PNNL-12199

A Brief History of Nuclear Criticality Accidents in Russia - 1953-1997

G.J. Vargo

April 1999

Prepared for the U.S. Department of Energy
under Contract DE-AC06-76 RLO 1830

Pacific Northwest National Laboratory
Richland, Washington

DISCLAIMER

PACIFIC NORTHWEST NATIONAL LABORATORY
operated by
BATTELLE
for the
UNITED STATES DEPARTMENT OF ENERGY
under Contract DE-AC06-76RLO 1830

Printed in the United States of America

Available to DOE and DOE contractors from the Office of Scientific and Technical Information, P.O. Box 62, Oak Ridge, TN 37831; prices available from (615) 576-8401.

Available to the public from the National Technical Information Service, U.S. Department of Commerce, 5285 Port Royal Rd., Springfield, VA 22161

A Brief History of Nuclear Criticality Accidents in Russia - 1953-1997

G.J. Vargo

April 1999

Prepared for
the U.S. Department of Energy
under Contract DE-AC06-76 RLO 1830

Pacific Northwest National Laboratory
Richland, Washington 99352

Summary

This report describes 14 nuclear criticality accidents that occurred in Russia between 1953 and 1997. These accidents are significant because of the loss of control of special nuclear material and the resultant radiation doses to personnel, potential damage to equipment, and release of radioactive material to the workplace and the environment. A qualitative analysis of the causes and contributing factors to these accidents is presented along with a description of the radiation health effects to workers. The primary cause of most of these accidents was inadequate design that allowed the use of process equipment that did not preclude nuclear criticality on the basis of geometry. Personnel errors and violations of procedures were major contributing factors to these accidents.

Acknowledgments

The author would like to acknowledge the support of the U.S. Department of Energy (DOE) Office of International Nuclear Safety and Cooperation, directed by Dr. Terry Lash. They have been critical in providing programmatic guidance and funding, and in establishing the government-to-government links that made it possible. The DOE Office of International Nuclear Safety and Cooperation manages a comprehensive collaborative effort to improve nuclear safety at Soviet-designed nuclear power plants in nine partnering countries. Collaborative work with the Federal Nuclear and Radiation Safety Authority of Russia (Gosatomnadzor) is part of this broader program, and strengthens the nuclear safety regulatory infrastructure in the newly independent states of the former Soviet Union by exchanging information on international experience and standards. Similar nuclear safety regulatory infrastructure exchanges, formerly sponsored by DOE and currently sponsored by the U.S. Nuclear Regulatory Commission, are underway in other countries of the former Soviet Union.

Contents

Tables

Introduction

In August 1997, the U.S. Department of Energy sponsored a training course on nuclear criticality safety for staff from the Federal Nuclear and Radiation Safety Authority of Russia (Gosatomnadzor) as part of its program to strengthen the nuclear safety regulatory infrastructure in the newly independent states of the former Soviet Union. When the course was planned in late 1996, no one had any idea that the following year would bring two nuclear criticality accidents in Russia – the first such accidents in either the United States or Russia in nearly two decades. When news of these events reached the U.S. organizers of the course, the Russian hosts were requested to provide some background on the history of nuclear criticality accidents in Russia. Our Russian hosts accommodated this request by arranging a presentation by Professor V.V. Frolov of the Nuclear Safety Division of the Institute of Physics and Power Engineering at Obninsk during the August 1997 nuclear criticality safety course. His presentation was supplemented by lively discussion and information given by various course participants including representatives of Gosatomnadzor and Minatom. This report is based on notes taken during his presentation and subsequent discussions during the August 1997 course. Because of the open, often rapid exchange between participants, it is impossible to provide complete attribution of all details.

This report describes 14 criticality accidents that occurred at Russian non-reactor nuclear facilities between 1953 and 1997. Only one accident took place at a civilian nuclear fuel fabrication facility (Electrostal); the remainder occurred at highly-enriched uranium and plutonium processing facilities. Reactivity accidents in reactors (e.g., Chornobyl, Chazma Bay) are not included. The predominant causes of the accidents were inadequate implementation of geometry control and breakdown in administrative practices (i.e., personnel errors). Eleven of the accidents occurred in water-moderated systems. Two accidents took place in systems that are considered by the Russians to be low-enriched uranium systems. External measures such as the addition of neutron absorber solutions were needed to terminate four of the events.

