these internal exposure doses it was assumed that inhalation was the main pathway into the body, that ^{106}Ru aerosols were insoluble (group Y), that the AMAD was 20 μm, that 6.7% of the activity inhaled was deposited in the alveolar section of the lungs and had a diameter less that 2.5 μm and that ^{106}Ru would be present in the lungs only since all the radionuclides deposited in the upper part of the respiratory tract would have been removed via the gastrointestinal tract by the time monitoring was carried out.

Using these assumptions, the equivalent dose to the lung from ^{106}Ru was estimated to be 15–50 mSv, giving an effective dose of 3–9 mSv. As mentioned above, ^{106}Ru concentrations exceeding the MDA of 1.11 kBq were found in only about 5% of SCE personnel, which means the effective dose from ^{106}Ru for 95% of SCE personnel was below 0.7 mSv.

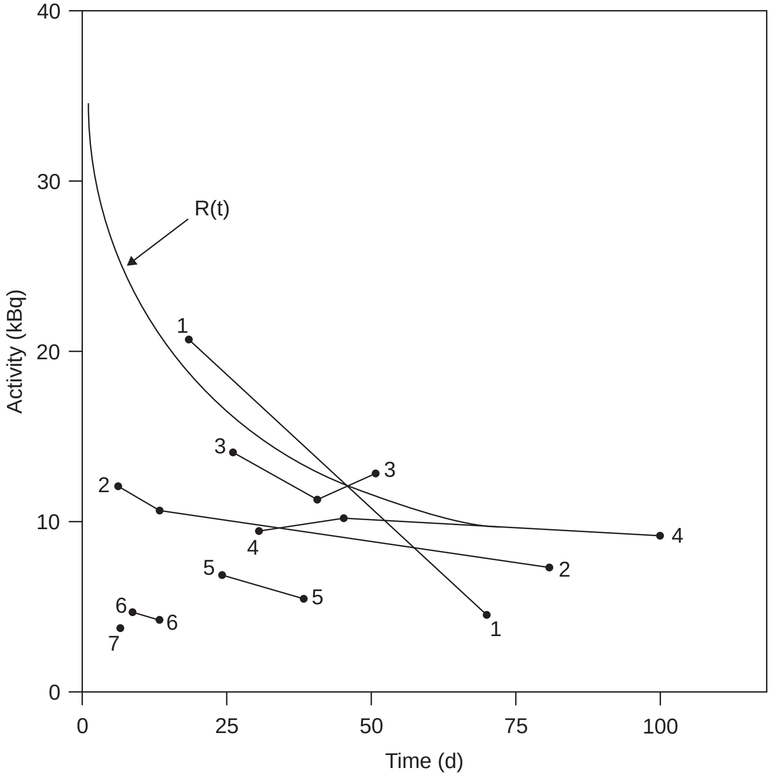


FIG. 18. Activity as a function of time of ^{106}*Ru measured in seven RCW personnel.* R(t) *is the retention function [24]. The numbers against the curves indicate the persons examined.*

If it is assumed that the distribution of doses induced by internal exposure in individuals can be approximated by a log-normal distribution with a standard deviation of 3 [25], then the arithmetic mean value of the distribution can be estimated to be 0.3 mSv. Hence the internal effective dose from incorporated radionuclides was about 5% of the effective dose from external radiation.

6.4.4. Internal doses from incorporated plutonium

Regular monitoring of plutonium incorporation had been carried out by the Bioassay Laboratory of CMSD for a number of years as there was no whole body counter at CMSD Tomsk-7 capable of carrying out these measurements directly. Estimates of the doses induced through inhalation following the accident were made in two ways: firstly, by comparing the level of ^{239}Pu activity in urine before and after the accident, and secondly, by calculating the ratio of ^{239}Pu/^{106}Ru measured in different working areas.

TABLE XII. ACTIVITY OF RADIONUCLIDES (kBq) MONITORED IN SCE PERSONNEL

Individuals	Dates monitored (1993)	Ru-106	Nb-95	Zr-95
1	23 April	20	22	13
	15 June	4.5	3.0	1.5
2	12 April	11	4.1	1.9
	19 April	10	4.4	1.5
	7 July	6.7	1.5	—
3	30 April	14	4.8	2.6
	13 May	11	4.4	1.5
	25 May	12	3.3	3.0
4	5 May	9.3	4.4	2.2
	18 May	11	3.0	2.2
	15 July	7.8	1.9	—
5	30 April	6.7	1.9	—
	14 May	5.2	1.5	—
6	15 April	4.4	2.2	—
	19 April	4.1	1.9	—
7	12 April	3.7	—	—

The concentrations of ^{239}Pu in the urine of 187 persons involved in the cleanup operations were monitored and the distribution of the samples as a function of ^{239}Pu concentration (Fig. 19) shows that they fit well with a log-normal function. These results were compared with those of 80 persons who had undergone the same type of examination during the seven years prior to the accident (Fig. 20), which could also be approximated to a log-normal distribution. As illustrated in Table XIII, comparison of the data showed that there were no significant differences between the groups.

A comparison of the results from the years before and after the accident, taking into account the t-criterion [26], did not disclose any differences and in some cases showed no variation in the average ^{239}Pu activity in the urine between the two periods (Fig. 21). These results demonstrate that there was no increase in the median level of ^{239}Pu excreted in urine resulting from cleanup operations.

However, as the biophysical analyses did not provide a reliable value for the intake of ^{239}Pu through inhalation, calculations were also carried out. For these it was assumed that the characteristics of ^{239}Pu-bearing aerosols were the same as for the

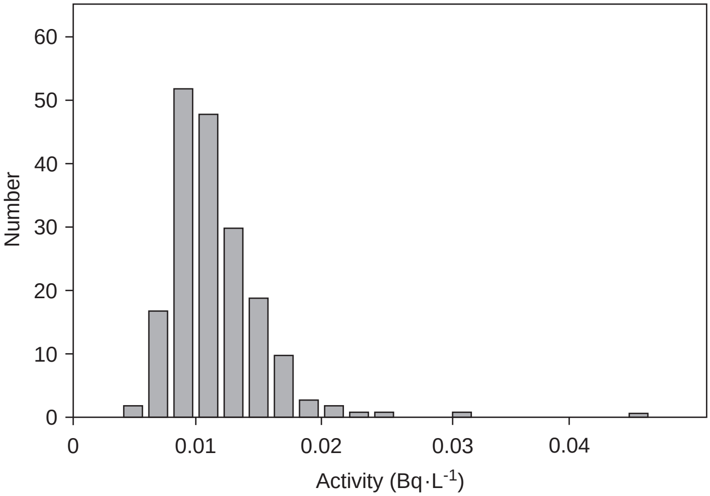


FIG. 19. Distribution of ^{239}Pu activity in daily samples of urine taken after the accident for personnel involved in cleanup operations.

