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RADIOACTIVE WASTE MANAGEMENT IN THE USSR: A REVIEW OF UNCLASSIFIED SOURCES

Volume II

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EXECUTIVE SUMMARY

The Soviet Union does not currently have an overall radioactive waste management program or national laws that define objectives, procedures, and standards, although such a law is being developed, according to the Soviets. Occupational health and safety does not appear to receive major attention as it does in Western nations. In addition, construction practices that would be considered marginal in Western facilities show up in Soviet nuclear power and waste management operations.

The issues involved with radioactive waste management and environmental restoration are being investigated at several large Soviet institutes; however, there is little apparent interdisciplinary integration between them, or interaction with the USSR Academy of Sciences. It is expected that a consensus on technical solutions will be achieved, but it may be slow in coming, especially for final disposal of high-level radioactive wastes and environmental restoration of contaminated areas. Meanwhile, many treatment, solidification, and disposal options for radioactive waste management are being investigated by the Soviets, as shown in general in Figure ES-1, and in particular for high-level wastes, as shown in Figure ES-2 (Falci 1990).

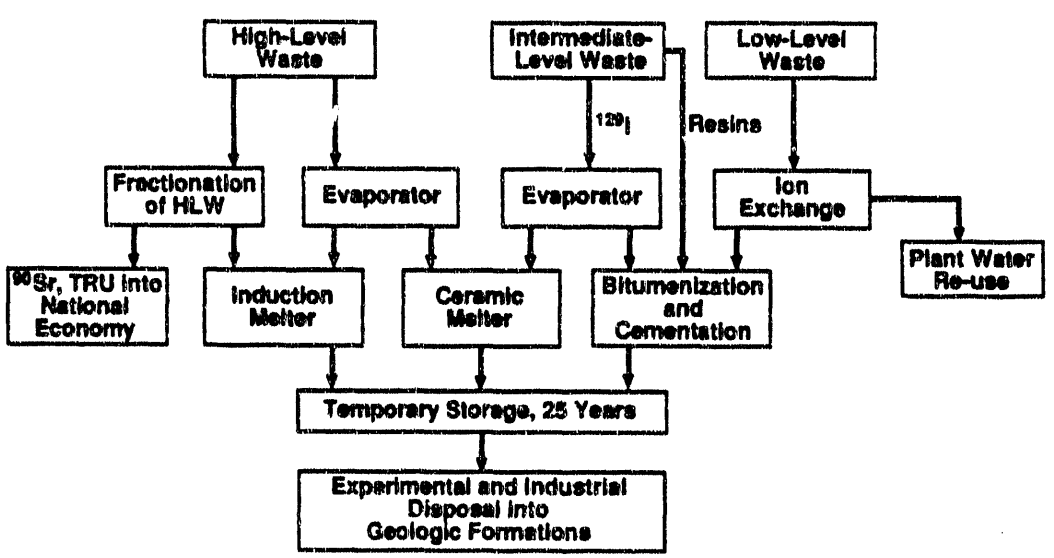


FIGURE ES.1. Management of Radioactive Wastes in the USSR (Falci 1990)