The most recent accident, involving a criticality at the Arzamas-16 (Sarov) facility in June 1997 is also described based on a combination of news accounts and expert opinion by non-Russian specialists. This accident bears a circumstantial resemblance to the early Los Alamos criticality accidents -- manual manipulation and misoperation of critical assembly components. The reluctance of our Russian hosts to discuss details of this event openly supports the belief that the accident may have involved actual nuclear weapon components.

The radiation levels and doses have been left in the originally reported radiological units. It is important to note that the radiological quantities of dose equivalent, the sievert, and its predecessor, the rem, are not physical quantities, *per se.* Rather, they are the product of the absorbed dose (in grays or rads) multiplied by a quality factor to account for the type of radiation to which an individual is exposed. These quality factors also take into account the fact that dose equivalent limits are based on extrapolations from higher absorbed doses at which deleterious effects in man can be directly assessed. In its 1976 recommendations for radiation protection, the International Commission on Radiological Protection (ICRP) specifically cautions that "dose equivalent should not be used to assess the likely early consequences of severe accidental exposures in man."[1] Similar cautions are expressed in the application of the more recent quantities, equivalent dose and effective dose.[2] In those cases involving fatalities where no absorbed dose was reported, estimates of the absorbed dose are offered based on data compiled by Young.[3] (1987). Unfortunately, neutron-to-gamma ratios are not available.

---

1 International Commission on Radiological Protection (ICRP). 1976. *Recommendations of the International Commission on Radiological Protection.* Oxford: Pergamon Press. ICRP Publication 26.

2 International Commission on Radiological Protection (ICRP). 1990. *1990 Recommendations of the International Commission on Radiological Protection.* Oxford: Pergamon Press. ICRP Publication 60.

3 Young, RW. 1987. "Acute Radiation Syndrome." In: *Military Radiobiology,* R.I. Walker and J.J. Conklin, eds. New York: Academic Press.

Criticality Accidents

1. March 15, 1953 -- Mayak Enterprise, the Urals
Shielded Cell with Plutonium Product Receiving Tanks (1953-1)

The equipment involved in this accident included seven 40-L tanks and components of a vacuum pump transport system located in a shielded cell. The tanks were used for the mixing, dilution, sampling, storage, and transfer of plutonium nitrate product derived from reprocessing of irradiated uranium reactor fuel. The vacuum transport system included a transparent glass vessel serving as a trap. Eight other 40-L vessels with the same geometry were located outside the cell. All 15 of the 40-L vessels were of an unfavorable geometry.

On March 15, 1953, the contents of two vessels, containing a total 650 g of plutonium in 31L, were to be transferred from the cell. The chief operator decided to transfer the solutions from the two vessels into a single vessel outside the cell. This was to be accomplished by connecting them to the vacuum equipment using hoses. The chief operator stood next to the receiving vessel during the solution transfer; the assistant operator was stationed inside the shielded cell several meters away from the vessel. When the transfer was completed, the chief operator disconnected the hose from the vessel, saw foam and reconnected the hose.

The operator in the cell saw that a part of the solution had entered the vacuum trap. At this point, the solution from the target vessel (outside the cell) was returned back into the initial vessels, diluted, cooled and then transferred into two empty vessels. No radiation monitoring equipment was available to the workers. The workers, lacking adequate training, failed to recognize the seriousness of the event and did not report the incident. Two days later, the chief operator presented symptoms of acute radiation syndrome. Inventory records and subsequent investigation results revealed that 5 L of solution was missing. The estimated yield of this single power burst was 2.5×10^{17} fissions. The chief received 1,000 rads; the operator received 100 rads. The medical outcome of these exposures was not reported; however, given the reported dose, the chief operator should have developed gastrointestinal syndrome and died within one week of the accident.

2. April 21, 1957 -- Mayak Enterprise, the Urals
Shielded Cell for the Purification of Uranium Solutions (1957-1)

The process equipment involved in this accident was used for the oxalate purification and the filtration of highly-enriched uranium solution. It consisted of a 500-mm-diameter process vessel equipped with a heater and a stirring device, a filter, and a vacuum trap on the solution outlet line contained within a shielded cell. No radiation monitoring devices were present in the cell. Over an undetermined period of time, the following conditions developed:

- No regular cleanout of the equipment was performed.
- There were errors in accounting for uranium and other ingredients.
- The temperature of the process vessel was not routinely monitored to ensure complete dissolution of product.
- The condition of the filter was not checked.