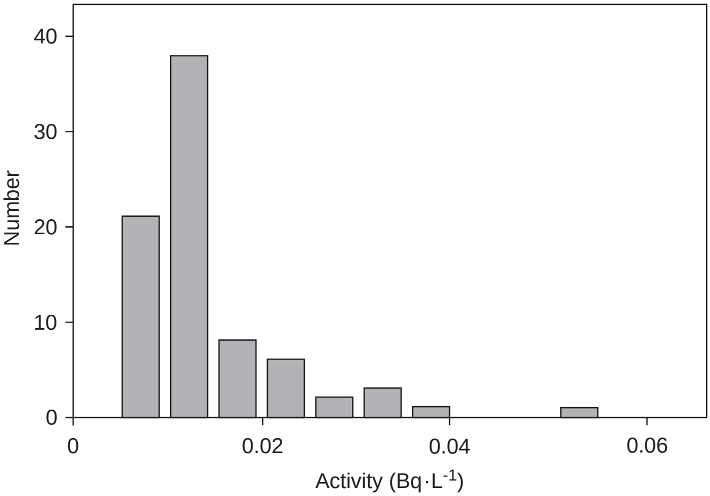


FIG. 20. Distribution of ^{239}Pu activity in daily samples of urine taken prior to the accident for personnel involved in cleanup operations.

TABLE XIII. RESULTS FROM THE ANALYSIS OF URINE SAMPLES

	Number of persons tested	Median of distribution ($Bq \cdot L^{-1}$)	Mean geometric standard deviation
All persons involved in the cleanup operations	187	0.013	1.4
Selected group after cleanup operations	80	0.013	1.39
Selected group prior to cleanup operations	80	0.013	1.56

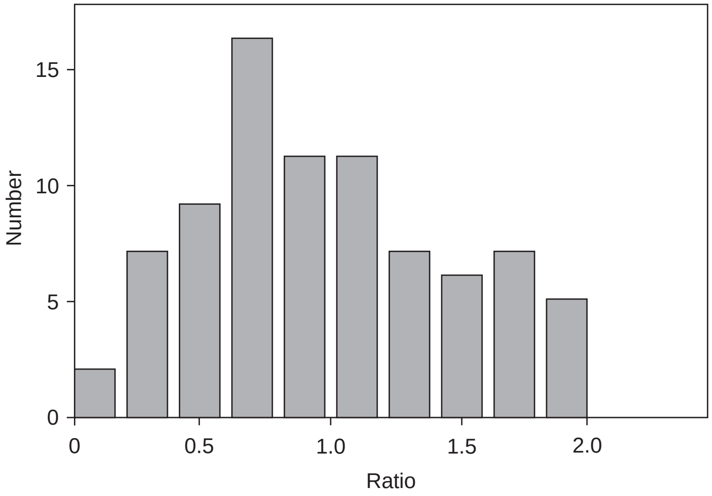


FIG. 21. Distribution of the ratio of activity due to ^{239}Pu in the pre- and post-accident periods.

TABLE XIV. EFFECTIVE DOSES FROM DIFFERENT SOURCES OF EXPOSURE

Source of exposure	% of total dose
External gamma	79
External beta	16
Internal gamma and beta	4
Internal from Pu-239	1

gamma and beta emitting radionuclides, and that the ratio of ^{239}Pu/^{106}Ru in the air during the cleanup was 0.3×10^{-3}. By using these assumptions the average internal dose equivalent induced by incorporated ^{239}Pu is calculated as 0.7 mSv for the lungs, with an effective dose of 0.06 mSv.

6.4.5. Total dose

The analyses described above show that the main source of exposure was from external gamma radiation and that the measurements taken were of sufficient accuracy to provide a reliable average value of 4.6 mSv. Table XIV gives the effective dose values resulting from each source of exposure relative to that from external gamma exposure.

Combining these figures gives an average individual dose of 7.2 mSv, with a total collective dose for all personnel of 13.3 man·Sv. These figures, taken with those in Table X, show that the dose limits specified by the radiation safety regulations for both the whole body and specific organs [2] were not exceeded to any significant extent for those involved in operations on the SCE site either during the accident or during the cleanup period.

7. SURROUNDING AREA

7.1. LIVING CONDITIONS

Much of the area contaminated by radionuclides from the accident is outside the SCE site, with some of the contamination affecting the village of Georgievka and to a much lesser extent the nearby village of Naumovka. Georgievka, which is

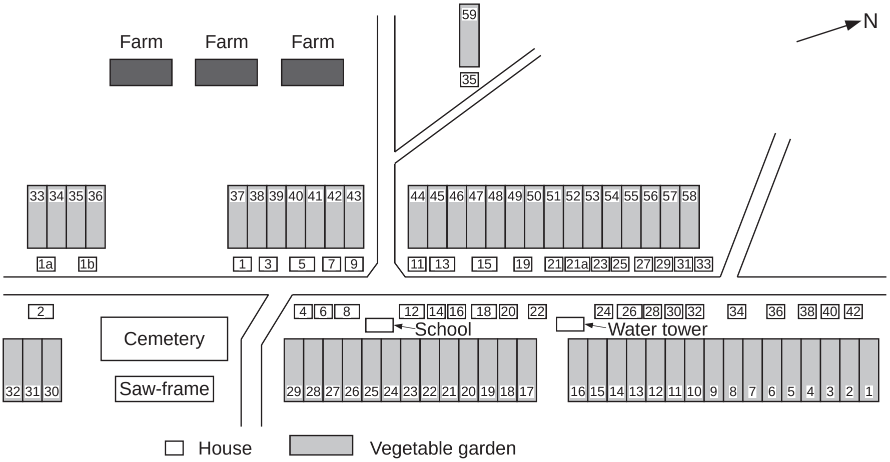


FIG. 22. Schematic map of the village of Georgievka.

situated about 16 km to the northeast of SCE, is made up of 38 farmsteads consisting typically of a small house, cattle-shed, yard and vegetable garden. The single storey dwellings are built from wood with floor areas varying between 25 m^2 and 40 m^2 with each farmstead covering a total of about 36 ha, including about 26 ha used for growing vegetables. Most of the dwellings are spread out along a single road, as shown in the schematic layout of the village in Fig. 22. The villagers keep some livestock. In 1993, this included 38 cattle (15 of these dairy cattle), 71 pigs, 22 sheep and 3 horses. The diet of the villagers consists mainly of locally produced foodstuffs including milk, meat (pork, mutton, beef), potatoes, as well as fresh and preserved vegetables (cabbage, cucumbers, tomatoes, carrots, onions).