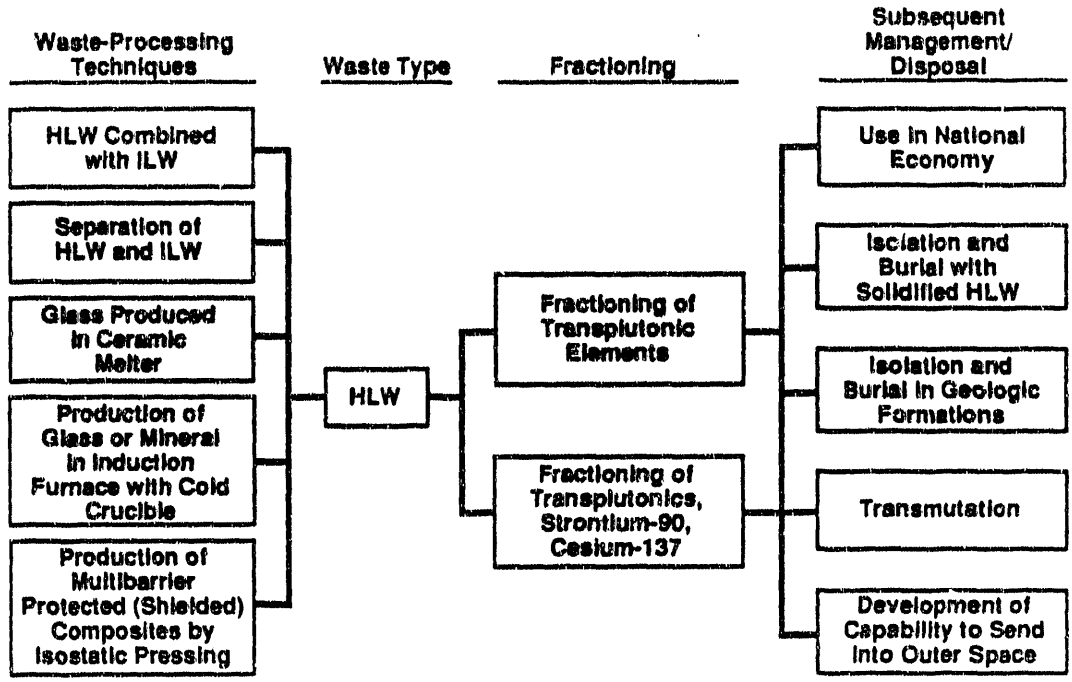


FIGURE ES.2. Options for the Management of High-Level Wastes in the USSR (Falci 1990)

The Soviets continue to state that reprocessing of spent fuel is preferable to its direct disposal. They believe that reprocessing/partitioning reduces the amount of long-lived wastes that must be disposed of and should allow for a careful and specific design of permanent disposal options. For some selected high-level wastes, final disposal appears to be being accomplished by in-tank solidification.

Recent information indicates eight areas that the Soviets are considering for a geologic repository. These include salt formations in the Caspian Sea area and crystalline rock formations in the southern Urals. A potential candidate repository site has been stated to be at or near Chelyabinsk-40. Disposal options other than a deep geological repository or deep boreholes were dismissed, according to a statement made by a Soviet during a recent U.S. National Academy of Sciences staff visit to the USSR. It was also observed during this visit and succeeding visits by DOE officials that the Soviets are emphasizing partitioning of elements from high-level wastes as a method of waste treatment and reduction of amounts to be vitrified, and engineered

barriers for containment of low-level wastes, while focusing less attention on site remediation and contaminant transport. Little or no attention is being placed on organic and other hazardous chemical wastes.

The Soviet proposal to the IAEA for an International Center at Chernobyl led to its establishment under an agreement signed on September 21, 1990 in Vienna. Proposals for another International Center at Chelyabinsk-40 are also being developed. The Soviets are continuing environmental restoration and radionuclide migration studies at Chernobyl and Chelyabinsk-40, the latter having an active laboratory referred to as the "East Urals" or "ONIS" laboratory.

GLOSSARY OF ABBREVIATIONS - GENERAL TERMS

AES	Atomic Energy Station
BN	fast breeder reactor [in Russian: Reaktor na Bystrykh Neytronakh]
BWR	boiling water reactor
CEC	Commission of the European Communities
CMEA	Countries belonging to the Council for Mutual Economic Aid/Assistance
DOE	Department of Energy
FBR	fast breeder reactor
GKAE	State Committee on Utilization of Atomic Energy
HLLW	high-level liquid waste
HLW	high-level waste
HTGR	high-temperature, gas-cooled reactor
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiological Protection
ILLW	intermediate-level liquid waste
ILW	intermediate-level waste
INPO	Institute of Nuclear Power Operations
JCCEM	U.S. - U.S.S.R Joint Coordinating Committee for Environmental Restoration and Waste Management
kWh	kilowatt-hour
LLLW	low-level liquid waste
LLW	low-level waste
LWGR	light water-cooled, graphite moderated reactor
MAPI	Ministry of Atomic Power and Industry
MOC	Memorandum of Cooperation
MSWU	million separative work units
MT	metric ton
MWe	megawatts-electrical
MWt	megawatts-thermal
NPP	Nuclear Power Plant
NRC	U.S. Nuclear Regulatory Commission
PUREX	Plutonium/URanium EXtraction process
PWR	pressurized water reactor
R&D	research and development
REE	Rare-earth elements
RBMK	Soviet boiling water, graphite moderated reactor [in Russian: Reaktor Bol'shoi Moznnosti kanalov]
TRU	transuranic elements
USSR	Union of Soviet Socialist Republics
VVER	Soviet pressurized water reactor [in Russian: Vodo-Vodyanoi Energeticheskii Reaktor]
RSFSR	Russian Soviet Federated Socialist Republic

