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The Russian Radiation Legacy: Its Integrated Impact and Lessons

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Information about the consequences of human exposure to radiation in the former Soviet Union has recently become available. These data add new insights and provide possible answers to several important questions regarding radiation and its impact on occupational and public health. The 1986 Chernobyl accident initiated a major and early increase in childhood thyroid cancer that resulted from ingestion of iodine-131 (^{131}I) by young children living in the most heavily contaminated areas of Belarus, Ukraine, and Russia. No significant additional cancer or other adverse medical effects have yet been reported in the affected populations and among clean-up workers. Major psychological stress independent of radiation dose has been observed in those people thought to be exposed. During the early days of the atomic energy program in the former Soviet Union, some unfortunate events occurred. The country's first atomic test in Semipalatinsk in 1949 exposed over 25,000 people downwind from the blast to significant doses of fission products, especially ^{131}I . During the late 1940s and the early 1950s nuclear material production facilities were developed near Chelyabinsk in the South Ural Mountains, which resulted in major releases into the environment and significant overexposures for thousands of workers and nearby populations. Chronic radiation sickness was observed early in exposed workers, and increases in leukemia and other cancers were also reported. The series of plutonium inhalation-related lung cancers and fatalities among workers exposed in that first decade appears to be unique. Long-term consequences of chronic radiation sickness and four decades of follow-up are being described for the first time. Villagers downstream from the plant consumed high levels of ^{137}Cs and ^{90}Sr and, it is reported, manifested increases in leukemia from internal and external exposures. Although the 40-year databases for retrospective dosimetry and epidemiology studies are just beginning to be integrated and evaluated, preliminary evaluations suggest that there may be graded, significant dose-rate amelioration factors for cancer and leukemia risks in workers and the general population relative to the risk data on the Japanese atomic bomb survivors. Even for plutonium-induced lung cancers in workers, such a dose-rate effect may be evident. These experiences give us insight into the consequences of protracted radiation at high and low doses and rates. If these findings are validated and confirmed, they can provide information that reduces some of the uncertainties in retrospective radiation dosimetry and radiation risk estimates (especially for low-level, chronic exposures) for activities related to medicine as well as the handling of nuclear materials and nuclear facility decommissioning, decontamination, and demilitarization. — *Environ Health Perspect* 105(Suppl 6):1385–1391 (1997)

Key words: plutonium, MAYAK, radiation risk, lung cancer, Chernobyl, Semipalatinsk, ^{90}Sr , radiation leukemia, thyroid cancer, ^{131}I

Introduction

There are important lessons to be learned from the radiation events that occurred in the former Soviet Union. In recent years, especially since 1991, we have learned

much about previous radiation events, even some that occurred more than 40 years earlier. It is important to note that most of these radiation exposures were related to

the military–industrial nuclear fuel cycle. They therefore provide new and different information from that in the traditional databases obtained from medical radiology exposures and instantaneous external exposures from atomic weapon detonations, which are the current basis for almost all radiation risk estimates. Thus, this new information can provide an independent source of radiation risk estimations and can add unique information about the role of protracted external and internal radionuclide exposures in radiation risk.

When these new data from the former Soviet Union become fully available, it is hoped they will provide the scientific community and decisionmakers with independent information regarding risks from low, medium, and high radiation doses and rates. One limitation of the current information on low and medium radiation doses is that they are extrapolated from high-dose and dose-rate information using conservative models.

These new data have an underlying problem common to all retrospective studies of radiation exposures and their consequences, i.e., the set of uncertainties that are associated with the reconstruction of radiation dose and the verification and validation of possible adverse health effects. Any careful follow-up study must attempt to use all possible means to reduce uncertainties associated with both dose and effect. With respect to effect, since the human exposures invariably are accidental, one is faced with the additional problem of specification of the relation of location and time of possibly exposed persons to the event(s). It is easier to provide estimates of group collective dose, but this does not always lead to accurate individual dose estimates. The confirmation and validation of all the facets of dose reconstruction can be aided by the use of modern tools of biological and physical dosimetry as well as newer models and methods of database management. Independent corroboration and ascertainment of pathological and clinical information will also require considerable attention.