As a result of these cumulative deficiencies, 3.4 kg of uranyl oxalate precipitate accumulated in the tank and a critical state was reached. The condition remained undetected for an undetermined period of time.

On April 21, 1957, an operator entered the cell and observed that the filter material was swelled and that the precipitate was discharging gasses. The reaction was terminated when part of the solution was forced from the tank into the trap. The operator, who remained in the cell for approximately 10 minutes, died 12 days later. Five other workers developed radiation sickness. Quantitative estimates of doses were not reported; however, the time between the operator's exposure and death is consistent with a dose of 7.5 to 10 Gy. The number of fissions was estimated to be 2×10^{17}.

3. January 2, 1958 -- Mayak Enterprise, the Urals
Critical Parameter Test Facility for Highly-Enriched Uranium Solutions (1958-1)

After the 1953 and 1957 Mayak criticality accidents, an experimental facility for determining critical parameters in uranium solutions was installed there. The equipment included a test tank, a neutron source and detectors, a control rod, and small-diameter connecting lines. On January 2, 1958, after completing an experiment, a staff of four decided to speed the draining of a solution. They unbolted the test tank from its mounting and three workers tipped the tank to drain the solution into several safe geometry tanks brought into the area for that purpose. At this point, the

combination of solution geometry in the tank and neutron reflection by the bodies of the workers became optimal, resulting in a criticality.

A single pulse of approximately 2.3 x 10^{17} fissions occurred. As a result, part of the solution was ejected from the tank. Five to six days later three of the four people died, indicating doses in the range of 10 to 20 Gy. The fourth person, who was 3 meters away from the tank, presented symptoms of acute radiation syndrome and reported loss of eyesight.

This accident was the result of an unauthorized and unreviewed modification to the equipment. The facility was dismantled after this accident.

4. December 5, 1960 -- Mayak Enterprise, the Urals
Shielded Cell for Purification of Plutonium Solutions (1960-1)

The major equipment in the cell consisted of a chemical processing vessel, a transfer tank, a filter, and a vessel with an unfavorable geometry. The latter, a 40-L vessel had a diameter of 350 mm and a height of 400 mm.. There was a criticality alarm system in the area. Measurements of plutonium mass were performed by sampling and chemical analysis of solutions and measurement of their volume.

Processing records were not well maintained. There were errors and corrections, often with no designation of the responsible persons. Total error in the plutonium mass in a number of cases reached100% (procedures stipulated that an acceptable error for loading product was 20%). On December 5, 1960, a technician found a discrepancy in the plutonium mass analysis for the process vessel. He did not check the results and transferred the solution to the filter.

The excursion occurred in the vessel with unfavorable geometry which (based on the results of the investigation) contained about 830 g of plutonium in solution and 170 g of plutonium precipitate. The excursion stopped after a single spike because some of the solution surged into the connecting lines. The alarm system was activated and all personnel evacuated safely. Later, when the staff began work on emergency response measures, the vacuum system used for transferring solution was switched off. As a result, the solution flowed back into the vessel, causing a second excursion. Several people outside the shielded cell received exposures of up to 5 rads. The estimated yield of the two excursions was 1x10^{17} fissions.

5. August 14, 1961 -- Siberian Chemical Combine
Facility for Condensing and Evaporating Uranium Hexafluoride (1961-1)

This event involved an experimental facility used for purifying uranium hexafluoride with an enrichment of 22.6%. The process line included the main cylinder, cooled by liquid nitrogen for condensing gaseous UF_6, additional vessels, a tank, and a pump with a cylindrical 60-L oil reservoir. The main cylinder lacked sufficient cooling, temperature control devices were not operational, and one of the two additional vessels was bypassed. As a result of unspecified personnel errors, a portion of uranium hexafluoride passed through the pump and accumulated in the oil reservoir. At the time of the accident, the uranium concentration was about 400 g/L.

The criticality monitoring system alarmed and the staff was evacuated. Surveys of the area made with portable gamma-sensitive instruments did not indicate abnormal radiation levels. Personnel decided that it was a false alarm and that work could be resumed.