CONTENTS

FIGURES

TABLES

1.0 INTRODUCTION AND SCOPE

Radioactive waste materials--and the methods being used to treat, process, store, transport, and dispose of them--have come under greatly increased scrutiny over the last decade both nationally and internationally. Nuclear waste practices in the Soviet Union, arguably the world's largest nuclear waste management system, are of obvious interest and may affect practices in other countries. In addition, poor waste management practices are causing increasing technical, political, and economical problems for the Soviet Union, and this will undoubtedly influence future strategies.

This report was prepared as part of a continuing effort to gain a better understanding of the Soviet radioactive waste management program. It is the second report on this subject, updating the first report Radioactive Waste Management in the USSR: A Review of Unclassified Sources, 1963-1990, PNL-7182, March 1990 (Bradley and Schneider 1990). This report includes only information obtained or reported after the publication of the first report, and thus, does not supersede it.

The scope of this study covers all publicly known radioactive waste management activities in the Soviet Union as of February 1991, and is based on a review of unclassified literature sources, including documents, meeting presentations, and data base searches of worldwide press releases. The study focuses primarily on waste management activities, but relevant background information on nuclear reactor operations is also provided in an appendix.

Information is given as presented in the references, with supporting analyses or inferences by the author given in brackets [], when sufficient information was available to assure the analyses are correct. In some cases, the same information may be given in more than one place in the report, where the information is pertinent to the respective report sections.

2.0 INSTITUTIONAL STRUCTURE

2.1 GOVERNMENTAL ORGANIZATION

In April 1990, it was reported that the State Committee for the Utilization of Atomic Energy (GKAE) had "ceased to exist" and that its director, Alexander Protsenko, now held a position in the Academy of Sciences Institute of Nuclear Safety. The GKAE's responsibilities will be carried out by the Ministry of Atomic Power and Industry (MAPI, sometimes referred to as Minatomenergoprom), headed by Vitaly Konovalov. At the same time, Viktor Sidorenko was made the first deputy minister of MAPI, responsible for nuclear power. MAPI was created in 1989 by merging the Ministry of Medium Machine Building with the Ministry of Nuclear Power, the later organization created after the Chernobyl accident. Viktor Sidorenko was previously at the Kurchatov Institute for Atomic Energy, and most recently was vice chairman of the State Committee for the Supervision of Safe Working Practices in Industry and the Nuclear Power Industry, Gospromatomnadzor. The other first deputy of MAPI is Boris Nikipelov, responsible for the nuclear fuel cycle, a job he carried over from the former Ministry of Medium Machine Building (Nucleonics Week April 19, 1990). Figure 2.1 shows the MAPI organization (MAPI 1990).

The USSR State Committee of Environmental Protection was created in January 1988. It has been given responsibility for ensuring environmental protection throughout the USSR; and has a national headquarters in Moscow, and regional headquarters in each of the republics. Its main activities include: outlining policies for state programs in ecology and environmental protection, developing regulations and requirements, inspecting activities in all industries that cause environmental pollution, issuing permits for disposal of waste, and helping to develop waste-free technologies. The Supreme Soviet has given the committee the mission to inspect all nuclear plants (National Academy of Sciences 1990).