Although the tragic accident in Ukraine at Chernobyl in April 1986 is the most well known, other events recently have been described that involved serious worker and population exposures. Two significant situations are the exposures associated with the early operation of the MAYAK nuclear facility near Chelyabinsk in the South Urals

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Abbreviations used: CRS, chronic radiation sickness; EAR, excess absolute risk; ERR, excess relative risk; kBq/m², kilobecquerels per meter squared; LET, linear energy transfer; MBq/m², megabecquerels per meter squared; mSv, millisieverts; PBq, petabecquerels; PY, person-years; RBMK, Russian graphite-moderated reactor; SMR, standard mortality ratio; Sv, sieverts.

and the exposures related to the testing of nuclear devices near Semipalatinsk in northern Kazakhstan.

The major after-the-fact health consequences of nonlethal radiation exposures are the induction of cancers and leukemias (1). For example, the presence of radioiodine in the environment soon after a radioactivity release as in Chernobyl and Semipalatinsk puts the thyroid gland at particular risk, especially in children. The consequences of whole-body exposure, acute or chronic, as in Hiroshima/Nagasaki and Chelyabinsk, are mainly the risks of generating leukemia and solid cancers. The Russian data support the general observation that the stochastic and deterministic effects are the result of doses directly in organs receiving significant exposure and reemphasize the importance of recognizing this factor in dose reconstruction. Some of the data suggest that, for radiation-induced leukemias, there may be a human dose-rate amelioration effect, as has been shown in animal studies (2). That is, quantitative demonstration of whether radiation absorbed slowly is less carcinogenic per unit of dose than that absorbed acutely.

In these studies there is a potential to gain new insight by integrating dose with dosimetry, integrating population dose reconstruction methodology with newer and traditional methods of individual biological and physical dosimetry. This will entail not only careful ascertainment and review of past exposures but also selected contemporary confirmation measurements of exposed groups of individuals.

Chernobyl

The violent disassembly of the Russian graphite-moderated reactor (RBMK) unit 4 at Chernobyl in the early hours of 26 April 1986, destroyed the reactor and released massive levels of fission products (3). The plume headed mainly north into Belarus, west into Ukraine, into adjacent parts of Russia and, to a lesser extent, over all of the Northern Hemisphere (4). The ^{131}I released was about 330 PBq; while the ^{134}Cs was about 35 PBq and the ^{137}Cs was about 70 PBq. (The exact amounts may never be known, but these are the generally accepted values based on several approaches to the source term.) These volatile radionuclides were released during the 9 days that the graphite-moderated reactor burned; only 25% were released initially (4). Thus, the resulting radioactive footprint was diffuse and the consequence of wet and dry deposition.

The most intense part of the radioactive footprint left a unique environmental marker. We were able to use satellite images to delineate the Chernobyl damage to the adjacent radiosensitive pine forest that runs 8 to 10 km west of the Chernobyl reactor (5). Infrared images were taken weekly by the Landsat 4 Thematic Mapper Satellite as it passed over most of the Earth. Images from the Chernobyl region were used and by enhancing the infrared reflectance wavelengths for those bands corresponding to chlorophyll and moisture, it was possible to discern living from dead pine trees. Thus, from an altitude of about 700 km, a crude spatial and temporal map of the heaviest hit region was developed. Because pine trees have about a median lethal dose of 6 Gy (6), the images, beginning approximately 3 weeks after the accident, indicated a western swath of dying and dead trees, the so-called red forest. It was later learned that the map was correct but the doses were not. The trees actually had received doses of over 100 Gy (7), but regardless of the dose, the technique showed where the doses exceeded a 6-Gy detection threshold. Over the next 10 years, much of the damaged forest left standing has shown major regrowth and repair. The more resistant deciduous trees showed significantly less radiation damage than other types of trees.

Acute radiation syndrome was diagnosed in 145 Chernobyl workers and rescue personnel; two died immediately, one more died of a heart attack, and 28 died within 2 months of burns and radiation sickness (8). Dosimeters used at the time of the explosion had a 20-mSv limit, so estimates of higher doses are based on clinical and biological end points (9).