Three hours later, the process was restarted. This resulted in a second spike of the same yield. The process operator, standing at a distance of about 0.5 m from the oil reservoir, received a radiation dose of about 200 rads. The yield from both pulses was estimated to be $1x10^{16}$ fissions. In both excursions, reactivity was compensated for by the increase in temperature and by some ejection of the oil. This facility was redesigned and reconstructed. Processing manuals and procedures were revised.

6. September 7, 1962 -- Mayak Enterprise, the Urals
Plutonium Scrap Recovery Facility (1962-1)

At the plutonium metal production facility, scrap material was stored in a scrap recovery facility. Based on historical experience, the plutonium content of the scrap was assumed to be 1% and no non-destructive assay or other testing was conducted to verify this assumption. There was no criticality monitoring system installed in the facility. Controls for reprocessing of scrap were based on weight and the assumed plutonium content of 1%.

To recover plutonium, scrap was loaded into a dissolver tank filled with nitric acid. The outer diameter of the dissolving tank was 450 mm and its volume was 100 L. The tank was equipped with a stirring device and a heater.

On September 7, 1962, a few minutes after the last operation was completed and the stirrer and heater were turned off, an alarm system was activated and the personnel left the room. (Note: the

inconsistency between this and the previous statement concerning the lack of a criticality monitoring system remains unexplained.) Forty to 50 minutes following the first pulse, two additional pulses occurred.

The investigation of the accident indicated that there was 1.32 kg of plutonium in the dissolver, with some of the plutonium scrap still undissolved, even though the tank was completely full. The reaction stopped when part of the solution was ejected from the dissolver. The yield of the three pulses was calculated to be $2x10^{17}$. There were no abnormal personnel radiation exposures because the dissolver had a 5-centimeter-thick lead shield, and at the time of the first spike, no personnel were close to the equipment.

7. January 30, 1963 -- Siberian Chemical Combine Highly Enriched Uranium Scrap Recovery Facility (1963-1)

The facility produced highly-enriched uranyl nitrate solutions. After measurement of uranium mass by sampling and analysis, the uranium metal scrap was sorted into batches for dissolution and recovery. Data logging practices were inconsistent and analytical results were recorded either as percent mass of uranium content, or as grams per kilogram. As a result, a batch containing 5% uranium could be identified as a batch containing 5 grams of uranium per kilogram, instead of the actual 50 g/kg.

The concentration problem was discovered when the solution was sampled and analyzed following dissolution. It was then divided and transferred to different vessels. Additional samples were taken; however, the results were in error by a factor of 10. (As it turned out, the scrap recovery facility had never previously received material with such a high uranium concentration, and the analyst failed to recognize the magnitude of the actual concentrations.) On the basis of the second erroneous analysis, 41 L of solution with an assumed concentration of 7.1 g/L and a true concentration of approximately 71 g/L was transferred to a tank with an unsafe geometry (diameter of 342 mm).

For the first six hours, the accident progressed as a series of power oscillations that were extinguished when part of the solution was expelled from the tank and later restarted as the solution flowed back into the tank.

After six hours the reaction reached a near critical state. Ten hours after the first fission pulse, it was terminated by transferring the solution into safe vessels. The first spike activated the criticality alarm system and the staff was evacuated. Four persons who were located at a distance

of about 10 m from the receiving tank received exposures from 6 to 17 rads. The yield from this accident was estimated to be 7.9×10^{17} fissions.

8. December 13, 1963 -- Siberian Chemical Combine Highly-Enriched Uranium Extraction Facility (1963-2)

This event involved a vacuum control trap installed behind processing equipment used for the extraction of highly-enriched uranium solution. Because of the equipment configuration, small quantities of the extraction solvent could be accidentally transferred into the trap. There were no mass balances used to monitor the amount of extraction solvent added to or lost from the process.

The trap consisted of a vertical cylinder with a hemispherical bottom. Its diameter was 0.5 m, its volume 100 L. Periodically, processing equipment connected to the trap would overflow; however, there was no way to observe or detect the accumulation of extraction solvent in the trap. Because of this situation, uranium solution would accumulate in the trap and the extraction solvent would gradually become saturated with uranium. When the accident occurred, the trap was filled with a uranium solution concentration equal to 33 g/L.