At the time of the accident, Georgievka had a permanent population of 73, of whom 18 were teenagers. In addition to the permanent residents, another 95 people lived temporarily in Georgievka during the warmer part of the year from May to August and spent on average about one and a half months a year in the village. Figure 23 shows a breakdown of the population by occupation and Table XV shows how many hours the inhabitants spent in different locations around the village each day during the summer months.

The mode of living of the temporary residents is similar to that of the pensioners living permanently in Georgievka. Their diet is based on potatoes and vegetables grown on their private plots. Table XVI shows the average consumption of locally grown produce by the inhabitants.

TABLE XV. TIME SPENT DAILY IN DIFFERENT LOCATIONS BY THE INHABITANTS OF GEORGIEVKA (HOURS)

	House	Yard	Vegetable garden	Street	Saw-frame	Outside village
Housewives and pensioners	10	4	6	4	—	—
Saw-frame workers	10	3.5	1.5	1	8	—
Agricultural workers	10	3.5	1.5	1	—	8
Farmworkers	10	8.5	4.5	1	—	—
School children	10	4	1	4	—	5
Children under school age	10	4	6	4	—	—

TABLE XVI. AVERAGE ANNUAL CONSUMPTION OF LOCALLY PRODUCED FOOD

Milk and milk products (L)	740
Meat (kg)	60
Potatoes (kg)	440
Vegetables (kg)	170

A considerable area of agricultural land was also affected by fallout from the accident, as well as large areas of forest and countryside not used for cultivation or rearing animals. A 3 km length of the main road running from Tomsk to Samus was also affected.

7.2. RADIOLOGICAL ASSESSMENTS

7.2.1. The village of Georgievka: deposition

Over 70 samples of snow and soil were collected and analysed following the accident. These showed the presence of ^{137}Cs, ^{90}Sr, ^{103}Ru, ^{106}Ru, ^{95}Zr, ^{95}Nb, ^{141}Ce, ^{144}Ce and ^{239}Pu. Comparison of these data with those collected in previous years showed that the levels of caesium and strontium found could be attributed to both the

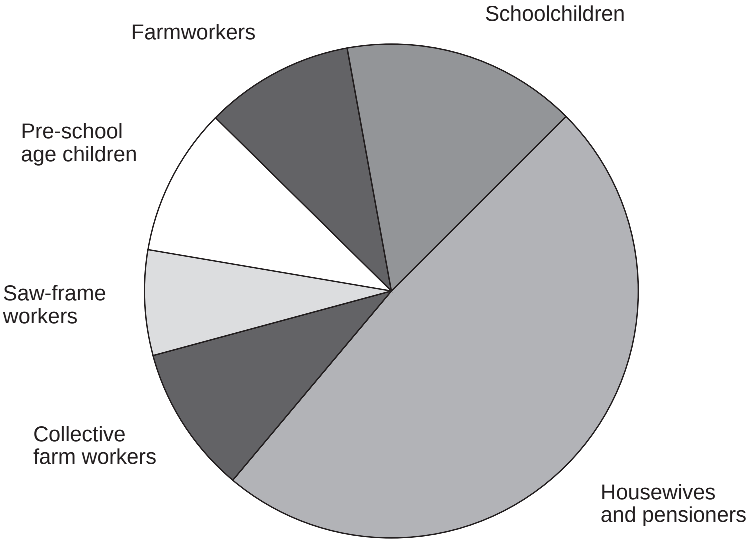


FIG. 23. Breakdown of the population of Georgievka by age/occupation.

accident and long term operations on the SCE site, while contamination from the other gamma emitting radionuclides resulted solely from the accident. Less than 10% of the plutonium contamination could be traced to the release, again indicating that the major part was due to long term activities at SCE. Generally speaking, there was very little difference between the composition of the radionuclides deposited in the village and that found in the other areas outside of the SCE site. Table XVII gives the average deposition levels in Georgievka due to the accident.

7.2.2. The village of Georgievka: external dose rates

As there were no fixed radiation monitoring posts located in Georgievka, it was impossible to obtain information on the radiological situation immediately after the accident. According to calculations [4] which took into account the weather conditions prevailing at that time, the radioactive cloud reached Georgievka between 20 and 30 minutes after the explosion at the RCW. Most of the inhabitants of Georgievka, apart from schoolchildren and agricultural workers, were in the village during the estimated 30–40 min it took for the radioactive cloud to pass over. Data collected on the afternoon of 6 April by the SCE ground radiation survey team showed that the dose rate increased from a background level of 0.08–0.15 $\mu Gy \cdot h^{-1}$ to 0.3–0.6 $\mu Gy \cdot h^{-1}$, with the beta flux density measured on the snow surface between 30 and 3000 $counts \cdot cm^{-2} \cdot min^{-1}$.

TABLE XVII. DEPOSITION IN GEORGIEVKA

Radionuclide	Ru-106	Ru-103	Zr-95	Nb-95	Ce-141	Ce-144	Pu-239
Activity (kBq·m^{-2})	30	1.4	24	54	1.1	1.1	0.015

TABLE XVIII. AVERAGE EXTERNAL DOSE RATE (μGy·h^{-1}) AT DIFFERENT LOCATIONS IN GEORGIEVKA

Month	Street		Vegetable garden		Yard		House	
	Activity	Number	Activity	Number	Activity	Number	Activity	Number
April	0.27	182	0.34	10	0.26	143	0.17	16
May	0.25	28	0.27	142	0.20	74	0.13	24
June	0.24	50	—	—	0.18	76	0.01	42
July	0.20	17	0.15	1	0.19	7	—	—
August	0.17	14	—	—	0.15	1	—	—
September	—	—	0.12	2	0.13	2	0.12	8

TABLE XIX. MEAN VALUES OF BETA FLUX DENSITY ON THE GROUND

Month	Beta flux density (counts·cm^{-2}·min^{-1})	Number of samples
April	464	169
May	281	129
June	261	36
July	92	15
August	43	8
September	35	2

After the accident, both SCE and CSSES regularly monitored the beta and gamma dose rates at different locations within Georgievka. The monthly variation of the averaged values of external dose rate and number of measurements taken are set forth in Table XVIII, while Table XIX presents the mean values of beta flux density on the ground.

