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Analysis of the 1957–1958 Soviet Nuclear Accident

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Summary. The presence of an extensive environmental contamination zone in Cheliabinsk Province of the Soviet Union, associated with an accident in the winter of 1957 to 1958 involving the atmospheric release of fission wastes, appears to have been confirmed, primarily by an analysis of the Soviet radioecology literature. The contamination zone is estimated to contain 10^5 to 10^6 curies of strontium-90 (reference radionuclide); a relatively small fraction of the total may have been dispersed as an aerosol. A plausible explanation for the incident is the use of now-obsolete techniques for waste storage and cesium-137 isotope separation. However, the source of the contamination was not unequivocally attributable to a single event, and its exact nature must await release of more information by the Soviet Union. Radioactive contamination appears to have resulted in resettlement of the human population from a significant area (100 to 1000 square kilometers). It therefore seems imperative to obtain a complete explanation of the cause (or causes) and consequences of the accident; Soviet experience gained in the application of corrective measures would be invaluable to the world nuclear community.

An extensive and comprehensive set of reports and speculations about a possible Soviet nuclear accident in the Urals has recently been published by Z. A. Medvedev (*1*, *2*), an exiled geneticist now living in London. He concluded that a radioactive contamination zone [also reported by Tumerman (*3*)] in Cheliabinsk Province was created in the winter of 1957 to 1958. He alleged that it resulted from a massive explosion at a military site [east of the city of Kyshtym and south of the city of Kasli near the Techa River (*4*)], where long-lived, high-level fission wastes had been improperly buried for many years, and produced hundreds of civilian casualties. On the basis of information from Soviet radioecology studies, which he believed were conducted near the site of the catastrophe, Medvedev suggested that the contamination zone contained 10^7 to 10^9 curies (Ci, a unit equal to 3.7×10^{10} disintegrations per second) of strontium-90 and extended over "several thousand square miles" (*1*, *2*).

We have conducted an independent analysis of the Soviet literature on radioecology and nuclear technology to resolve our doubts about the nature and consequences, indeed even the occurrence, of the incident (*5*–*7*) reported by Medvedev. After analyzing the evidence from ex-Soviet citizens (*1*–*3*), the Central Intelligence Agency (*4*), and radioecology publications, we have concluded that a major airborne release involving moderate- to long-lived fission products (but, inexplicably, with most of the cesium-137 removed) occurred near the city of Kasli (50-kilometer radius) in Cheliabinsk Province of the U.S.S.R. in the winter of 1957 to 1958. Our analysis indicates that an extensive area ($\geq$ 25 to 100 square kilometers) was contaminated with high levels of radioactivity—about 1 mCi of ^{90}Sr (chosen as the reference radionuclide) per square meter. The total area contaminated at levels significantly above fallout background could exceed 1000 km^2.

It was not possible for us to determine whether the contaminated zone was created by a single event, several events (permutations and combinations of accidents and nonaccidents), or complex releases associated with a single accident. However, it appears that the incident involved the release of 10^5 to 10^6 Ci of ^{90}Sr (reference). In addition, extensive ice and snow cover may have delayed the transfer of some of the radionuclides into soil and surface waters for up to 5 months (*8*). The data suggest a minimum airborne contribution to the contamination zone on the order of (0.3 to 1) $\times$ 10^5 Ci of ^{90}Sr. The critical missing information is the history of the drainage of one large water body and the time sequence of radionuclide inputs (and losses) between 1948 and 1975.

The available evidence indicates that the most likely cause of the airborne contamination was the chemical explosion of high-level radioactive wastes associated with a Soviet military plutonium production site. An absolute determination of the cause is limited both by the fragmentary nature of the available information and by the potential censorship of isotopic content and concentration data in Soviet open literature publications.

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Radioecology Studies in the Contamination Zone

We have surveyed an extensive set of contemporary Soviet radioecology articles devoted to field studies in an area that may have been accidentally contaminated, such as the Kasli area (KA) (*9–57*); locations of contaminated study sites are never provided directly by Soviet authors. A pervasive characteristic of these studies is the statement that the radioisotopes, moderate- to long-lived fission products (primarily ^{90}Sr, but also ^{144}Ce, ^{137}Cs, ^{106}Ru, and ^{95}Zr), were experimentally applied *once* as nitrate solutions (*12–16, 33, 41, 46*) to soil or water surfaces, in quantities sufficient for accurate radiological analyses. The level of application was typically between 0.3 and 3.4 mCi/m^2—except for ^{137}Cs (4 to 8 μCi/m^2) in association with ^{90}Sr (0.6 to 3.4 mCi/m^2) in terrestrial studies—over land and water areas which are often incredibly large for experimental studies.

Reticence about site identification in ecological research is most peculiar. The interested reader will encounter later papers by authors associated with KA studies which make this point effectively (*58–60*). In two cases (*58, 59*), data were obtained from an area (Kunashak district) northeast of the site alleged to be the source of the contamination; this may have served as the "control" for KA radioecology investigations.

Research results reported by contemporary scientists at other locations in the U.S.S.R. (*61*) show that high levels (millicuries per square meter) were not required for radiological analyses. The levels applied in KA studies were, in fact, producing either genetic effects or demonstrable toxicity (*15–17, 29, 32–35, 37–40, 54, 56, 57*). This could confound studies of radionuclide transport, the stated object in the majority of cases. The methods by which these large areas were contaminated were not provided.