The initial pulse was small (1×10^{15} fissions), but sufficient to trigger the criticality alarm system.. All personnel were safely evacuated. Over the next six hours, a gamma radiation detector registered 16 pulses with decreasing amplitude and periodicity after which the system appeared to remain subcritical. Assuming that the reaction had terminated, the staff proceeded to turn off the vacuum system. When this was done, some of the solution that had been expelled or drawn from the trap flowed back into it, causing an additional pulse and subsequent power oscillations. A cadmium solution was injected into the trap to terminate the excursion. The total yield was estimated to be 2×10^{16} fissions over a period of about 18 hours.

9. November 13, 1965 -- Electrostal Fuel Fabrication Plant Uranium Hexafluoride Conversion Facility (1965-1)

Similar to facilities in the United States and elsewhere, the commercial fuel fabrication facility at Electrostal receives uranium hexafluoride (UF_6) and converts it into uranium dioxide (UO_2) as the first step in the fabrication process. A vacuum system was used to improve removal of the converted UO_2 powder from the reaction vessel. The vacuum system used a rotary vacuum (i.e., hogger) pump that relies on a water seal. Two filters were located upstream of the vacuum pump to prevent UO_2 powder from entering the equipment. These filters were not included in any inspection or material control program and no non-destructive assay (NDA) measurements for

uranium accumulation were performed. On November 13, 1965, the criticality alarm system was activated and the staff evacuated the area. An investigation of the accident showed that both filters were punctured and the powder had accumulated in the water reservoir of the pump; 157 kg of slurry were extracted from the vessel, which had a diameter 300 mm and a height of 650 mm. The uranium had an enrichment of 6.5% and a mass of 51 kg. The yield from the single pulse was $1x10^{15}$ fissions. One worker received a dose of 3.5 rad. The UO_2 powder vacuum system was dismantled.

10. December 16, 1965 -- Mayak Enterprise, the Urals
Highly-Enriched Uranium Scrap Recovery Facility (1965-1)

The equipment involved in this event consisted of three dissolver tanks of 450-mm diameter (an unsafe geometry) located in a cell with other process equipment. The dissolvers were equipped with jacket heaters and ultrasonic agitators to promote dissolution of scrap materials. The maximum safe mass of uranium for a single dissolver tank was 2 kg. Because of poor recordkeeping and personnel errors, a total of 2.2 kg was added to one of the tanks.

Procedures allowed 15 hours for complete dissolution of a scrap batch. After only 40 minutes of operation, the operator disconnected the heater and the stirrer because of a scheduled cleanup activity in the cell. Ten minutes after this, the criticality alarm system was activated. The gamma detectors registered 11 power pulses during the next 7 hours, with increasing intervals between them of up to 60 minutes.

Because of the equipment configuration in the room, there was some uncertainty about which dissolver tank contained the critical mass. After the eleventh spike and identifying which dissolver was the source of the power pulses, staff injected a cadmium solution into the tank and terminated the reaction. The yield of the 11 power pulses was $7x10^{17}$ fissions. The staff was exposed to small doses of radiation, 0.03 rads, well within occupational limits.

11. December 10, 1968 -- Mayak Enterprise, the Urals
Plutonium Extraction Facility (1968-1)

This accident occurred during a test of a new extraction process. Low-concentration aqueous plutonium solutions (up to 0.4 g/L) were being transferred into a large tank (4000 L). Sampling results indicated two abnormal process conditions: a plutonium concentration of 0.5 g/L and the presence of organic contaminants in the solution. The shift supervisor directed an operator to

remove the organic contaminants from the tank. To do this, they used a 20-L glass bottle (safe geometry), and a 60-L vessel (unsafe geometry), a rubber hose and a pump.

When the first bottle was filled, the shift supervisor and the operator noticed that the liquid was dark brown, indicating high plutonium content in the organic phase. Liquid from the 20-L bottle was poured into the 60-L vessel. The shift supervisor directed that the operation be repeated and left the area. When the operator poured the second portion of liquid from the 20-L bottle into the 60-L vessel, he saw a flash of light and ran away.