Measurements of external dose rate and beta flux density showed that the level of contamination in the village over the scale of a farmstead did not vary by more than a factor of 2 at any given time. However, there were larger small scale variations within local plots.

The variation of external dose rate with time followed that expected from the half-lives of the contaminants and did not appear to be influenced by other factors such as penetration into the ground or decontamination. However, the variation of external dose rate in the vegetable gardens, where a rapid reduction by a factor of 2 during May and June was observed, constituted an exception to this pattern. This reduction can be accounted for by ploughing and subsequent migration of the radionuclides into the soil. Surface measurements of beta flux density were taken on houses, personal belongings and skin. Table XX illustrates the mean values for the beta flux density from these items taken over a period of several months.

The Institute of Biophysics carried out calculations of the migration coefficients of activity from the soil to different articles (defined as the ratio of the surface beta flux density on the articles to that on the ground in the village). The values obtained were 3.2×10^{-2} for footwear, 1.5×10^{-2} for clothes, 0.9×10^{-2} for floors, 0.7×10^{-2} for underwear and bed linen and 0.5×10^{-2} for skin. These values are similar to the ones obtained in inhabited areas contaminated by the accident at Chernobyl.

7.2.3. The village of Georgievka: contamination of food

During the summer and autumn of 1993, the activity concentrations of the food consumed by the inhabitants of Georgievka were regularly monitored by CSSES. More than 20 samples of locally produced food were taken and in all cases the activity concentration of gamma emitting radionuclides from the accident was lower than the sensitivity threshold of the measuring equipment (0.2–1.0 $Bq \cdot kg^{-1}$). In September 1993, the Institute of Biophysics analysed two large (10 kg) samples of milk and potatoes taken from several different farmsteads. The results of gamma spectrometry (^{106}Ru, ^{137}Cs) and radiochemical (^{90}Sr, ^{239}Pu) measurements are contained in Table XXI and show that the activity concentrations in food were less than 2 $Bq \cdot kg^{-1}$.

7.2.4. Agricultural land

The agricultural land contaminated by fallout from the accident belongs to the Sibiryak farm, whose main buildings are at Naumovka. On 13 April 1993, there were 743 ha of ploughed land, 248 ha to be used for hay and 139 ha of pasture falling within the area defined by the 0.2 $\mu Gy \cdot h^{-1}$ contour.

The ploughed land was used mainly for growing animal feed and produced about 1.5 $t \cdot ha^{-1}$ while the land used for hay making was generally uncultivated and

TABLE XX. MEAN VALUES OF SURFACE BETA FLUX DENSITY (counts·cm^{-2}·min^{-1}) IN GEORGIEVKA

	April		May		June		September	
	Beta flux	Number	Beta flux	Number	Beta flux	Number	Beta flux	Number
House floor	7.1	15	10.8	38	1.0	43	0.62	4
Clothes	—	—	—	—	1.3	40	1.1	14
Underwear	—	—	—	—	0.58	38	0.61	18
Footwear	—	—	—	—	3.1	56	2.5	3
Skin	—	—	—	—	—	—	0.35	5

TABLE XXI. ACTIVITY CONCENTRATIONS (Bq·kg^{-1}) IN MILK AND POTATOES SAMPLED AT GEORGIEVKA

	Ru-106	Cs-137	Sr-90	Pu-239
Milk	0.061	1.36	0.16	3.5×10^{-3}
Potatoes	0.23	0.49	0.10	3.9×10^{-3}

produced about 3 t·ha^{-1}. In the wetter areas, sedge was prevalent, which can produce about 15 t·ha^{-1} of animal feed. Part of the fodder produced was sold, with the remainder going to feed the 350 head of dairy cattle owned by the Sibiryak farm. The annual milk production was 1000 t and was sold mainly to people living locally.

The average activity density on agricultural land resulting from the accident ranged from 40 to 120 kBq·m^{-2}, with maximum values as high as 240 kBq·m^{-2}; the external dose rate was below 0.25–0.3 μGy·h^{-1}. The composition of the radionuclides was similar to that already discussed. The radionuclides contributing most to the total activity were characterized by low migration coefficients to plant and animal products. During the first year following the accident, the plants were mainly affected through their roots as the contamination fell onto a blanket of snow. Estimates indicate that zirconium, niobium and ruthenium in the fodder will give rise to an activity concentration of no more than 3 Bq·kg^{-1} and that the activity concentration in products from animals consuming these fodders will not exceed 5 Bq·kg^{-1}.

7.2.5. Tomsk–Samus road

The Tomsk–Samus road is the only one suitable for motor transport between the inhabited areas in the northern part of the district and the city of Tomsk. The contaminated portion of the road had a 10 m wide asphalt surface on which the external dose rate reached 4 μGy·h^{-1} on 6 April, with a beta flux density of 3×10^4 counts·cm^{-2}·min^{-1}. Transport leaving the area via the trunk road was found to have contamination levels reaching 1000 counts·cm^{-2}·min^{-1}.

7.3. REMEDIAL ACTIONS AND THEIR EFFECTIVENESS

7.3.1. Decontamination of Georgievka

Decontamination of the area started on 13 April, while a blanket of snow was still on the ground, and continued until the end of July. The non-uniformity of the contamination meant that only selected places had to be decontaminated; these included the street, plots of land attached to the houses, farms and the saw-frame area. Initially, several square metres of snow were removed from the different locations and then, after the snow had thawed and in locations where local hot spots could still be found, small areas (0.2–1.0 m^2) of the ground surface were removed. A total area of 0.8 km^2 (1.6 km × 0.5 km) was decontaminated. This involved the removal of about 380 t of soil and snow for subsequent burial. Photographs 5–7 show some of the activities associated with the decontamination of the village of Georgievka.

Any planks of wood, firewood, garbage and other items that were contaminated were also removed. The final stages of decontamination consisted of deep ploughing the vegetable gardens, the application of mineral fertilizers and asphalting the main street in Georgievka. The decontamination procedures were carried out until the levels of beta flux density were below 100 counts·cm^{-2}·min^{-1} on internal surfaces of houses and personal belongings and less than 200 counts·cm^{-2}·min^{-1} on surfaces in other areas such as the street and vegetable gardens. In addition, the external dose rate had to be below 0.2 μGy·h^{-1} in dwellings, less than 0.3 μGy·h^{-1} in covered household areas and under 0.4 μGy·h^{-1} in uncovered areas (open yards, vegetable gardens, etc.).