The exclusive use of the nitrate appears unusual, since in our country isotopes were typically supplied as chlorides (except zirconium, as the oxalate) for research purposes (*62*). Contemporary Soviet scientists, working at the Urals Scientific Center, reported application of the isotopes exclusively as chlorides (except zirconium, as the oxalate) in other, unrelated radioecology studies (*63, 64*), indicating that Soviet practice was probably not significantly different. The nitrate form is that in which fission products were usually held during fuel reprocessing, radiochemical separations, and high-level liquid waste storage (*62, 65–77*).

The reporting of data, often for the first time, after relatively long times—that is, 6, 10, 11, 13, or 14 years following contamination (*9–13, 15, 17, 27, 30, 41, 42, 46, 47, 54, 55, 57*)—is also an unusual characteristic. Twenty studies (*10–17, 30, 41, 42, 46–48, 51, 53–55, 57*) indicate a starting date between 1957 and 1961, assuming a 1-year time lag between data collection and publication. The majority of these indicate a date of contamination in 1957 to 1958 (*10–12, 14–17, 30, 42, 46–48, 51*). There are internal inconsistencies in one series of terrestrial radioecology papers (*18, 20–23, 25–27, 29–32*) about the date of contamination. However, the confusion is alleviated by information in three independent sources (*17, 30, 78*). The combined information indicates that the terrestrial study area was first contaminated in the second half of 1957.

Several papers (*9, 42, 57*) indicate that isotopes were deposited in a single aerosol event, a critical revelation which supports an accident case. In one instance, the application was to a group of 13 closed (nonflowing) lakes (*42, 45, 46, 48–53*), two of which had surface areas of 4.5 and 11 km^2. The radioisotopes reportedly deposited were ^{144}Ce, ^{90}Sr, and ^{106}Ru (activity ratios $\sim$ 10:1:1, respectively); there was no mention of ^{137}Cs until 12 to 15 years later. The initial ^{90}Sr concentrations were approximately 0.8 mCi/m^2 for the two lakes described. In another case, ^{90}Sr was applied to the canopies of two distinct forest types (30 to 60 years old) (*9, 57*). The implication that these were part of planned experiments is unrealistic [this is our conclusion, but also see (*79*)].

An indication that not all the lakes in the group of 13 were heavily contaminated (perhaps only two were) may be provided by a cryptic reference (*80*) in a Soviet textbook on radioecology to "the situation in a certain region prior to the beginning of global fallout caused by accidental contamination of a water body. Since the ^{90}Sr concentration in the water was rather low the water body was used for a variety of purposes (water supply, farming, etc.)." This refers to data from a Soviet paper on the human food chain (*81*) associated with a contaminated lake, which was to have been presented at a 1966 symposium, but which was withdrawn. Another indication is that extensive, long-term radioecology studies have been reported on only the smaller of the two water bodies described above (*42, 46*).

Another large, "natural" water body (*19, 24, 28, 39, 40*) with a partially open drainage—Medvedev's Lake X, with an estimated surface area $>$ 10 km^2 (*1, 2, 5, 6*)—had a ^{90}Sr concentration in 1969 to 1975 (0.2 μCi/liter in water) comparable to that of the two lakes described above at the time of their original contamination. Unlike the other two, it had obviously received a significant quantity of ^{137}Cs (the activity ratio of ^{90}Sr to ^{137}Cs in water reportedly varying between 8:1 and 40:1); it had also apparently received higher inputs of airborne or liquid activity because of proximity to the source. If the conditions represented an equilibrium after a single input in 1957, then the ^{90}Sr inventory of this one system alone could have been 1×10^6 Ci (*5*); our estimate based on the most recent Soviet data (*28, 40, 82*) is (1 to 2) $\times$ 10^5 Ci. Since we do not have a detailed history of this lake's drainage, it was not possible to determine absolutely whether this water body received ^{90}Sr and ^{137}Cs in proportions similar to those reported in the studies of terrestrial areas ($^{90}Sr/^{137}Cs$ activity ratio $\geq$ 100:1) or whether the isotope ratio was more nearly unity—that is, typical of unseparated fission products (*69*). The latter case seems more likely on the basis of our review of other Soviet experiences (*43, 61, 82, 83*) and the most recent information on this lake (*28, 40, 82*).

This lake also has four companions which are contaminated to varying degrees with ^{90}Sr (0.002, 0.007, 0.024, and 0.1 μCi/liter) and ^{137}Cs (only one value given, 0.01 μCi/liter; $^{90}Sr/^{137}Cs$ activity ratio, 10:1) (*28, 43*). This group appears distinct from the set of closed lakes described earlier. One is reported to have an uncontaminated shore and appears to contain ^{137}Cs at a level many orders of magnitude higher than that of ^{90}Sr (*28*). One is said to be "adjoining" another; "riverine" ducks have been collected in associated radioecology studies; and inundation, along with deposition of contaminated sediment on the "riparian belt," was reportedly responsible for high contamination levels in one shorebird nesting area (*28*). The presence of small, temporary (but uncontaminated) water bodies, streams, and pools around one water body (after the spring thaw) was also noted (*27, 28*). These observations appear to be more consistently explained by "a waterborne release (i.e., involving contamination of a river system, a series of lakes/reservoirs, and associated floodplain/marsh areas)," which we suggested earlier (*5*), than by an aerosol event.

For our analysis, we have assumed that this large water body and its companions were contaminated by the same event [based on cross-references in (*27,*

28, 40)] that resulted in contamination of the other areas described, but that a large fraction of the radioactivity may have entered in liquid rather than aerosol form and over a longer time period. We cannot dismiss the possibility that this large water body was primarily contaminated by a totally different mechanism, such as earlier chronic releases (4, 5). We are aware of at least one other case where high concentrations of fission or activation products, including a ^{90}Sr concentration of 0.01 μCi/liter in water, have been maintained in a closed lake (size and location unknown) by chronic discharges from a Soviet reactor complex that began operating before 1957 (83). Thus, any judgment about the actual source of radionuclides for this one large water body must be tempered with caution.