The criticality alarm system was activated and all personnel were evacuated. However, the shift supervisor returned to the processing area and tipped the vessel in order to pour some liquid into the drain. This resulted in the second power pulse in the same vessel. The first spike yielded $1x10^{16}$ fissions and the second $5.0x10^{15}$ fissions. The shift supervisor died. (Note: the interval between the accident and time of death was not reported.) The operator developed symptoms of acute radiation syndrome and both his legs were subsequently amputated. Additional details were not given.

12. December 13, 1978 -- Siberian Chemical Combine Box for Temporary Storage of Plutonium Metal Ingots (1978-1)

This accident occurred in a section of a glove-box line where plutonium metal ingots were packaged in storage boxes. Each storage box, intended to store a single ingot, was designed with polyethylene and cadmium inserts to permit a relatively close spacing array in the storage vault. The box design was deficient in that it was physically possible to load more than the single intended ingot into a box. There were no NDA instruments in use in the glove-box line, responsibilities for material control and accountability were not clearly defined, and different personnel were routinely assigned to the same work station.

On December 13, 1978, an operator proceeded to complete the loading of a storage box started earlier by another operator. This involved removing ingots from one storage box and placing them into a similar one and recording the material transfers prior to transferring the newly loaded storage box to another glove box. While the operator was placing an ingot into a storage box, an excursion occurred. The criticality alarm was activated, and facility staff were evacuated. An investigation showed that the excursion took place after the operator loaded a third ingot into the container and had begun loading the fourth. The fourth ingot was physically ejected, likely as a result of rapid thermal expansion. The operator then extracted the other ingots manually.

The yield was $3x10^{15}$ fissions. The operator received a dose of up to 250 rads to the whole body, and up to 2000 rads to the hands. The large extremity dose is consistent with similar accidents involving solid components (as opposed to solutions, in which the characteristic x-rays and ultraviolet are self-absorbed). Seven others received doses between 5 to 60 rads.

13. May 15, 1997 – Novosibirsk Fuel Pellets Fabrication Plant Slab Tanks for the Storage of Uranium Scrap Solution (1997-1)

On May 15, the Novosibirsk Fuel Pellets Fabrication Plant located in eastern Siberia had a subcritical multiplication or criticality accident. A chain reaction occurred in one or both of the tanks individually containing ~600 L of uranium solution. At one point, the intensity of exposure within 0.5 meters from the tank was reported at 0.1 Sv/h (10 rem/h).

The equipment involved in the accident consisted of two vertical slab tanks (600-L capacity each) used to accumulate used-etching solution generated during fuel-element chemical treatment before the fuel is clad. The tanks were 3.5-m high, 2-m wide and 0.1-m deep and separated by 0.8-m surface-to-surface spacing. Steel plates are used to preclude access between the tanks and maintain moderator control. Upon subsequent inspection, it was found that each tank had a bulge near the bottom, increasing the thickness to approximately 0.14 m.. This is believed to be an initial manufacturing defect and not the result of an operational event.

This accident involved a violation of at least two and possibly three criticality safety contingencies: geometry control, enrichment control, and concentration control. The tanks were certified as having a safe geometry for ^{235}U-enrichment up to 36%, but plant staff operated the tanks with highly enriched uranium (HEU) solutions at 90+% enrichment. During more than 10 years of operation, sediment/precipitant containing highly enriched uranium accumulated on the casks bottoms and walls. The additional increase of width to 0.14 m near the tank bottom led to a less critically safe geometry.

The first nuclear excursion took place at 10:55 on May 15, 1997. Recurring events were observed at 18:55 and 22:10 on May 15, and at 02:30, 07:10, and 13:00 on May 16. Russians estimate the main peak had a value of $1.0x10^{15}$ total fissions. After the first excursions on May 15, the staff devised a method of adding 50 L of boron solution to the tank; however, this was not successful in preventing further excursions. On May 16, an unspecified quantity of lithium chloride was added to the tank and the solution mixing pumps were turned on. These actions prevented additional excursions. Subsequently, nearly 155 kg of sediments were removed from the scrap tanks, representing a 10- to 30-cm-thick sludge accumulation.

The Emergency Alarm System (criticality alarm) was activated automatically and personnel were evacuated from the accident area. No abnormal personnel radiation exposures were observed and no releases outside the plant were documented. The apparent cause of the event was operation of the equipment above its design enrichment without adequate safety review and/or modification.