The USSR State Atomic Inspection Committee, set up in 1986 following the Chernobyl accident, incorporates the former State Sanitary Inspectorate of the Ministry of Health. The committee is engaged in monitoring and developing the basic documents that outline the norms for radiation safety and sanitation and

for nuclear power plant operation. Documents on radiation safety are currently being developed, and the rules for power stations are expected be issued in 1990. A document outlining procedures for radioactive waste handling in the USSR is being prepared and the committee is trying to resolve the issue of an adequate margin of safety in operations and waste storage and is currently implementing monitoring in the 30-km zone around nuclear power stations (National Academy of Sciences 1990).

Another important environmental management organization appears to be the Ecology Committee of the USSR Council of Ministers, which has been stated to be the primary legislative/regulatory body responsible for environmental issues. An initial draft of an Environmental Protection Act is being revised for submittal to the Council of Ministers after being criticized as being too stringent and beyond the reach of current Soviet technology (Lesperance 1990).

In another development, V. V. Orlov has succeeded Academician Evgeny Velikhov as the President of the USSR Nuclear Society. He is the deputy director of the Research and Development Institute of Power Engineering, and is reportedly promoting new types of reactors (Nucleonics Week November 1, 1990).

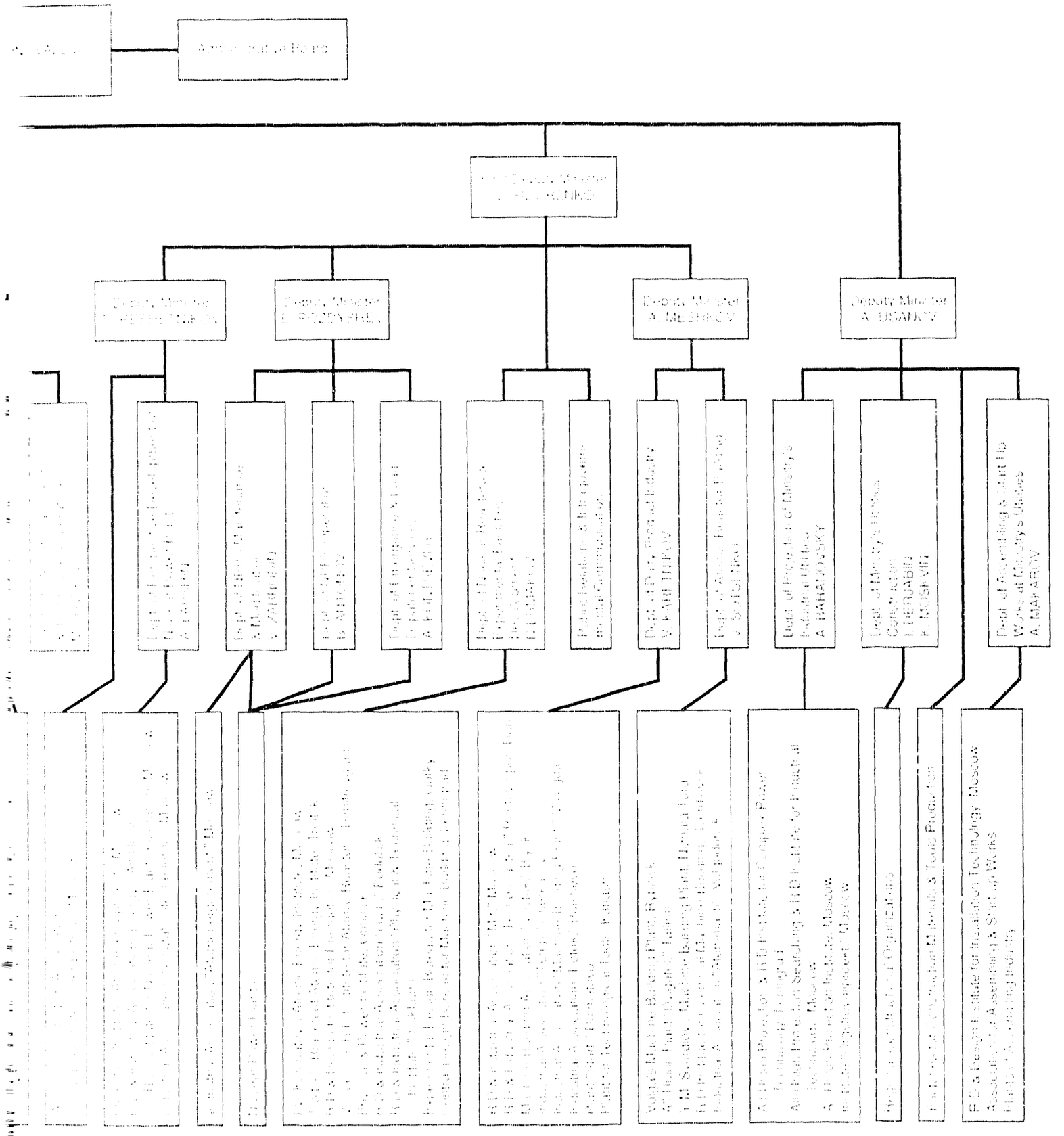
2.2 MAPI RESEARCH INSTITUTES INVOLVED IN WASTE MANAGEMENT