The location of the radioecology study area can be determined within reasonable limits by combining fragments of information (on fauna, vegetation, soil, and so on) from the literature (6). For example, one publication (49), together with information in one of its own citations (84), indicates that the group of 13 lakes was located in the forest-steppe zone in the eastern Urals between the cities of Cheliabinsk and Sverdlovsk. The author was associated with the Sungul Nuclear Research Institute (70), one of two nuclear installations reportedly located near Kasli (4), when he published his first work in 1961 (53). The biota and soils reported in KA field studies are consistent with those of that area (8, 85, 86). One paper specifically places the terrestrial study area in Cheliabinsk Province (30) and another uses Lake Alabuga, located just east of Kasli, as a control for a radiobiology study (43). The particular set of soil-vegetation types studied are proximate near Kasli (85, 86). There are more than 100 lakes, indicated on high-resolution maps (see below), within a 50-km radius of Kasli; the majority have closed drainages.

One can estimate the extent of the area contaminated with ^{90}Sr by an aerosol at $\sim$1 mCi/m^2 by several methods (6). An estimate can be based on the interconnecting watershed-water area required for the three heavily contaminated lakes described earlier, for instances where these lakes, of surface areas 4.5, 11, and $>$10 km^2 (open drainage), are proximate. Another method (1, 2, 5, 6) is based on the area required to support a reasonable harvest of 16 animals from a deer herd under the climatic conditions of the region (8, 86). A third method involves examination of spatial separation between the major soil-vegetation types (11-14, 17, 26, 35, 38, 41, 44, 57) subjected to long-term studies. These methods indicate a minimum size for the high-level contamination zone of 25 to 100 km^2 depending on the degree of conservatism associated with the estimate (5, 6); that is, whether one assumes patchy versus continuous plume deposition and total versus fractional removal of animal populations in sampling.

Identification of Affected Area

Because of the population density in this region of the industrial Urals (8) and the reported levels of ^{90}Sr contamination (87, 88), the incident probably resulted in the evacuation or resettlement of the human population from a significant area. Comparisons of high-resolution (1:250,000) maps of the area between Cheliabinsk and Sverdlovsk based on materials produced before (1936 to 1954) and after (1973 and 1974) the accident indicated deletion of 30-odd names of small communities (population $<$ 2000) from within the dashed area of Fig. 1. None of the names shown on the earlier editions within the 70-km-long southwest-to-northeast arm of the dashed area in Fig. 1 appear on the later editions. A somewhat wider zone (10 to 15 km compared to 7 km) runs in a southeasterly direction toward the Sverdlovsk-Cheliabinsk highway, generally along the Techa River; however, names of a few communities still remain. A number of the communities whose names no longer appear had evidently grown to a population of 2000 or more by the late 1950's (89, 90); these include Boyevka, Yugo-

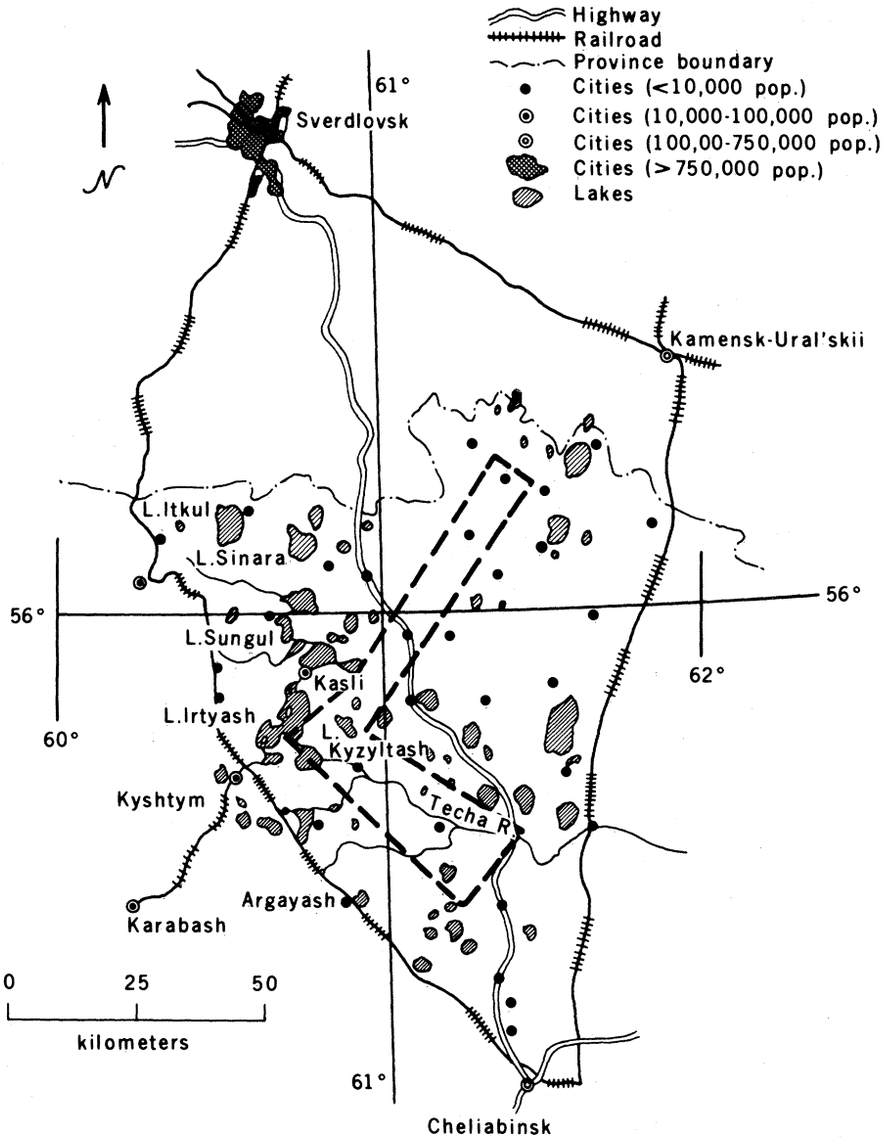

Fig. 1. Geographic region in which a Soviet catastrophe involving nuclear wastes is reported to have occurred. The map is based on geographic features before the accident. The dashed area indicates a zone in which extensive changes in population centers and surface hydrologic features appear after the accident. Redrawn from (89).