Mitigation activities since the accident have employed some estimated 300,000 to 600,000 liquidators or clean-up personnel consisting of approximately half civilian and half military. Not all of these people carried radiation dosimeters during the first few months after the accident, so reconstruction of personal doses to the early liquidators has

been completed primarily by indirect means or by use of biological end points. The lack of dosimeters was most significant for the first 6 weeks after the accident. Preliminary estimates of the average worker doses received during the first 3 months after the accident are about 300 mGy, based on limited biological dosimetry. Overall average doses to clean-up workers taken from the Russian Obninsk Registry are estimated at about 170 mGy in 1986, 130 in 1987, 30 in 1988, and 15 mGy in 1990 (10). When full-dose reconstruction is completed, these estimates may need adjusting for possible additional exposure from internal emitters.

Evacuations took place during the weeks following the accident such that by September 1986 some 116,000 people were reported to have been relocated. Thirty hours after the accident, the 49,000 inhabitants of nearby Pripjat were evacuated and within 3 days, the 11,000 occupants of 15 villages within the 10-km zone of the reactor were also removed. By May 7, 42,000 additional people from 83 settlements within the 30-km zone were also evacuated. The rest, mainly in Belarus, were evacuated throughout the summer of 1986 (11).

The whole-body doses to the 4 million people in heavily contaminated areas (i.e., $>37\text{ kBq m}^2$, five times the levels from fallout from atmospheric weapons tests) are still being estimated (12). Based on past experience, the apparent low average dose estimates at this time make it unlikely that there will be measurable increases in leukemias or other cancers from the whole-body exposures of the population (13). There are plans for joint epidemiology studies to determine if the incidence of leukemias was increased (11).

The principal medical consequence of Chernobyl to date is a significant increase in childhood thyroid cancer, which appears to be directly related to consumption of radioiodine-laden milk during May and June 1986. About 400,000 persons had thyroid radioiodine measurements performed, including about 100,000 children then under the age of 15 (Table 1). While about

Table 1. Preliminary estimates of thyroid dose distributions among children with thyroid measurements.

Estimated thyroid dose, mGy	Belarus		Ukraine	
	Number	Percentage	Number	Percentage
0-300	13,556	49.8	45,938	60.3
300-1000	8,631	31.7	19,293	25.3
1000-20000	2,808	10.3	5,684	7.5
2000-5000	1,743	6.4	3,698	4.9
5000-10000	370	1.4	1,012	1.3
>10000	111	0.4	530	0.7
Total	27,217	100	76,155	100

half the children reportedly received thyroid doses below 300 mGy, some 5 to 8% received over 2 Gy and about 600 received over 10 Gy (11). Efforts at retrospective dose estimation for radioiodine based on cesium measurements long after the fact will have to correct for the different dynamics of radiocesium compared to radioiodine in the environment. This information can add additional structure to the role of the spatial and temporal distribution of these radionuclides for both dosimetry and the health statistics. Preliminary results indicate that the childhood thyroid nodules and cancers are likely to have resulted mainly from ingestion of large quantities of radioiodine. Efforts are being made to obtain better estimates of individual thyroid doses for these children (14).

Children under 15 years of age rarely show thyroid neoplasms; the normal rate per 5-year interval is thought to be less than 0.5 per million children. With what appears to be a very short latent period, about 4 to 5 years, the comparable rate since 1990 seems to have increased up to 3 to 100 per million children (Table 2) (11). The cancer rate has not diminished and is now well over 1000 cases. The data also show that boys have about a 50% higher rate than girls (15). It is likely that the final incidence will rise further, up to about 3000 to 6000 cases (Figure 1).

Recently, there have been reports of possible increases in cataracts in children exposed to low linear energy transfer (LET) radiation, and the preliminary data suggest the possibility that the radiation dose threshold for this condition may be quite low, if it exists at all (16).