2.2.1 All-Union Research Institute of Inorganic Materials, Moscow

The work at this Institute includes basic research on radiochemistry and development of equipment for radiochemical processing. The Institute employs about 300 scientists, including some at a second location in Moscow and one in Siberia. The Institute is also responsible for the management and permanent disposal of high-level nuclear waste and for setting standards for disposal as broken down into the following specific areas (National Academy of Sciences 1990):

- Management of HLW from power plants and military installations.

FIGURE 2.1. Ministry for At



omic Power and Industry (MAPI 1990)

- Metallurgy of radioactive elements. During a recent visit by U.S. scientists, it was noted that large single crystals of technetium have been prepared, and its complexes in solution have been thoroughly explored. Speciation of TRU elements in solution is also emphasized.

- Metallurgical processing technology for metals used in reactors, particularly zirconium, titanium, and beryllium.

- Clean-up processes for liquid low-level waste, both from nuclear plants and from other research institutes, including medical institutes. Water resulting from cleanup is discharged into the Moskva River.

- Superconducting materials, on which work is just getting started.

2.2.2 Kurchatov Institute of Atomic Energy, Moscow

The I. V. Kurchatov Institute reports to the Ministry of Atomic Power and Industry. It is the Soviet Union's main nuclear power research institute, and is also responsible for work at Chernobyl Unit #4 (Nucleonics Week May 17, 1990).

2.2.3 Khlopin Radium Institute, Leningrad

The Khlopin Radium Institute, founded in 1922, is affiliated with laboratories at Gatchina and elsewhere. Of the 600 staff at the Khlopin Institute, approximately 100 are currently involved in radio-ecological modeling (focused on Chernobyl) and 50 on waste management issues such as the separation of organics from radioactive waste, making of various waste forms and subsequent geologic disposal (National Academy of Sciences 1990).

The Institute, now directed by Dr. Alexander I. Karelin, was responsible for developing fuel reprocessing plants in the USSR. Institute scientists, who developed the first reprocessing plant in the USSR, which was stated to have been active since 1949, are now "developing" the second reprocessing plant for power reactor fuel. Dr. Karelin indicated the Institute had departments or divisions dealing with research areas such as (Bradley December 1990):

--Physical sciences, which is involved with atomic fission,

--Geochemistry of uranium and radium,

--Radiological chemistry,

--Ecology and radiation monitoring [headed by Dr. Galkin], which covers the northwest sector of the USSR and the Baltic Sea, with its main task being the monitoring of the entire Leningrad area and the Sosnoviy Bor Power Station near Leningrad,

--Analytical measurements, and

--Fuel and materials disposal.

Other activities at the Institute include diverse studies such as particle accelerators, non-destructive testing, and design of reprocessing equipment. It is also active in developing technologies for trapping gases such as iodine-129, krypton-85, tritium, and carbon-14 from radiochemical plants (Falci 1990). Separation of organics from radioactive waste is being studied by ionization and magnetic separation. Results indicate that the process eliminates detergents, oils, and complexates yielding non-toxic products (National Academy of Sciences 1990).