The amount of activity removed from the village during decontamination was estimated from the volume of snow and soil removed. On the assumption that the average density of the layer removed was 1.5 g·cm^{-3} with a thickness of 2 cm, an area of 1.25×10^{-2} km^2 was decontaminated. This amounted to 1.6% of the total area decontaminated or 3.5% of the area of private plots (0.36 km^2), where decontamination was more thorough.

Assuming that decontamination removed the surface layer where contamination was highest, the activity was reduced by between 10% and 17%. For other

Photo 5. Monitoring the main street in Georgievka.

calculations the decontamination factor was assumed to be 0.15. Hence, the collective dose to the population of Georgievka that was avoided through decontamination was estimated to be 1.2×10^{-3} man·Sv, while the dose to personnel carrying out the decontamination amounted to 1.4×10^{-3} man·Sv. Thus overall the decontamination led to a slight increase in the collective dose.

7.3.2. Food supply

A number of measures were initiated to reduce the intake of activity through the consumption of locally produced foodstuffs. People were urged to refrain from growing vegetables on their private plots during 1993 and this was encouraged by importing and delivering fruit and vegetables free of charge. The amount and kinds of produce supplied compensated almost completely for the average annual yield from each private plot and made it possible for the population to manage without growing and consuming locally produced foodstuffs.

Private livestock initiated for slaughter in 1993 was purchased from villagers, enabling them to buy meat from external sources; this again allowed them to avoid

Photo 6. Removal of contamination near a home in Georgievka.

the consumption of locally produced foodstuffs. In addition, uncontaminated fodder (mixed feed, potatoes, etc.) was delivered free of charge to private farmsteads. The amount supplied to each owner depended upon the size of the plot and in general corresponded to the amount of fodder stored annually. This action made it possible for the animals to be fed with uncontaminated fodder from the time they were put into their stalls in October. As an additional preventive measure, the gathering of mushrooms and berries from the forests was prohibited. Putting these measures into place required purchasing 20 t of meat and supplying 430 t of potatoes, 13.1 t of vegetables and fruit, 4.5 t of mixed feed and 12 t of fodder.

The reduction in collective dose achieved through the delivery of fruit and vegetables to the population was estimated to be 1.8×10^{-4} man·Sv. This estimate assumed that all the permanent and temporary residents (168 people) ate only imported products for a period of one year starting at the beginning of September. The gross consumption of potatoes was assumed to be 7.39×10^{4} $\mathrm{kg \cdot a^{-1}}$ (440 $\mathrm{kg \cdot a^{-1}}$ per person) and that of other fruit and vegetables 1.31×10^{4} kg. The collective dose avoided through the purchase of local meat was estimated to be 9.7×10^{-6} man·Sv, on the basis of the assumption that all the people who consumed meat (73 permanent

Photo 7. Removal of contaminated soil and snow from Georgievka.

residents) excluded local meat from their diet (the annual meat consumption being 60 kg per person) during the period from October 1993 until September 1994.

Providing imported fodder reduced the collective dose by an estimated 2.5×10^{-5} man·Sv, on the assumption that animals were kept in their stalls from October 1993 until June 1994 and that the transfer of released radionuclides from fodder to the milk chain was completely eliminated. It was also assumed that the use of imported fodder completely prevented the transfer of radionuclides to meat intended for slaughter in the autumn of 1994.

The overall collective dose to the local population that was avoided by introducing all of the provisions outlined above was estimated to be 2.1×10^{-4} man·Sv.

7.3.3. Evacuation of children

In the first days after the accident all seven children under school age were taken away from the village to stay with relatives. The relocation of the other children was organized by the authorities and carried out on a voluntary basis with parental consent. During their absence, the children were offered the chance to stay at sanatoriums and rest homes in the Tomsk region if health reasons justified it and to go on free long term excursions.

All the 18 children had left the village by the middle of April and were away for about two and a half months. The effective dose that was avoided by evacuating the children was estimated to be 2.3×10^{-3} man·Sv.

7.3.4. Agricultural land

The assessment of the contamination of agricultural land made within the month following the accident and the predicted contamination of future crops indicated that there was no reason to halt or reduce agricultural production. Nevertheless, a set of recommendations were established which included the regular monitoring of agricultural products and the certification of products for sale. Rapid fixing of radionuclides in the soil was accomplished by lowering soil acidity, increasing the potassium content and organic component by chalking, the introduction of peat into the soil (100–200 $t \cdot ha^{-1}$) and the introduction of potassium based fertilizers. Deep ploughing was considered unnecessary because of the low humus content in the soil but sealed tractor cabs were provided to give better protection to agricultural workers. Cereals were harvested immediately to avoid contamination through resuspension and the more highly contaminated agricultural land was excluded from the annual farming cycle. This last measure took into account the small area of the agricultural land falling into this category and the low yield of products compared with that for the rest of the region and resulted in 625 ha of arable land and 72 ha of grazing ground being excluded from use in 1993. Cows were moved to other land for grazing and the fodder that would have been produced was replaced by about 1000 t of mixed feed delivered free of charge to the local inhabitants but at a cost of 61 million roubles.

The averted collective dose derived from the soil–grass–milk–human chain was estimated to be 3.6×10^{-4} man·Sv on the assumption that the grass grown on the excluded land (about 2×10^{3} t) would have been sufficient for feeding a herd of 350 cows for 150 days from the beginning of the grazing season on 1 June and that the milk yield from each animal was 10 $L \cdot d^{-1}$.

7.3.5. Tomsk–Samus road

On the morning after the accident, restrictions were placed on the movement of vehicles over the contaminated part of the road to prevent the spread of radioactivity. Patrols were set up and militia posts were established to prevent traffic from moving away from the road into the contaminated area. Radiation monitoring and decontamination posts were set up at each end of the contaminated section and traffic was only allowed to pass directly along the road and was prohibited from stopping or taking side roads.

Decontamination started by removing contaminated snow from the road and its edges and then washing down the road surface. By 15 April the cracks had been filled with bitumen and measurements of beta flux density showed that the levels had dropped to between 40 and 100 counts$\cdot$cm$^{-2}\cdot$min^{-1} on the road surface. Parts of the road were later re-asphalted and the roadside covered with sand where the beta flux density was particularly high.

This work was completed by 29 April and produced conditions where no further decontamination of the road was required as the beta flux density measured on the road surface and sides was less than 10–15 counts$\cdot$cm$^{-2}\cdot$min^{-1}. The maximum value of external dose rate was 1.5–2.5 μSv$\cdot$h^{-1} on the 700 m section of the road which crossed the axis of the contamination.