Another consequence of the accident is related to communication, miscommunication, and lack of communication. A serious cloud of doubt arose, especially about the manner in which the initial official information was disseminated. Fear precipitated by exaggeration in the popular press was mixed with public pronouncements attempting to

minimize the risks. This contributed to a resulting widespread radiophobia. An underlying assumption of this condition gives credibility to the notion that many adverse health conditions stem from hidden radiation exposures, sometimes synergistically interacting with chemical environmental pollution. Although there now is no dosimetric support for this belief, its consequent psychological stress is quite real to many of the residents near and far from the reactor. The effects of this widespread stress may have ramifications beyond the area of psychology; whether it exacerbates a wide spectrum of adverse consequences has yet to be proven. Reports of thousands of premature deaths, especially among the liquidators, may be only anecdotal and have not yet been subjected to rigorous analysis or shown to be related to radiation exposure. Caution should be taken to avoid overinterpreting these reports. Most of the population who experienced stress and feelings of anxiety after the accident have not received consistent and credible assistance in either understanding their stress or mitigating it. It remains a challenge for the scientific and the political community to address jointly.

Chelyabinsk

In 1948, a nuclear weapons production complex, MAYAK, was established on the Techa River in the Southern Urals, approximately 100 km northeast of Chelyabinsk. A town of approximately 100,000 or more people (Chelyabinsk-65, now Ozersk) was constructed nearby to support and staff the facility. During its first 5 years of operation in particular, inadequacies in technology and safety procedures resulted in massive releases of radioactivity into the surrounding environs as well as significant worker exposure. Radioactive materials in the vicinity of the MAYAK plant in the southern Urals are as follows:

- releases into the Techa River, 3×10^6 Ci (contaminated area, 10^6 km²)

- releases into Lake Karachay, 120×10^6 Ci
- releases into other bodies of water, amounts unknown
- buried solid waste, 2×10^6 Ci
- storage containers, 10^6 Ci
- release from 1957 Kyshtym accident, 2×10^7 Ci (contaminated area, 23×10^3 km²)
- scattered by wind from exposed bed of Lake Karachay (1967), 0.6×10^6 Ci (contaminated area 1.8×10^3 km²)
- releases into the atmosphere from normal operations: significant; quantity unknown

Annual worker overexposures exceeded 1 Gy for about one-fourth of the radiochemical workers and about 7% of the reactor workers in the 1948 to 1953 period (Table 3). Instances of 2 or more Gy of external radiation in a year were recorded. Internal doses were also high, and it is reported that between 5 and 10 workers died of chronic radiation damage to the lungs from plutonium inhalation (Table 4) (17).

In 1957, an explosion in a fuel reprocessing facility released a large plume of long-lived radionuclides covering a swath to the northeast of some 25,000 km². A decade later, a prolonged drought lowered the water level of a radioactivity holding pond (Lake Karachai) to the point that a severe wind storm was able to resuspend significant amounts of radioactivity and add another 10% or more to the East Ural Radioactive Trace. Radioactive material released from MAYAK into the Techa River from 1948 to about 1955 caused the surrounding areas to become heavily contaminated, with levels of contamination decreasing relative to distance. Today the river bank still emits about 0.01 Gy/hr, and radioactivity can be found all the way to the Arctic Ocean, via the Techa, Iset, and Ob River systems.

Four decades later the worker radiation doses have been related to increased incidences of lung cancer and leukemia.

Table 2. Number and incidence of childhood thyroid cancer (children under 15 years at time of diagnosis) in Belarus, Ukraine, and Russia before and after the Chernobyl accident.

Area	Number			Rate, million		
	1981-1985	1986-1990	1991-1994	1981-1985	1986-1990	1991-1994
Belarus	3	47	286	0.3	4.0	30.6
Gomel	1	21	143	0.5	10.5	96.4
Ukraine	25	60	149	0.5	1.1	3.4
Northern 5 regions	1	21	97	0.1	2.0	11.5
Russia	NA	NA	NA	NA	NA	NA
Bryansk, Kaluga	0	3	20	0	1.2	10.0

NA, not available.