14. June 17, 1997 -- Arzamas-16
Misoperation of Critical Assembly (1997-2)

Information on this accident was compiled from a variety of Russian and western news sources. Although nearly every news account has one or more verifiable factual errors, collectively, it is possible to reconstruct a general overview of the event in sufficient detail to understand the causes and significance of the accident. The events bear some resemblance to the 1945 and 1946 Los Alamos criticality accidents described by Stratton[4] (1967) involving hands-on manipulation of fissile material and reflectors in a critical assembly.

At 10:50 (Moscow time) on Friday June 17, 1997, a researcher at the Arzamas-16 facility was involved in a criticality accident and received a lethal dose of radiation. While the exact details of the equipment involved are not available, the experiment apparently involved one or more pieces of highly enriched uranium and a copper reflector. According to news accounts, the researcher was attempting to complete an experiment before the weekend.

The accident occurred inside a vault designed to provide adequate shielding for operating personnel in the event of a criticality. Normally, the experimental components would be slowly brought into position using remote-handling operated outside the vault. To save time, the researcher violated safety rules and brought the critical assembly components dangerously close together by hand. The researcher was initially working under the supervision of a second person, a "controller." This second person was called out of the vault shortly before the accident. No startup neutron source was used to provide a positive count rate on safety monitoring equipment – a significant violation of basic safety requirements for this type of work.

Apparently, the researcher used more uranium than was specified for the experimental configuration. (Some accounts state that he admitted to a calculational error in the amount of fissile material needed for the experiment.) Then, he "tried to cover the construction with a thin copper reflector, which dropped to the floor. [The researcher] immediately saw the flash

---

4 Stratton, WR. 1967. *A review of Criticality Accidents.* Los Alamos: Los Alamos National Laboratory. LA-3611.

indicating that the chain reaction had begun."[5] He immediately emerged from the vault and told his colleagues what happened, blaming slippery gloves for the accident.[6] He also reported the accident personally to the site director.

The assembly remained critical for several days and operated as a "mini reactor" according to one Russian television account[7]; however, it is unknown if this was a steady state or quasi stable (i.e., oscillating) configuration. The configuration was successfully disassembled and was finally disassembled on June 24, 1997, using a robot brought to the site especially for that purpose. Following disassembly of the array, the "flow of neutron fell by 10 million times and reached parameters which are considered normal for this kind of production facility."[8]

The researcher "fell sick within 30 minutes."[9] Initial dose estimates included statements such as "several hundred roentgens,"[5] and "several hundred rems."[7] He was taken to the local hospital in Sarov, approximately 225 km from Moscow, but was soon evacuated to Moscow Clinic No. 6, famous for the treatment of the victims of the 1986 Chornobyl accident. Despite heroic treatment, the researcher died approximately 64 hours after the accident at 02:55 on June 20, 1997. Later estimates of the victim's dose made by the Ministry of Atomic Energy (Minatom) were placed at 50 Sv and the dose to his hands was estimated to be on the order of 150 Sv.[5] The latter is consistent with the early Los Alamos accidents described by Stratton (1967) in which the victims received large doses (and burns) to the hands from the large emission of characteristic x- and ultraviolet radiation associated with the criticality in a metal-air system.

These data are generally consistent with the most severe form of acute radiation injury – the neurovascular syndrome. Because of the relatively small number of reported cases, this is the least well understood of the radiation-related deaths. The threshold for this syndrome is approximately 50 Gy.[10] The relatively quick onset of disorientation and unconsciousness at 30

---

5 Nucleonics Week 38(28) p. 1. July 10, 1997.

6 Post-Soviet Nuclear and Defense Monitor. July 7, 1997.

7 "Segodnya" newscast, Moscow NTV, June 20, 1997 1800 GMT

8 Itar-Tass World Service June 24, 1997 0955 GMT (in Russian).

9 Nucleonics Week 38(26) p.1. June 26, 1997.

10 Young, RW. 1987. "Acute Radiation Syndrome." In: *Military Radiobiology,* R.I. Walker and J.J. Conklin, eds. New York: Academic Press.

minutes post-exposure supports this diagnosis. In most cases, the interval between onset and death is less than 48 hours. Given the relatively small number of cases in this dose range and the great uncertainly in both the dosimetry and effectiveness of treatment, the observations are not necessarily inconsistent.