7.3.6. Total dose averted

The collective dose over the year following the accident for the permanent population of Georgievka was estimated to be 17.7×10^{-3} man·Sv. Had protective measures not been introduced, this figure would have risen to 21.2×10^{-3} man·Sv and for temporary residents it would have been 7.2×10^{-3} man·Sv. Most of the reduction in collective dose was achieved through the evacuation of children and the absence of the temporary residents.

7.4. COST AND EFFICIENCY OF THE REMEDIAL ACTIONS

Rather than being necessitated by the level of contamination, the measures that were rapidly introduced were aimed principally at reducing the anxiety and tension caused by the accident to the local inhabitants. Estimates were made of the economic efficiency and viability of the investment made in some of the countermeasures introduced and compared with the recommended value of unit collective dose. Table XXII shows the activity yields, expenditure, averted doses and relative cost of an averted unit of collective dose (expenditures are given in both roubles and US dollars using the prevailing exchange rate).

The most expensive measures introduced from a cost effectiveness point of view were those related to agricultural products because of the extremely low transfer of radionuclides to them from the soil. If the commonly used criterion of 10 000–100 000 \$$\cdot$(man$\cdot$Sv)$^{-1}$ is applied for alpha sources, none of the protective measures undertaken following the SCE accident can be justified. Significantly, this reflects the fact that the purpose of the measures deployed in the aftermath of the accident was not just to reduce dose levels, but also to reassure the people.

TABLE XXII. COST OF PROTECTIVE MEASURES

Measure	Effect	Averted dose (S_A) (man·Sv × 10^{-3})	Expenditure (X) (roubles × 10^6)	X/S_A	
				Roubles (man·Sv)$^{-1}$ × 10^9	Dollars (man·Sv)$^{-1}$ × 10^6
Decontamination of inhabited areas	1.25 ha decontaminated, 376 t of soil and snow removed	1.2	4.6	3.8	3.5
Evacuation of children	18 children evacuated for 2.5 months	2.5	10.0	4.0	3.6
Purchase of locally produced meat	20 t purchased	0.01	48.0	4800	4400
Supply of imported fodder	Mixed feed: 4.5 t Potatoes: 403 t Haylage: 12.0 t	0.025	81.1	3244	2950
Suspension of farming and supply of fodder to Sibiryak	Arable land: 642 ha Grazing land: 72 ha Mixed feed: 1000 t	0.36	62	169	154
Total		4.275	216	50.5	46

7.5. PREDICTED DOSES TO THE LOCAL POPULATION

7.5.1. Introduction

The local population’s exposure to radiation as a result of the accident was assessed using both predicted and measured doses. The predictions were made for two situations: with and without the protective measures in place so that the effectiveness of the measures could be assessed.

Calculations were made of the annual individual and collective effective dose rates to the local population taking into account only those radionuclides released during the accident. The pathways considered in estimating dose rates were external irradiation from the cloud passing over the area, external doses induced from ground contamination, inhalation of radionuclides from the cloud as well as those resuspended from the ground and consumption of contaminated foodstuffs. The pathways of potential radiation uptake by the local population are shown diagramatically in Fig. 24.

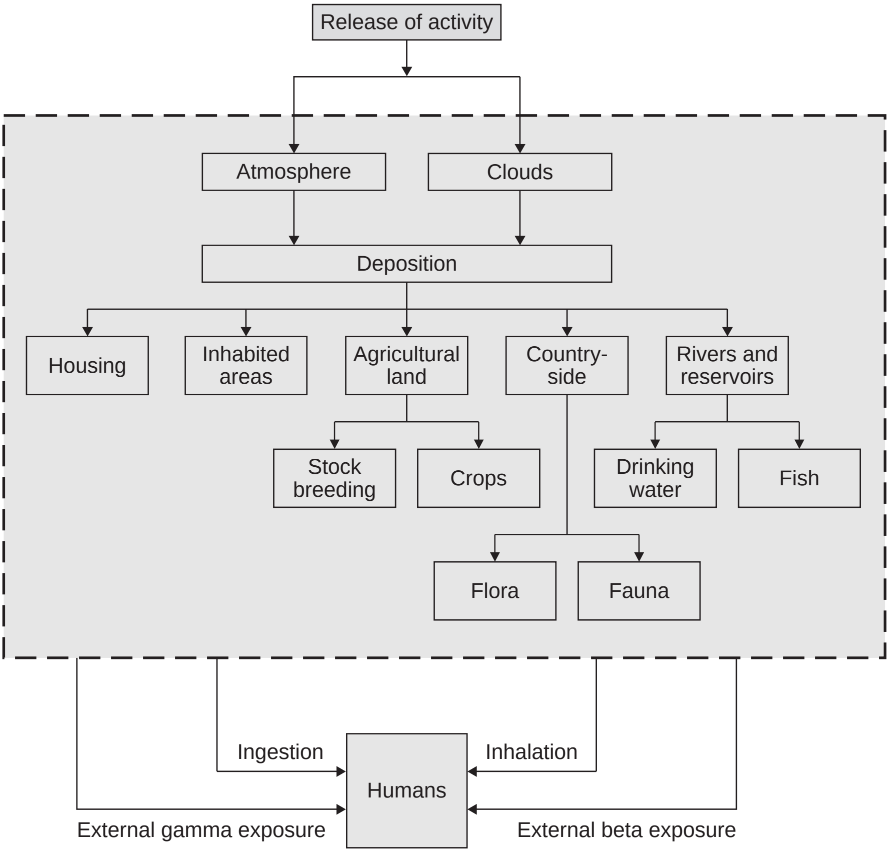


FIG. 24. Pathways of irradiation to the body from a release of radioactivity.

The doses were calculated for cases with and without the protective measures under the following assumptions:

(1) Decontamination of the inhabited areas was carried out from day 7 to day 134 after the accident and 50% of the farmsteads had been decontaminated after 85 days;
(2) There were no children in the inhabited area for the two and a half month period beginning on 10 April 1993;
(3) The only locally produced foodstuff consumed by the local residents was milk, while all other food was imported;
(4) Only imported fodder was used to feed privately owned cattle while they were housed in their stalls;

(5) The temporary residents were not living in the area;
(6) No agricultural work was carried out in the village.

7.5.2. Estimated doses to the local population

The predominant source of external gamma radiation was from the radionuclides of Zr, Nb and Ru deposited onto the ground. These contributed 75–85% of the total effective dose for the various groups in the population. The estimated average doses to which the various groups in the population of Georgievka were exposed during the year following the accident are listed in Table XXIII. Figure 25 shows the distribution of individual external doses from gamma radiation during the same period. The total predicted effective doses were between 0.14 and 0.37 mSv in the absence of protective measures and between 0.13 and 0.35 mSv with them in place. The maximum dose received by any villager was less than 0.4 mSv.