Koneva, and Russkaya Karabolka in the northeast arm and Metlino and Asanova in the southeast arm of the dashed area in Fig. 1 (*91*). Further, population centers in other parts of the region appear to have developed extensively in the same period; nowhere else in the Sverdlovsk-Cheliabinsk area have such extensive deletions of community names occurred. Collectively, this information could be construed to indicate relocation of the human inhabitants in a time frame consistent with a contamination incident.

Modification of surface water flow patterns in the Techa River drainage in order to reduce the hydrologic transport of long-lived fission products, rather than aerosol contamination, may have played a significant role in relocating inhabitants from the southeast arm of the dashed area in Fig. 1. The northeast arm (or a segment thereof) may represent the primary area contaminated by a radioactive plume originating near the junction of Lake Kyzyltash and the Techa River, a location reported to contain Soviet plutonium production facilities (*4*). The orientation is that expected for a winter event in this region: prevailing winds are southwesterlies (*84, 86, 90*).

The Techa River no longer drains from Lake Irtyash through Lake Kyzyltash (as indicated in Fig. 1). Water that would have entered Lake Kyzyltash from Lake Irtyash has been diverted into a canal (Fig. 2). The canal transfers water around Lake Kyzyltash and two new reservoirs [also see the map in the German edition of Medvedev's book (*2*)] to a point downstream. A new drainage for Lake Irtyash has also been provided, through Lake Berdenish, into the same canal. Former tributaries of the Techa, which entered in the reach between Lake Kyzyltash and the new reservoirs, now drain into canals, and flows are similarly diverted to a point well downstream. The radioecological evidence cited earlier suggests that Medvedev's Lake X and its companions are water bodies isolated by the canal system (Lake Kyzyltash, new reservoirs, and so on).

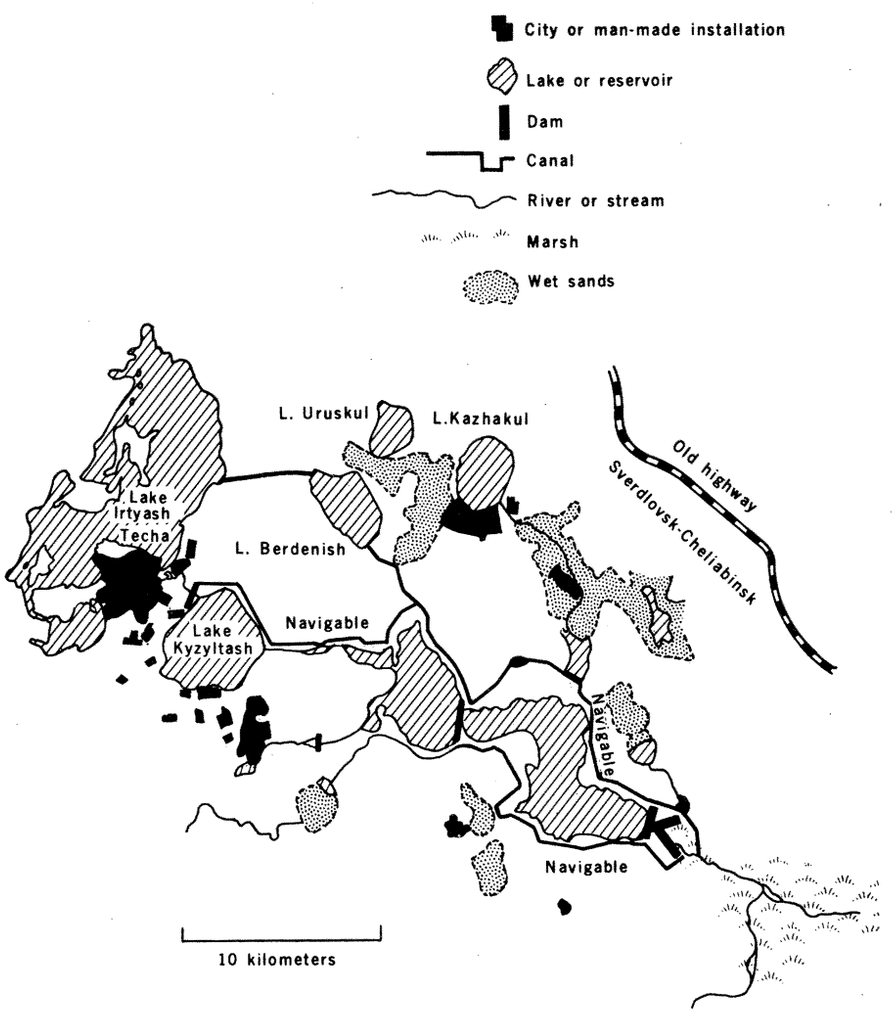

Fig. 2. Reservoir and canal system apparently constructed to reduce hydrologic transport of radioactive materials down the Techa River system. The map is based on features after the accident (1973).