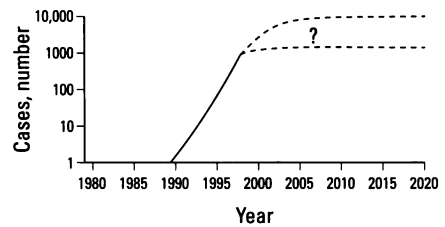


Figure 1. Childhood thyroid cancer cases to date and estimation of possible future incidence.

Table 3. MAYAK workers, external exposure.

	Reactor		Radiochemical plant	
	1948–1953	1954–1958	1949–1953	1954–1958
Working interval	1948–1953	1954–1958	1949–1953	1954–1958
Number of workers	2000	700	3000	1800
Average individual dose, rad/year	33	6.5	70	17
Percent exceeding 100 rad/year	6.5	0.15	23	0.1

Table 4. Populations exposed, southern Urals.

Area	Number exposed	Received high doses	Relocated
Techa River, 1948–1955	124,000	28,000	7,500
Kyshtym, 1957	272,000	45,000	10,000
Lake Karachay, 1967	42,000	4,800	None
Chelyabinsk-40 + nearby villages	~100,000	?	?
MAYAK workers, 1948–1972	12,000	~10,000	?

Analysis of the situation is seriously complicated, however, by high cigarette consumption rates in these populations. Furthermore, many of the exposures are both internal and external, although the initial impression is that external exposures generally account for about 80 to 90% of the total (17). Worker dose records may be quite complete in many respects, but an independent assessment of the dosimetry has not yet been done. More than half the original worker cohort is still being followed. The worker populations are those either at the reactors or at the plutonium reprocessing plants. Available data show that the highest exposures were sustained from 1948 to 1958 (Table 3). During this decade, the mean external dose to men was less than 1 Sv.

In addition to the oncologic risk, workers who were heavily exposed during the 1948 to 1958 period were at risk for chronic radiation sickness (CRS). The condition is characterized by chronic fatigue, depression, and an altered blood picture (18). The occupational doses during that decade were quite high, averaging about 3 Gy, and included about 11% of the workforce receiving an average of 6.3 Gy external radiation. After 1958, radiation dose rates were markedly reduced and no workers employed after that date were reported to manifest CRS.

The leukemia rate in workers at the reprocessing plants peaked about 2 to 5 years after the peak exposure rates and is in agreement with that observed in Japanese atomic bomb survivors (19). The data also suggest that the leukemia excess relative risk is about 1.4 per Gy, which is approximately 3-fold less than that for the atomic bomb survivors

(17). This might suggest that protracted exposure lowers the risk but does not markedly change the latency period.

Lung cancer mortality was elevated in the radiochemical plant workers and was even higher in workers at the plutonium production facility but not in the nuclear reactors where all exposures were primarily from external sources (Table 5) (19). Lung cancer mortality in workers at the nuclear plants does not appear elevated in exposed groups, some of whom averaged over 5 Sv (Table 6).

From 1948 to 1958, doses in male workers with measured Pu body burdens were about 5 Sv (including 43% from external gamma exposure), but the Pu production workers averaged about 14.3 Sv (only 6% was gamma). They showed a standard mortality ratio (SMR) of 5.3 for lung cancer compared to an SMR value of 2.3 for the radiochemical workers. Preliminary evaluation of the data suggests the risk over a 50-year period to be 1.42% per Sv (20). The lung cancer risk does not seem to diminish with time as in leukemia. However, the excess relative risk per Sv is similar to that of atomic bomb survivors (0.46 per Sv) (17). More recent analyses suggest that the excess relative risk may be about 0.23 per Sv, ranging from

Table 5. Radiochemical (internal-Pu) and nuclear reactor (external-gamma) workers (hired between 1948 and 1958).

Cohort	Plutonium workers	Reactor workers
Numbers of workers with known status	1,479	1,841
Person-years	31,693 ^a	67,097
Lung cancer deaths	105	47
Average external gamma dose, Gy	1.78	1.02
Average lung dose from Pu, Sv	6.56	—

^aPerson years calculated from 1970 when Pu burdens were first estimated.