Over 90% of the internal dose was due to the inhalation of the radionuclides ^{106}Ru and ^{239}Pu. The amount inhaled as the radioactive cloud passed overhead was about a quarter of that inhaled during the first year after the accident from wind blown contamination.

No reliable assessments of the ^{239}Pu concentration in local foodstuffs arising from the accident could be made as no information was available on the levels existing in previous years. In the estimation of the internal dose from ingestion it was therefore assumed that all ^{239}Pu activity in local products was attributable to the accident. Even with this assumption, the ingestion dose still constituted less than 1% of the total effective dose. By comparison, the dose to adults due to the accident was found to be only 6% of that from ingestion of Sr and Cs originating in other sources.

Estimates of the situation during the second year after the accident showed that it would be dominated by the presence of ^{106}Ru and ^{239}Pu. The external dose would be expected to fall by a factor of 6.4 as a result of the decay of the released radionuclides and inhalation resulting from resuspension was expected to drop by a factor of 50.

The fall in internal dose from ingestion of food was estimated to be between 1.5 and 1.9 if the migration coefficients for soil to milk and soil to root crops remained the same as in the first year. Under these conditions, the individual effective doses for the various groups in the population in Georgievka were estimated to be between 0.016 and 0.049 mSv during the second year.

7.6. RADIATION MEASUREMENTS AND MONITORING IN GEORGIEVKA

During the month following the accident, measurements of external exposure doses and incorporated radionuclide concentration were made on selected individuals

TABLE XXIII. PREDICTED EFFECTIVE DOSES DURING THE 12 MONTHS FOLLOWING THE ACCIDENT

		Number	Individual dose (mSv)								Collective dose (10^{-3} man·Sv)
			External exposure		Inhalation		Ingestion		External beta exposure	Total effective dose	
			Cloud	De-position	Cloud	Re-suspension	Milk	Potatoes			
Pensioners	A	36	2×10^{-5}	0.237	0.009	0.035	1.8×10^{-4}	2.8×10^{-4}	0.023	0.30	11.0
	B		2×10^{-5}	0.222	0.009	0.033	1.3×10^{-4}	—	0.022	0.29	10.3
School children	A	11	—	0.212	—	0.042	2.0×10^{-4}	5.0×10^{-4}	0.013	0.27	2.9
	B		—	0.092	—	0.038	1.3×10^{-4}	—	0.006	0.14	1.5
Children under school age	A	7	2.5×10^{-5}	0.262	0.008	0.031	4.3×10^{-4}	1.3×10^{-4}	0.017	0.32	2.2
	B		2.5×10^{-5}	0.108	0.008	0.029	2.9×10^{-4}	—	0.007	0.15	1.1
Saw-frame workers	A	5	2×10^{-5}	0.312	0.009	0.035	1.8×10^{-4}	2.8×10^{-4}	0.011	0.37	1.8
	B		2×10^{-5}	0.293	0.009	0.033	1.3×10^{-4}	—	0.010	0.35	1.7
Agricultural workers	A	7	—	0.101	—	0.023	1.8×10^{-4}	2.8×10^{-4}	0.011	0.14	0.95
	B		—	0.095	—	0.022	1.3×10^{-4}	—	0.010	0.13	0.9
Farm workers	A	7	2.5×10^{-5}	0.266	0.009	0.035	1.8×10^{-4}	2.8×10^{-4}	0.023	0.33	2.3
	B		2.5×10^{-5}	0.247	0.009	0.033	1.3×10^{-4}	—	0.022	0.31	2.2

Note: case ‘A’ is without protective measures and case ‘B’with protective measures

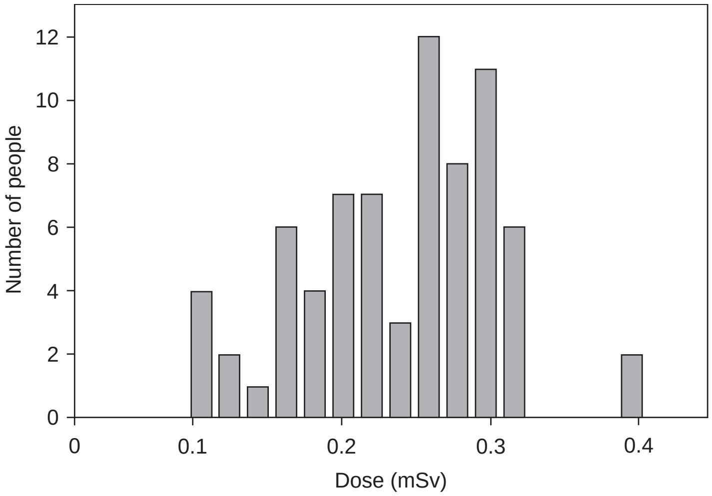


FIG. 25. Distribution of calculated gamma doses to individuals in Georgievka during the first 12 months after the accident.

in Georgievka and the neighbouring villages of Polskaya Malinovka, Naumovka and Petropavlovka. Individual monitoring was carried out using LiF thermoluminescent dosimeters.

Activity concentrations in whole body and lung were measured using portable body counters equipped with a scintillation detector and a Ge(Li) semiconductor detector respectively. The limit of detection for ^{106}Ru, ^{95}Zn and ^{95}Nb in the lungs was 1.5 kBq. The detection limit for whole body activity was 0.1 kBq.

Table XXIV details the average doses in various villages and Fig. 26 gives the distribution of individual doses in the village of Georgievka for the period between 19 May and 29 June 1993 taking into account the natural background.

An average value of 0.89 is obtained for the ratio of calculated external doses to measured doses (with natural background subtracted). Figure 27 shows the distribution of this ratio over this period.