The fact that these two new reservoirs have been isolated hydrologically from the surrounding drainage area (hardly typical practice) strongly indicates that they have been specifically designed to prevent waterborne contaminants (such as ^{90}Sr) from moving farther downstream in the Techa River system. Combined with Lake Kyzyltash, the total surface area available for storage is in excess of 70 km^2, perhaps indicative of the scale of the original watershed-water surface that was most heavily contaminated. The total surface area enclosed by the dashed lines in Fig. 1 is less than 1000 km^2; the exact fraction contaminated is unknown.

Another significant observation is that the northeast arm of the dashed area in Fig. 1 contains three water bodies—lakes Uruskul, Berdenish, and Kyzyltash—of the appropriate sizes and other characteristics to coincide with those described in radioecology studies (*19, 24, 28, 40, 48*). The center line of the possible plume deposition zone also intersects the Sverdlovsk-Cheliabinsk highway at a point 100 km from Sverdlovsk [Tumerman's observations (*3*)?].

The Soviet Union has published its fish stocking records and associated fisheries statistics (*92*) in the open literature, as part of a fisheries improvement program. As expected, the lakes within the dashed area in Fig. 1 have not been stocked, the object of the program being food production for humans. Lakes, including Itkul, Sinara, and companions to the north, have been stocked virtually all around the periphery of the dashed area in Fig. 1 and extensively outside, but not inside. This seems to provide additional support for a conclusion that the total extent of the area currently affected is not significantly larger than 1000 km^2.

We recognize that one has to be cautious about interpreting differences observed on a sequence of maps over a period of 20 to 40 years. However, we believe that the combined information presented supports a case involving an accident or other unplanned environmental contamination, provides further definition of the scale, and seems to contain too many coincidences with other sources to be totally explainable by chance.

Soviet Nuclear Development: Potential Sources

The KA event occurred during a period of intense development and testing of nuclear weapons and reactor technology. The intensity of development was greater in the U.S.S.R. than in the

United States (*93*) because the Soviet Union was racing to achieve parity. At this stage, the two technologies were closely linked (*66, 69, 93*). The reactors that produced the bulk of the fission product inventory outside the U.S.S.R. were graphite-moderated plutonium producers fueled with nearly natural uranium, typified by those at Hanford (*69*). Some heavy water–moderated production reactors were also in existence in 1957 (*94*). Contemporary Soviet production reactors were believed to be similar (*70, 93*).

Because of the secrecy associated with Soviet nuclear development, any analysis of radiochemical separations and waste storage is necessarily limited. Ironically, our only good reference is a 1966 Soviet biomedical research paper in which waste constituents are reported (*95*). The information indicates that the U.S.S.R. developed sodium uranyl acetate precipitation (*96*) for fuel reprocessing and may have used it into the 1960's. The United States originally used bismuth phosphate precipitation for plutonium production (*97*), but discontinued it in the early 1950's in favor of solvent extraction (*94, 98*). Fission product concentrations in first-cycle liquid wastes from the acetate process would typically have been 10 to 100 Ci/liter. Underground tank storage [the U.S. practice (*99*)] for 3 to 5 years would have been expected before this material could have been reclassified as intermediate level (< 1 Ci/liter). At that point, other storage or disposal techniques might have been considered, such as cribbing, earthen pit storage, or deep-well injection (*100*). There is also some evidence that the Soviet Union had developed a solvent extraction process by 1957 or 1958 (*75, 101*).

Although acid storage of high-level waste concentrates in stainless steel tanks was reported to be typical Soviet practice by 1962, this may have referred only to wastes produced by newer solvent extraction processes (*102*), not the acetate process. The alternative of long-term storage of high-level wastes in open, surface reservoirs of earth (both lined and unlined) appears to have been seriously explored (if not implemented) by the U.S.S.R. because of economic considerations (*101, 103, 104*). An intriguing series of related laboratory studies of the potential use of unlined, low-flow-rate, cascaded reservoirs for deactivation and disposal of wastes was published between the late 1950's and the middle 1960's (*63, 105*). In the one known Soviet field test of an unlined system, which was a failure, a gully 3 km long was simply dammed and wastes were directly discharged into it for years before leaks were discovered (*104*).

The potential for accidents and chronic leakage appears to be much greater with earthen reservoir storage of liquid high-level wastes than with controlled tank storage. Mechanisms for dispersal and ^{137}Cs separation would also be more varied because of soil interactions. However, the relationship of these phenomena to an analysis of hazards associated with high-level waste technology outside the U.S.S.R. seems peripheral (*7*).

One other major difference between U.S. and Soviet technologies existed; the U.S.S.R. was producing fission products for agricultural and industrial use on a massive scale. In 1958, reported production of ^{137}Cs was to exceed 1×10^6 Ci (*106*). Contemporary U.S. production of long-lived fission elements was less by orders of magnitude (*107, 108*).

The KA event predates serious consideration of the use of nuclear explosives in civil engineering (that is, for peaceful purposes) (*109*). Although the incident occurred during a period of intense atmospheric testing of large nuclear weapons, extensive evidence against this fallout as the source of the KA contamination zone exists and has been published previously (*7*).

One can hypothesize a case involving accidental detonation of a small (kiloton class) device at a facility for combined weapons production, radiochemical separations, and high-level waste storage. The contamination from a low-yield device could be obscured by that from a particular part of a complex installation and represent only the dispersal mechanism. However, in the United States components of the weapons production process were spatially separated, and installation of a triggering mechanism or arming of a nuclear explosive in proximity to the facilities described seems most improbable. Nonetheless, this serves as an example of a type of accident whose cause (gross negligence, sabotage, "act of God") is essentially unrelated to the technology and could not be deduced without an on-site forensic investigation.