The primary cause of this accident was the apparently deliberate violation of safety procedures that required such experiments to be performed using remotely-operated equipment. The lack of independent verification of the researcher's calculations of the amount of fissile material needed was a significant contributing factor. The lack of a startup neutron source to provide positive indication on safety monitoring equipment was also significant, but might not have been adequate to prevent the accident, given the manual positioning of components in the array.

Observations and Conclusions

Table 1 shows a summary of the accidents. Each is identified by year and event number. In addition to a description of the system involved in the accident, a qualitative analysis of the criticality safety barriers compromised in each accident is presented.

Analyses of the causes and consequences of these accidents allow the following observations:

1. The use of equipment having an unsafe geometry was the leading cause of accidents between 1953 and 1978. The installation of geometrically safe equipment could have prevented nine of these accidents.

2. Violations of operating practices and equipment configuration controls were major contributing factors to criticality accidents.

3. The lack of an adequate maintenance and surveillance program was a contributing factor in three accidents.

4. Inaccurate or incomplete analytical results contributed significantly to two accidents.

5. Material control and accountability problems contributed significantly to five accidents.

6. None of the accidents resulted in damage to process equipment.

7. Immediate evacuation of staff at the first indication of criticality is important in limiting radiation exposure. Heroic attempts to mitigate a system once criticality has occurred likely contributed to two unnecessary fatalities.

8. Accident mitigation measures should be undertaken only after the cause of the accident is identified and reliable measures are in place to control the situation. In at least two cases, actions undertaken to mitigate or secure a criticality accident inadvertently resulted in additional nuclear excursions.

This list of accidents cannot be assumed to be complete. For the period 1946-1966, Stratton[11] reports 29 criticality accidents in the United States. Of these, 21 involved systems intended for research into critical parameters of fissile material systems, while only one such system (Arzamas-16 in 1997) was reported in Russia. Also, the number of near accidents remains unknown. Hopefully, this report will be supplemented by important but still missing data as more information on the history of the Soviet nuclear complex becomes available.

---

11 Stratton, WR. 1967. *A review of Criticality Accidents.* Los Alamos: Los Alamos National Laboratory. LA-3611.

Table 1. Summary of Russian Criticality Accidents

Designation	Fissile Material*	System Type	Barriers or Controls Compromised					Estimated Yield	Acute Radiation Effect Cases	Fatalities
			Geometry/ Equipment Design	Enrichment	Moderator	Mass/Volume	Concentration			
1953-1	Pu	aqueous	X					$2.5x10^{17}$	2	1
1957-1	HEU	aqueous				X	X	$2x10^{17}$	6	1
1958-1	HEU	aqueous			X			$2.3x10^{17}$	4	3
1960-1	Pu	aqueous	X			X	X	$1x10^{17}$	-	-
1961-1	LEU	UF_6/oil	X					$1x10^{16}$	1	-
1962-1	Pu	aqueous				X	X	$2x10^{17}$	-	-
1963-1	HEU	aqueous	X				X	$2x10^{17}$	-	-
1963-2	HEU	organic	X			X		$2x10^{16}$	-	-
1965-1	LEU	UO_2/water slurry	X					$1x10^{15}$	-	-
1965-2	HEU	aqueous	X			X		$7x10^{17}$		
1968-1	Pu	aqueous/ organic	X					$1.5x10^{16}$	2	1
1978-1	Pu	metal	X			X		$3x10^{15}$	1	
1997-1	HEU	aqueous		X				10^{15}	-	-
1997-2	HEU	metal	X		X	X		not reported	1	1

* Pu - plutonium; LEU - low-enticed uranium; HEU - highly enriched uranium

Distribution

No. of
Copies

(2) Office of Scientific and Technical Information

ANL:
JL Binder
DJ Hill

ORISE:
ME Berger
RL Goans
WM Hart
RC Ricks
RE Toohey

ONSITE

PNNL:
DJ Bradley
DP Couch
LR Dodd
AL Doherty
BM Durst
AY Glukhov
BF Gore
SW Heaberlin
RA Jensen
SL Larson
RA Libby
AT Luksic
RL Moffitt
DF Newman
RP Omberg
GR Petersen
AW Pritchard
RI Scherpelz
KL Soldat
PS Stansbury
DJ Strom
GJ Vargo (20)
JC Wiborg