The Khlopin Radium Institute research facility at Gatchina, near Leningrad, consists primarily of hot cells used to conduct R&D on reprocessing of reactor fuels with emphasis on partitioning HLW streams. The Institute is studying partitioning of HLW streams into cesium, strontium, and transplutonium elements and is producing radiation sources from cesium (using phosphate glass) and strontium (using borosilicate glass) (National Academy of Sciences 1990). See Section 7.0 for further information on research at Gatchina.

2.3 OTHER RESEARCH INSTITUTES INVOLVED IN WASTE MANAGEMENT

2.3.1 Radon, Zagorsk

The Radon facility, located near Zagorsk (about 100 km east of Moscow), was established in 1964 and serves a population of approximately 30 million in the Moscow region. [This waste management facility handles municipal waste and industrial/medical/research low- and intermediate-level radioactive wastes and is one of about 35 such facilities.] It employs about 1800 persons at the site and an additional 300 in Moscow. Solids and solidified liquid wastes are stored in shallow-land burial with cement used for solidifying low-salinity

waste streams and bitumen used for high-salinity wastes. Recently, it was reported that Radon was conducting demonstration studies on vitrification of low- and intermediate-level wastes (Atomnaya Energiya October 1990; National Academy of Sciences 1990). Further information on waste management activities at Radon is given in Section 9.0.

2.3.2 Institute of Physical Chemistry, Moscow

This institute of the USSR Academy of Sciences, directed by Yuriy M. Polukarov, although focusing on metals corrosion and electrochemistry, is also involved in waste management. Activities include development of nuclide adsorbents (ferrocyanide compounds), radionuclide migration and adsorption rates in soils. They are also studying the chemistry of technetium, including fabrication of the pure metal (National Academy of Sciences 1990).

2.3.3 Nuclear Safety Institute, Moscow

Leonid Bolshov's Nuclear Safety Institute, established as a result of the Chernobyl disaster, is now in the process of rapid growth. The Soviet Politburo decided to create an independent institute within the Academy of Sciences to supply the government and the public with an independent view of the problems related to nuclear power generation, including impacts, and providing expert judgment--scientific or otherwise.

The Institute currently has 130 full- and 240 part-time employees with expected growth to 500 full-time employees. The Institute works with industries cooperatively under contract. The programs include (National Academy of Sciences 1990):

- radiological measurements in the field
- mathematical models
- government orders on entire fuel cycle, health effects, etc.
- training of power plant operators
- modeling of severe accidents,
- ecological problems, including global impacts.

3.0 INTERNATIONAL EXCHANGES AND AGREEMENTS

3.1 ARGENTINA

A breeder reactor cooperative agreement was signed in Moscow by the leaders of both nations on October 25, 1990. The agreement covers exchanges of breeder reactor technology, with all information to be covered by IAEA safeguards. (Nucleonics Week November 8, 1990)

3.2 COMMISSION OF THE EUROPEAN COMMUNITIES

Discussions are continuing between the Soviet Union and Commission of the European Communities (CEC) with respect to concluding three agreements covering nuclear safety, exchange of fissile material and nuclear fusion research and development. Detailed discussions are expected during the fall of 1990, where the Commission will negotiate on behalf of Euratom, which will be the CEC party to the accords. The CEC is also considering a proposal for broader economic assistance for the Soviet energy sector, including nuclear power (Nucleonics Week August 23, 1990a).

3.3 FEDERAL REPUBLIC OF GERMANY

West Germany is looking for a new Soviet partner in its bid to build a high-temperature gas-cooled reactor in the USSR, due to protracted negotiations with Techsnabexport (TSE). The USSR State Ministry of Petrochemistry, according to West German officials, would perform a feasibility study on the economics of using HTRs for generation of process heat in the oil industry. The study would likely be completed by the end of 1991, in time for a 1992 decision by the Petrochemistry Ministry on whether to build an 80-MW HTR, the so-called HTR Module reactor of German design, in the USSR (Nucleonics Week April 1990).