0.21 at lower doses to about 0.4 per Sv at doses of about 25 Sv (Table 7) (20).

From about 50 years of age onward, the age-specific lung cancer mortality rate was 2 to 3 times higher in Pu-burdened workers than in reactor workers or the general population. The reactor workers, despite large doses (mainly external low LET) did not experience increased mortality rates with increasing dose, at least in the range studied (Table 8).

The villages along the Techa River downstream from the MAYAK plant were subjected to effluent releases, especially during the first 5 years of the plant's operation. High concentrations of ⁹⁰Sr and ¹³⁷Cs were incorporated into the local food and water supply. As a result, internal radionuclide doses reached very significant levels in the closest villages (Table 9). Some of the population and some of the heavily exposed workers had symptoms of chronic radiation syndrome. Five to 20 years later, acute leukemia and chronic myelogenous leukemias were recorded in the affected populations (21). Initial evaluations suggest an absolute leukemia risk factor of 0.48 to 1.1 per 104 person-years (PY) Gy, a value some 3 to 5 times lower than that for the atomic bomb survivors (2). The ⁹⁰Sr bone burdens and doses were high, and the adjacent marrow was heavily irradiated. Coupled with the worker leukemia data and compared to other studies in which the

Table 6. Lung cancer mortality rates at different doses of external γ -irradiation among MAYAK nuclear workers.

	Dose, Gy				
	0.45	1.37	2.69	5.54	Total 1.02
Observed number of deaths	22	17	6	2	47
Expected number of death	32.17	14.66	8.29	1.11	56.23
Standard mortality ratio	0.68	1.16	0.72	1.81	0.84
	(0.40–1.17)	(0.58–2.30)	(0.26–2.03)	(0.19–17.46)	(0.57–1.22)
Age-standardized mortality rate	49.5 ± 11.2	83.9 ± 21.7	51.4 ± 25.2	131.0 ± 106.5	60.5 ± 9.5
Excessive relative risk per 1 Sv	–0.704	0.117	–0.103	0.146	–0.161

Table 7. Lung cancer mortality from α radiation doses to lung among MAYAK radiochemical plant workers.

	Dose, Sv					Total 6.56
	0.7	3.7	11.7	24.6	89.6	
Observed number of deaths	27	24	21	13	20	105
Expected number of deaths	23.48	12.40	3.80	1.24	1.27	42.18
Standard mortality ratio	1.15 (0.67–1.98)	1.94 (0.99–3.79)	5.53 (1.90–16.05)	10.51 (1.74–63.40)	15.78 (2.73–91.38)	2.49 (1.75–3.53)
Age-standardized mortality rate	83.3 ± 21.3	140.1 ± 39.8	400.1 ± 119.2	760.8 ± 297.0	1142.7 ± 363.7	180.2 ± 3.8
Excessive relative risk per 1 Sv	0.213	0.256	0.385	0.386	0.165	0.227
Excess absolute risk for 50 years, % per Sv	0.77	0.93	1.39	1.40	0.60	0.82

Table 8. Age-specific lung cancer mortality rates, cases per 10⁵ person-years among MAYAK workers.

Age, years	Pu-burdened workers	Nuclear reactor workers	National average values
30–39	0	0	4.8
40–49	69 ± 22	41 ± 16	40.9
50–59	353 ± 54 ^a	87 ± 24	157.2
60–69	824 ± 127 ^a	267 ± 61	296.7
70–79	1275 ± 385 ^a	546 ± 206	279.7 ^b
80+	0	735 ± 733	—

^aSignificantly higher than in the other two groups. ^bRate is for age 70+.

Table 9. Dose estimates, Techa River inhabitants from selected villages.

K _m from point of discharge	Number of inhabitants	External dose, rem			Internal dose, rem	
		Children	Adolescents	Adults	Red bone marrow	Bone surfaces
7	1242	106	213	101	164	226
27	892	71	143	68	127	190
78	3230	5.8	11	5.7	61	143
138	1372	1.9	3.2	1.9	22	53
237	1135	NA	NA	NA	17	40

NA, not available.

peak dose rate varied, it is likely that there is a wide range of values for a dose-rate reduction factor (Figure 2). Unlike animal studies of the effects of chronic ⁹⁰Sr exposures (1), no increase in estrogenic cancers was reported in the exposed people.