Radioactive "Fingerprints"

We must introduce a caveat at this point—one that applies to some extent to all the cases discussed. That is, we assume, despite obvious evidence of censorship of information about methods, site location, and so on, that the scientific data in our Soviet references had not been altered to mask the occurrence of a specific type of incident, such as a reactor accident. We have discounted this possibility because supplemental evidence seems to be available, but the reader should recognize this as a potential problem (*6, 7*).

The catastrophic ejection of the entire nonvolatile fission product inventory of a production reactor after a prior release of the more volatile ^{137}Cs (*76*) does not appear to have a very credible basis in fact. The Windscale experience in Britain in October 1957, which Soviet authors acknowledge as the largest radioactivity release in reactor history (*87*), would appear to be more typical; in that case (*110*) the principal fission products released were ^{131}I (2×10^4 Ci) and ^{137}Cs (600 Ci; $^{90}Sr/^{137}Cs$ activity ratio, 0.015). Meltdown of the fuel would seem a requisite for our more extreme case. The association of ^{90}Sr, ^{106}Ru, and ^{144}Ce at appropriately high concentrations in KA radioecology studies is not consistent with requirements of a $^{90}Sr/^{137}Cs$ fractionation mechanism based on differential volatility (*76*) in a hypothetical meltdown accident—that is, that both Sr and Cs be significantly separated not only from one another but from Ce and Ru as well. An accident of the type hypothesized would also result in the release of large quantities of Pu. We have found no mention of Pu in the extensive KA radioecology investigations (*111, 112*).

The radioactive "fingerprint" provided by the KA field studies seems instead to indicate an accident involving radiochemical separation operations or waste storage operations associated with the production of weapons-grade Pu, or both. The five radioisotopes (^{95}Zr, ^{90}Sr, ^{106}Ru, ^{137}Cs, and ^{144}Ce) reported in these investigations become dominant in high-level liquid wastes after 1 to 2 years of decay following removal from a reactor (Table 1). Promethium-147, a low-energy beta emitter, while present, would not ordinarily be reported in environmental studies.

Terrestrial radioecology studies report ^{90}Sr and ^{137}Cs activities in soil and organisms whose ratios (^{90}Sr : ^{137}Cs) are two or more orders of magnitude greater (that is, $\geq 100:1$) than those in unseparated fission wastes. Although both isotopes are dominant in long-lived wastes (more than 5 years after removal from a reactor) (Table 1), the $^{90}Sr/^{137}Cs$ activity ratio is essentially equal to unity. The fact that ^{144}Ce was apparently dominant over ^{90}Sr by an order of magnitude at the start of soil (*13, 14*), terrestrial ecology (*15, 17, 57, 78*), and aquatic ecology (*48*) studies argues against release from a high-level waste facility after long-term

Table 1. Ratios of individual reactor fission product activities to the activity of ^{137}Cs for various decay times (*67, 113*).

Isotope	Activity ratio					
	Initial	200 days	350 days	500 days	700 days	1800 days
Strontium-89	42.0	3.2	0.45			
Strontium-90*	1.0	1.0	1.0	1.0	1.0	1.0
Yttrium-91	50.0	5.0	0.92	0.16		
Zirconium-95	54.0	5.8	1.1	0.23		
Niobium-95	33.0	12.0	2.5	0.54		
Ruthenium-103*	59.0	0.94				
Ruthenium-106*	1.6	1.1	0.84	0.64	0.44	
Tellurium-129*	7.7					
Iodine-131	37.0					
Tellurium-132	56.0					
Xenon-133	85.0					
Barium-140*	350.0					
Cerium-141	63.0	1.9				
Praseodymium-143	79.0					
Cerium-144*	34.0	20.0	14.0	9.6	5.7	0.39
Neodymium-147	32.0					
Promethium-147	2.3	2.0	1.8	1.6	1.4	0.62
Total activity per curie of ^{137}Cs†	988.0‡	53.9	23.6	14.8	9.5	3.0
Percent of initial activity	100.0	5.5	2.4	1.5	1.0	0.3

*Includes daughter activity. †Fuel irradiation time, 100 days; ^{137}Cs inventory of a 1000-megawatt (thermal) reactor after 100 days operating time, 7×10^5 Ci. ‡Includes ^{137}Cs contribution.

storage. In one series of aquatic studies ^{106}Ru was also present at the same level as ^{90}Sr at time zero (*48*), and again there is no indication that ^{137}Cs contributed significantly to the total activity. These isotopic activity ratios are what one would expect in reprocessed fission wastes (after a decay time of approximately 1 to 2 years) if and only if ^{137}Cs had been somehow separated (Table 1).

The data in Table 1, coupled with observed variations in actual high-level wastes (*113*), indicate that an activity ratio for ^{144}Ce:^{90}Sr:^{106}Ru:^{137}Cs of approximately 10:1:1:1 actually holds true, within a factor of 2, for the period from 200 days to 2 years. Thus, while the activity ratios reported in KA studies agree well with those in reprocessed wastes for ^{90}Sr, ^{106}Ru, and ^{144}Ce, an intervening ^{137}Cs removal mechanism is required to reduce its level to less than 1/100 that of ^{90}Sr.

Potential Dispersal Mechanisms for High-Level Wastes

One can postulate accident cases where a large quantity of fission products could have been dispersed to the atmosphere (*5-7, 114, 115*). This might have happened, for example, as a result of a violent conventional explosion or fire following a nuclear criticality (superheating effect), ignition of highly flammable solvents, deflagration or detonation of certain historical nitrate wastes, detonation of radiolytically produced hydrogen gas, or even steam pressure buildup (from radiolytic decay heat) in a storage system associated with a radiochemical separations plant.