3.4 INTERNATIONAL ATOMIC ENERGY AGENCY

The Soviet proposal for an International Research Center at Chernobyl was established under an agreement signed on September 21, 1990 in Vienna, Austria. The agreement sets forth the protocol for international research at

the center and defines the services and facilities to be provided by the governments of the USSR, Byelorussia and the Ukraine as well as specifying the role of the IAEA in development, coordination, and dissemination of research results (Nuclear Waste News November 22, 1990)

The IAEA, working with four other United Nations and European Community agencies and with some 100 technical experts from eight counties, has organized "a major project" to reassess the conflicting, sometimes flatly contradictory, findings on the causes, health and environmental effects, and precautions against a repetition of the Chernobyl-4 accident. Participating organizations include the U.N.'s Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), the Food & Agricultural Organization (FAO), and the World Health Organization (WHO). The Commission of the European Communities (CEC) also is participating (Nucleonics Week May 10, 1990a). Field work on the study was completed by late 1990, and the IAEA expects to publish the final revision by May 1991 (Nucleonics Week December 6, 1990).

3.5 IRAN

In March 1990, it was reported that the Soviet Union agreed to build two nuclear power plants in Iran. This was part of a "wide ranging protocol," signed on March 6, 1990 (Times March 8, 1990).

3.6 JAPAN

The Japan Atomic Industrial Forum (JAIF) signed an agreement with the USSR Academy of Sciences on August 28, 1990 in Tokyo during a visit of Japanese nuclear facilities by a delegation of the Soviet Academy of Sciences. Work was anticipated in the areas of development of nuclear-grade materials and site-selection methods (Nuclear News October 1990).

3.7 UNITED KINGDOM

Britain and the Soviet Union signed an agreement on April 10, 1990, calling for prompt notification of nuclear accidents and information exchanges on nuclear installations (Nuclear Waste News April 12, 1990).

3.8 UNITED STATES

The U.S. Department of Energy (DOE) has entered into an agreement with the Institute of Nuclear Power Operations (INPO) under which INPO will essentially run a new bilateral program aimed at improving the operation and management of civilian reactors in the Soviet Union. The initiative was proposed by U.S. Energy Secretary Admiral James K. Watkins (ret.) in September 1989, and is being implemented under the Memorandum of Cooperation in Civilian Nuclear Reactor Safety and the Atomic Energy Agreement. This agreement is part of a larger international initiative launched in September 1988 at the inaugural meeting of the U.S.-USSR Joint Coordinating Committee for Civilian Nuclear Reactor Safety. A delegation of U.S. government and INPO officials, led by DOE Assistant Secretary for Nuclear Energy William Young, met with their Soviet counterparts March 12-16, 1990, and formalized the initiative with Soviet Minister for Atomic Power & Industry (MAPI) Vitaliy Konovalov and Deputy Minister for Plant Operations Erik Pozdyshev. The agreement will focus on three aspects of nuclear plant operations: the use of operating instructions in both normal and emergency situations, personnel training, and management and operational control. The U.S.-USSR representatives agreed to focus the first activities under the agreement to the first-generation PWRs at Novovoronezh (Nucleonics Week March 29, 1990).

On May 25, 1990, DOE Secretary James Watkins and the Soviet Minister of Atomic Power and Industry, Vitaliy Konovalov, signed the ninth atomic energy agreement between the U.S. and the USSR. The 5-year agreement includes cooperation on environmental restoration and waste management (Nuclear Waste News May 31, 1990). Presidents George Bush and Mikhail Gorbachev renewed a U.S.-USSR civilian nuclear cooperation agreement, previously signed in June 1973 and November 1985, on June 1, 1990, for "scientific and technical cooperation in the field of peaceful uses of atomic energy" (Nucleonics Week June 7, 1990a).