Semipalatinsk

Semipalatinsk is the name usually associated with the atomic device testing site in northern Kazakhstan, just south of the Altai region of Siberia. Since 1949, this site has been used to test atomic devices detonated in air, on the surface, or underground. Until the 1963 limited test ban treaty required underground containment of fission products, many atomic plumes emanated from the site.

Of particular concern is the first explosion on 29 August 1949. Table 10 shows that approximately 25,000 people reportedly

were exposed to average doses more than 130 mSv, and about 10% exceeded 1 Sv (22). Recently, a concerted effort was mounted to reconstruct the doses and evaluate the possible health effects. Initial information is now available on individual lifetime risk, on health detriment, and on annual radiogenic cancer mortality. It is understood that there may not yet be a cancer or leukemia registry for the population. Nevertheless, initial calculations estimate that the leukemia risk appeared within 2 years, peaked at approximately 10 years, and seemed to return to normal levels at 25 years (22). In contrast, for lung cancers, a review of data on men estimated to have received more than 500 mSv appears to show an increase by approximately 10 years, a peak at about 25 years followed by a shallow reduction in lung cancer mortality rate to approximately half the peak value in 45

years (22). Cancer morbidity and mortality data, particularly from possible radioiodine impacts on thyroid disease, is not yet available. The dose reconstruction and health effects evaluations are in progress.

There are nuclear material processing sites in Siberia at Tomsk-7 and at Krasnoyarsk-26. These began operation somewhat later (1955) than those mentioned above and perhaps because of lessons learned from the first enterprises, population and worker overexposures may be less significant. To date, specific information on possible health effects have not been reported. In April 1993, a chemical explosion at Tomsk-7 destroyed a processing tank and parts of the facility. Worker exposures are reported to have been less than 1 cSv. A trace contaminated about 250 km² and extended some 20 km to the northeast. External dose rates seem to have been low, less than 2 times background, but plutonium contamination was also present at levels of about 20 MBq/m² (23).

The complex at Krasnoyarsk is largely underground. Little is known of any exposure problems. On the banks of the Yenisey River in Siberia, there is concern about radioactive effluents that may have been released. There are reports of contamination at levels up to 10 times that of background levels (23).

Nuclear-powered submarines and surface vessels have had their share of mishaps, releases, and overexposures, but an integrated evaluation of consequences is not yet available.

Discussion and Conclusions

One of the major post-cold war issues is the clean-up, decommissioning, and possible decontamination of sites associated with the manufacture and testing of atomic weapons. In the United States, for example, total clean-up cost estimates range up to a trillion dollars over the next several decades, assuming a policy of complete restoration to preatomic era levels is implemented. Perhaps the radiation lessons from the former Soviet Union will provide significant relevant radiation exposure and health effects information that will be useful in setting priorities for the order in which the sites are to be cleaned up and will assist in identifying sites where the risk to the nearby population may truly be minimal.

Compilation of these data, which constitute a collective dose that is likely to be larger than that received by the atomic bomb survivors, provides the potential for a human database for chronic, protracted low