Explanations for the aberrantly low $^{137}Cs/^{90}Sr$ activity ratios are also potentially quite varied (*6*). The possibility of an incident associated with large-scale radioisotope production seems enhanced by the fact that in 1957 to 1958 the major ^{137}Cs separation scheme was the ammonium alum process (*62, 65, 69, 107*). This process fulfilled all the requirements for a production process stated by Soviet authors (*65*) in their first comprehensive paper on the subject. However, this paper (*65*) did not provide a ^{137}Cs production scheme since ^{137}Cs had already been separated from the material supplied; the alum process was the only production method referenced (*62*). The importance of the alum process is that the resulting wastes could contain significant quantities of ammonium nitrate [certain hexone solvent extraction wastes, and potentially others (*74*), also shared this feature (*66, 69, 73*)].

The explosive qualities of NH_4NO_3 have been well recognized; less well known is the fact that it is a major ingredient in slurry explosives (*116, 117*). At least five major disasters have involved accidental detonation of fertilizer-grade NH_4NO_3 by apparently spontaneous mechanisms (*116*). A chemical explosion occurred at the Chalk River Nuclear Research Laboratories in 1950 in a pilot plant evaporator used to concentrate fission products from a nitric acid–ammonium nitrate solution (*115*). The cause was "the buildup of too large a concentration of ammonium nitrate in the hot evaporator concentrate." Thus a precedent already exists for a radioactive waste explosion when significant quantities of NH_4NO_3 are present.

The ultimate expression of the accident could have occurred, following failure of a cooling system or other safety mechanisms on a large waste storage container, when superheating of slurries or solid residues left in the tank produced either a deflagration resulting from reactions between nitrates and organic contaminants [acetate or solvent decomposition residues (*114*)] or a detonation of NH_4NO_3-containing wastes. The potential energy release could be quite large; for example, 1000- to 3000-m^3 tanks two-thirds full of 2 to 8 molar NH_4NO_3 could release 0.1 to 1 kiloton equivalent of TNT (*116*). Waste storage tanks are usually arranged in groups called farms, and a violent explosion in one tank could breach the containment of a companion by ground shock; thus a simultaneous atmospheric and liquid release (from the companion) of high-level wastes with significantly different radionuclide contents could occur. An accident involving tank breach, rapid liquid leakage, and aerosol dispersal of precipitate [the third cesium separation case discussed in (*6*)] could require the involvement of only a single tank, but a mechanism for aerosol dispersal of the precipitate is not evident to us. However, these cases are by no means the only explanation for the source of contamination.

Additional Support for a High-Level Waste Accident

Potential failures of safety mechanisms (cooling systems) on storage tanks containing high-level liquid wastes, resulting in evaporation and drying, have been recognized as a significant hazard (*68, 71, 77*). Soviet authors appeared particularly concerned with explosions resulting from such failures in a paper (*77*) delivered at a symposium in 1959.

Further evidence may be provided by a Soviet paper (*37*) presented at a 1969 symposium on the handling of radiation accidents. The purpose of that paper was to determine criteria for evacuation of areas accidentally contaminated by fission products (aged 200 to 350 days) from a radiochemical separations facility. The paper reports results of an experimental contamination of field plots for dosimetric measurements in a 3-month study. The large size of the study area (indicated by physical and land-use

features such as haystacks, forest plots, asphalt highway, water bodies, and collective farms), presence of contamination on clothing of farm workers, data on human inhalation and ingestion, and data for various seasons again suggest the implausibility of a planned experiment. The authors provide data for differential contamination of terrestrial surfaces by a radioactive cloud; methods or references are not provided. This dosimetric study has been reported as the source of radioactive contamination utilized in a series of KA terrestrial radioecology investigations. However, early works in the series were ongoing (*18, 29, 30*) 3 to 9 years before the stated date of contamination—an apparent inconsistency.

Conclusions

One can postulate a credible accidental release of separated fission wastes from high-level liquid waste storage associated with a Soviet installation in 1957 to 1958 by conventional means—that is, without nuclear criticality. One accident could have involved detonation of dried high-level wastes, containing NH_4NO_3 and from which ^{137}Cs had been deliberately separated, following failure of a cooling system on a waste storage tank. Cases involving detonation of nuclear explosives or reactor accidents (note our previous caveat) appear to deserve little consideration as the sole source of the KA contamination zone. The evidence has firmly convinced us that a major release from a KA installation did occur, regardless of the cause.

Many different types of accidents, in addition to those discussed, could be postulated to explain the atmospheric or liquid release of radioactive materials from a Soviet military plutonium production site in 1957 to 1958; most would not be credible in the light of U.S. practice or experience. We have not considered other accidents whose causes are unrelated to the technology. We have not seriously attempted to analyze a situation involving multiple accidents, combinations of accidents and nonaccidents, or a complex single event, because all the potential causes discussed contain considerable speculation already; further additions seem pointless. We have singled out the NH_4NO_3 waste-explosion case because it provides a seemingly credible dispersal mechanism and is consistent with observations of ^{137}Cs separation in the terrestrial contamination zone. This is not the only reasonable explanation for the incident; confirmation must await release of information by the Soviet scientific community.