The calculated individual doses from external exposure for the population of Georgievka agree well with the results from individual dose measurements apart from those for the agricultural workers working at the Sibiryak state farm. The estimated dose for these workers was calculated on the assumption that they were absent 8 hours each day from Georgievka and that during this time the dose rate was zero. However, this assumption is not completely valid, as the village of Naumovka and the farm at Sibiryak were also contaminated, albeit to a much lesser degree. Perhaps this explains the difference between calculated and measured doses. Another explanation

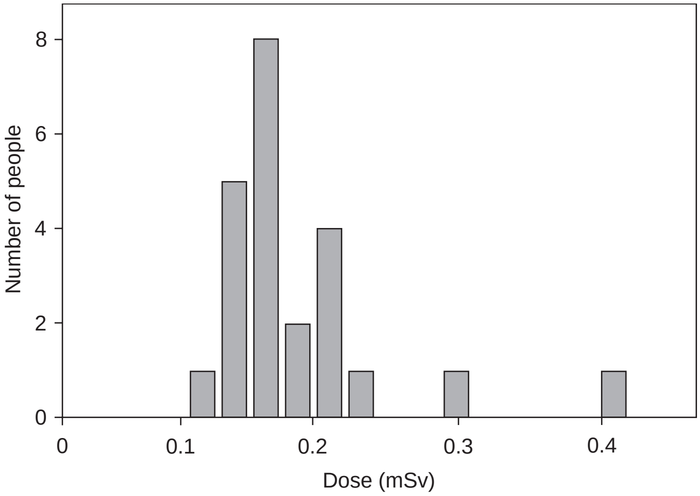


FIG. 26. Distribution of external gamma doses to individuals in Georgievka during the period from 19 May until 29 June 1993.

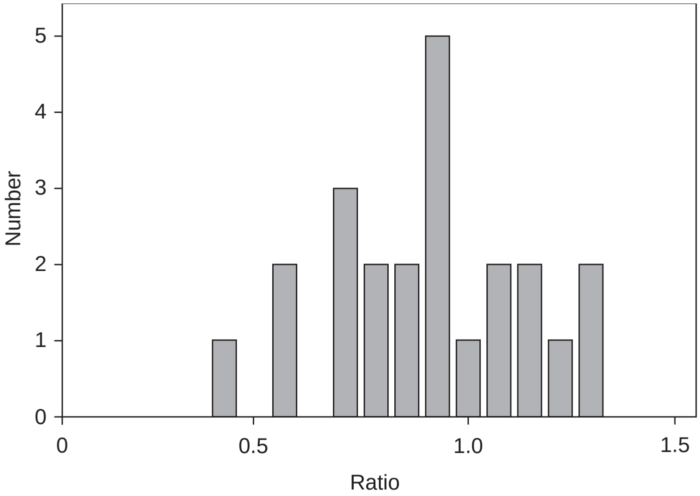


FIG. 27. Ratio of calculated to measured external doses for the period from 19 May until 29 June 1993.

TABLE XXIV. AVERAGE DOSES FOR THE PERIOD 19 MAY to 29 JUNE 1993

	Number of people	Average dose (mSv)	Standard deviation
Georgievka	23	0.19	0.063
Naumovka	19	0.16	0.034
Petropavlovka	4	0.13	0.023

for the discrepancy could be that, at the time decontamination and other measures were being implemented, the agricultural workers from Georgievka were not required to work and may have remained at home for some of the time.

An examination of 22 persons from Georgievka and 11 from Polskaya Malinovka using whole body counters failed to disclose the presence of radionuclides released in the accident in any of their bodies. The calculated values for inhalation and ingestion of released radionuclides by the residents of Georgievka were substantially lower than the minimum detectable limit of activity so that this result is not surprising. ^{137}Cs activity readings of 4.6 kBq (12 May 1993) and 2.75 kBq (24 April 1993) were measured on two people from the same family in Georgievka. Repeated examinations showed that two and a half months later the concentration had fallen by a factor of two, which is typical for the intake of a single radionuclide into the human body. No tests were carried out to determine the incorporated concentrations of ^{239}Pu in the inhabitants of Georgievka.

8. RECOMMENDATIONS

One of the few benefits that can be derived from an accident is to learn as much as possible from an investigation into its cause and ensure that all findings are widely disseminated. The cost of dealing with an accident can be very large and it is therefore only prudent to ensure that as much as possible is found out about an accident and its consequences.

In the case of the accident at SCE there remain some unclarified points, although minor, from which lessons could very well have been learnt. Unfortunately it is probably too late to find answers to these outstanding points and therefore valuable information may well have been lost.

8.1. CAUSE OF THE ACCIDENT

The fundamental cause of this accident was the lack of compressed air being fed into Installation AD-6102/2 to ensure a thorough mixing of the solutions. Investigations indicate that the most likely cause was operator error, although component failure in the plant or control system malfunction cannot be totally ruled out.

Without knowing more about the situation leading up to the accident, it is difficult to give specific recommendations. However, if operators are to be relied upon for important operations which could compromise the safety of a plant, it is essential that plant managers ensure that operational procedures are continually appraised, equipment is updated and personnel adequately trained for the type of work involved. Operational procedures of this type should have double checks at the very least and wherever possible be backed up with interlocks to ensure that situations which compromise safety are eliminated as far as possible. If the cause was component failure, then only a thorough investigation will enable faults of this type to be eliminated.

8.2. INFRASTRUCTURE

Managers of large nuclear sites have a responsibility to ensure that the infrastructure exists to cope not only with emergency situations but also for the day-to-day running of a complex site. It is extremely important that the exposures to personnel, the environment and the local population be monitored effectively and comprehensively so that any problems can be identified and rectified as soon as possible.

During the course of the investigations into the accident at SCE, there were instances where extra equipment would have helped in determining the impact of the accident. In line with a general policy in the Russian Federation, there was no means of measuring levels of beta radiation, even though this source was found to have contributed 10% of the dose to individuals in the accident at Chernobyl. There was also no direct means of measuring doses arising from the intake of ^{239}Pu, as no whole body counter was available with this capability. Not only did this have repercussions during the emergency, it also meant that background data on the day-to-day radiological situation, both at SCE and in the surrounding area, were not complete. Had it been a more serious accident, the absence of a full complement of equipment could have been more damaging.

All organizations should be encouraged to check continuously the equipment at their disposal for monitoring the effects of their operations and ensure that it is suitable for both normal and emergency situations.

8.3. EDUCATION

The difference between the technical knowledge and awareness of those who work in an organization such as SCE and that of the local population can be very large. Some of the measures taken to cope with the accident at SCE were introduced with the primary aim of reducing the dose levels but were also very much prompted by the need to reduce the stress and anxiety in the local population. The cost of introducing these measures was high and they would not have been justifiable if only radiological protection criteria had been taken into consideration.

Reducing the anxiety and stress in the local population in the aftermath of a nuclear accident is of vital importance and but will never be easy. However, a sustained effort to ensure that people living close to a nuclear establishment are informed of its purpose and of the actions necessary in an emergency might go some way to relieving anxiety and stress and may even reduce the level of response needed to cope with any accident.

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