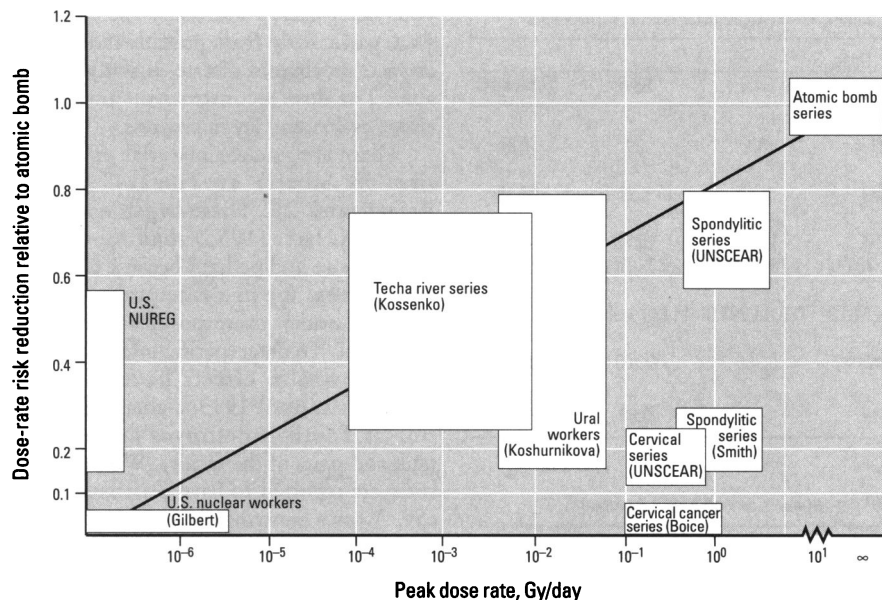


Figure 2. Leukemia risk dose-rate reduction factor relative to that of atomic bomb survivors.

Table 10. Number of exposed persons with average radiation doses less than 130 mSv on 29 August 1949 (as of 28 December 1994).

Dose, mSv	Sex	Age at time of exposure			Total
		0-19	20-49	≥ 50	
>130	Male	5,165	4,509	1,335	11,009
	Female	5,198	6,551	2,264	14,013
	Total	10,363	11,060	3,599	25,022
Consisting of	Male	722	573	157	1,452
	Female	767	905	303	1,975
	Total	1,489	1,478	460	3,427
>500	Male	2,125	1,898	626	4,649
	Female	2,088	2,606	1,001	5,685
	Total	4,213	4,504	1,627	10,344
>1000	Male	609	441	173	1,223
	Female	609	619	264	1,492
	Total	1,218	1,060	437	2,715

and high LET radiation that is unique in the world. If the preliminary indications suggested are indeed validated, radiation protection will gain several important new insights and tools. We will be able to confirm whether the animal studies were correct in indicating that the average latency period appears to become longer in many if not most cancers when the dose rate is reduced (1). We will learn the essential factors that relate plutonium lung burdens to lung

cancer risk, an important factor in understanding lung cancer risks from radon daughter product inhalation. We already know from animal studies that the risk for leukemia from protracted relative to acute radiation appears to be quite low. From the Techa River ^{90}Sr exposures to people, we may learn if there is also a significant human radiation leukemia dose-rate deduction factor. Additionally, the clinical information on chronic radiation syndrome is unique and

may provide better insights into the significant pathways involved in initial injury and subsequent repair of radiosensitive systems. This information can assist in improved planning for treatment of unintentional or accidental overexposures.

The special demonstration of childhood sensitivity to Chernobyl's radioiodine-induced thyroid abnormalities unfortunately is still unfolding. The dramatic inverse relationship between age and sensitivity is one of the initial observations, as is the relatively short latency period in children between exposure and onset of disease.

The cost of the cold war was enormous and still is not fully calculated. Cost of radiation health effects, disease, and environmental degradation must be included. As large as these costs appear to all of society, they are small relative to those of an atomic war. Society so far has been successful in implementing a nuclear deterrent, a victory for us all. However, the experience of these early atomic workers in the former USSR and their neighbors taught us that the consequences of significant radiation overexposure cannot be ignored. These exposed people should be considered radiation heroes, and we must learn all we can from their costly experiences.

The data also show us that at very low doses (in the range of natural background radiation), radiation consequences indeed may be negligible and controllable. The data also add a new dimension to our knowledge about radiation and its effects and show how large radiation doses must be to initiate demonstrable latent health effects.

It is only with this kind of full-spectrum information, which permits us to integrate radiation quality and dose distribution in space and time, that radiation protection philosophy will become based more firmly on sound and solid science. Information about which exposures are significant and which are not must be validated carefully before being incorporated into any radiation databases. That this process has begun is reassuring. This radiation legacy is one from which we all must benefit as we address the potential for a peaceful and effective role for the atom in medicine, industry, and society.

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