We are unable to reconcile the allegations of large numbers of civilian casualties (*1–3*) with reported concentrations of radioactivity in radioecology studies. Our estimated radiation dose rates, based on a ^{90}Sr reference concentration of 1 mCi/m^2 and several potential mixtures of 200- to 350-day-old reactor fission products (Table 1), are small fractions of those delivered to inhabitants of the Marshall Islands who were accidentally exposed to fallout radiation following a nuclear test in the Pacific [Bravo shot, Operation Castle (*118*)] in 1954. By analogy with the effects observed in the Marshall Islands (*118*), including the absence of severe injuries or death, we would conclude that prompt evacuation and personnel decontamination should have prevented the development of acute radiation sequelae. A complete assessment of the consequences for humans is seriously limited by present uncertainty about the exact distribution of contamination, 1957 population near the release site, residence time in the contamination zone, isotopic content and particle size of the source material, and actual circumstances of the event. Again, we believe that such an assessment must await the release of information by sources in the Soviet Union.

Although we believe that the KA phenomenon resulted from use of now-obsolete waste storage and isotope separation techniques, it has not been our objective to dismiss this incident as a historical event; instead, we wish to provide a vehicle whereby we can obtain more information. It appears probable that modern practices for handling high-level wastes (denitrification, conversion to anhydrous melts or solid matrices, and so on) could have prevented all of our postulated accidents.

It seems apparent that the Soviet nuclear program has had to contend with severe environmental contamination involving reactor-generated fission products. The extensive body of publications in the open literature indicates the seriousness with which the Soviet scientific establishment viewed the problem. However, the reluctance to provide detailed information about the nature of the source, site, and so on, coupled with the probable existence of more research, documented but internal to the Soviet Union, limits the usefulness of the experiences gained by Soviet scientists. As scientists involved in evaluating hazards associated with radioactive releases to the biosphere, we urge the Soviet scientific community, which was engaged in the aftermath of the KA incident, to share all pertinent information with others concerned with achieving the safe development of nuclear energy. Soviet experience gained during the application of remedial measures on an unparalleled scale following this accident is clearly unique and would be invaluable to the world nuclear community.

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111. This case would also require either that an extremely large area had been contaminated by ^{137}Cs (> 100 times that for ^{90}Sr), or that overlap had occurred between high-level (millicuries per square meter) ^{137}Cs and ^{90}Sr contamination zones (caused by a shift in wind direction during the accident) in order to produce the ^{90}Sr/^{137}Cs activity ratios (> 100:1) reported in terrestrial radioecology study areas. If such ^{137}Cs-contaminated areas actually existed, one might legitimately ask three questions: (i) Why is there a preponderance of ^{90}Sr research papers in the Soviet literature? (ii) Why have Soviet scientists used data from their own long-term research on ^{90}Sr to forecast its migration in soils (*44*) but, in a similar exercise, used British data (*112*) to forecast ^{137}Cs migration? (iii) Why were the first ^{137}Cs data in Soviet soil radioecology studies not reported until 10 years after application (*12*) and only ^{144}Ce and ^{90}Sr data reported earlier (*13,14*)?
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Teratogenic Effects of Alcohol in Humans and Laboratory Animals

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Historically, alcohol has often been noted to have an adverse effect on offspring. The Bible, Judges 13:7, says: "Behold, thou shalt conceive and bear a son: and now drink no wine or strong drink." In early Carthage there was reported to be a prohibition against the bridal couple drinking on their wedding night for fear of producing a defective child. According to Aristotle, "Foolish, drunken and harebrained women most often bring forth children like unto themselves, morose and languid," and in 1834 a report to the British House of Commons said: Infants of alcoholic mothers often have a starved, shriveled, and imperfect look (*1*).

In 1899, Sullivan (*2*) reported the first empirical work on the fetal effects of maternal drinking during pregnancy. Female drunkards in the Liverpool jail had a stillbirth and infant death rate of 56 percent, more than double that of nonalcoholic female relatives. Noting that the outcomes of successive pregnancies were increasingly adverse as a woman's alcoholism progressed, Sullivan concluded that "maternal intoxication" was the main source of damage to the fetus.

Despite these early warnings, little further research was reported during the next 50 years. Haggard and Jellinek (*3*), reflecting the prevailing attitude in 1942, attributed developmental problems in children of alcoholic mothers to poor postnatal nutrition and chaotic environmental circumstances rather than to intrauterine exposure to alcohol. But by 1957 (*4*), a medical thesis, filed in Paris and apparently never published, described quite clearly the malformations, growth deficiency, and poor development of foundling home children whose mothers were alcoholic.

In this article we discuss the work of the past 10 years that implicates alcohol as a teratogen, describing data from three sources: clinical studies, prospective human studies, and research with experimental animals. Alcohol is of particular interest as a teratogen because of its wide use, and the wide range of effects on offspring exposed in utero. Malformations, intrauterine death, growth retardation, central nervous system abnormalities, and behavioral deficits have all been demonstrated in humans and laboratory animals exposed to alcohol in utero. Mental retardation is the most pronounced behavioral effect of heavy intrauterine exposure to alcohol.

Alcohol, like other drugs with a molecular weight between 600 and 1000, passes freely across the placental barrier (*5*), and concentrations of alcohol in the fetus are at least as high as in the mother (*6, 7*). Prior to the 1940's it was assumed that the uterus was virtually impervious to harmful extrinsic factors circulating within the mother (*8*). However, full realization of the teratogenic potential of environmental agents came with the thalidomide tragedy, and now alcohol joins the list of agents with demonstrated teratogenic effects.

Fetal Alcohol Syndrome

In 1968, in a relatively obscure French medical journal, Lemoine and colleagues (*9*) described 127 offspring of alcoholics, emphasizing their remarkable similarity of facial characteristics, growth deficiency, and psychomotor disturbances. Lemoine said the children resembled each other to such a degree that the diagnosis of maternal alcoholism could be made from examination of the child.

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