Technical exchanges involving the United States have also included several recent visits. A U.S. National Academy of Sciences group, headed by Dr. Frank Parker, visited the Soviet Union from February 10-25, 1990. Following the agreement signed in May 1990 by Watkins and Konovalov, a series of

fact-finding visits were scheduled on environmental restoration and waste management. Subsequently, a Soviet delegation, headed by Boris V. Nikipelov, First Deputy Minister, Soviet Ministry of Atomic Energy and Industry, visited the United States from March 26-April 3, 1990. A reciprocal DOE team headed by Leo Duffy, Director of the Office of Environmental Restoration and Waste Management, visited the Soviet Union from June 18-27, 1990. Potential areas for technical exchanges discussed during this visit included vitrification, partitioning of HLW streams, geohydrological modeling and the exchange of scientists and studies (Falci 1990).

A further step on cooperation in the area of environmental restoration and nuclear waste management was taken on September 18, 1990, when W. Henson Moore, Deputy Secretary of DOE, and Vitaliy Konovalov, the Minister of MAPI, signed a Memorandum of Cooperation (MOC). A U.S.-USSR Joint Coordinating Committee for Environmental Restoration and Waste Management (JCCEM) was provided for under the agreement (Nuclear Waste News September 27, 1990). On November 12-16, 1990, U.S. DOE specialists visited the USSR to hold the first fact-finding meeting JCCEM as established by the MOC. The JCCEM is the governing body for workshops and technical exchanges with the USSR for Environmental Restoration and Waste Management (Bradley December 1990).

4.0 WASTE MANAGEMENT IN THE FRONT END OF THE FUEL CYCLE

The Soviets have been practicing underground leaching of uranium ore deposits (as well as extracting rare earth elements) since the early 1960s, primarily on low-grade ores with a uranium content of 0.03 to 0.05%, and ores located in complicated geologic settings. At present, about 30% of the uranium recovered in the USSR is by underground leaching. The technique has been used on near surface ore bodies at 40 to 80 m in depth, as well as ore bodies located up to 600 m in depth, using leachants of sulphuric acid or carbonate-bicarbonate solutions. The Soviets report that uranium recoveries as high as 85% are obtained using acid, and 70% using carbonate solutions. They have used several methods to overcome plugging of pore spaces in the ore bodies due to chemical or mechanical effects, including treating the wells with carbon dioxide gas or hydrochloric acid. Hydrochloric acid has been reported to be used in amounts of up to 15 kg per ton of ore treated, or up to 150 kg per kg of uranium recovered. Carbonate solutions are used up to about 3 kg per ton of ore treated (Skorovarov et al. 1990a).

The Soviets are studying methods of commercial scale beneficiation of uranium ores using hydrocyclones for ore classification, especially "clay-pyrite-uranium-phosphorus" ores as well as some "uranium-phosphate-carbonate" ores. They have also carried out "extensive investigations" to develop the technology of magnetic fractionation of the initial ore, followed by leaching processes. Pilot tests are planned using "high gradient and large volume gradient magnetic separators using superconductors." The processes being developed also produce nitrophosphorus fertilizers (Skorovarov et al. 1990b).

The Soviets stated recently that they have about 5×10^9 tonnes of mill tailings with an annual production of about $6\text{-}7 \times 10^6$ tonnes resulting from uranium mining operations. They have "temporary storage" of their tailings and expect to cover them by the year 2000, returning 166,000 acres back to the "economy." A reduction of 300 fold [presumably of radioactive release] was stated to be achievable, probably through the use of a 1.5 meter clay and grass cover (Falci 1990).

5.0 NUCLEAR REACTOR OPERATIONS WASTE MANAGEMENT

Waste management at Soviet nuclear reactor sites emphasizes activities to reduce the amounts of liquid and solid wastes, and concentration of liquid wastes with the reuse of the purified water. The main waste management activities are as follows (Nikiforov September 1990a):

- interim storage of liquid waste concentrates in corrosion-resistant tanks
- incorporation of all categories of liquid wastes into "highly water resistant materials"
- storage of solidified wastes in surface or near-surface facilities until regional "repositories" are established at reactor sites
- volume reduction of solid wastes to improve "radionuclide stabilization"
- off-gas clean-up to specified discharge standards.

Incorporation of wastes from reactor operations into bitumen is the most advanced process in the USSR. Based on test results, two types of bitumators are being used: up to 500 L/h capacity for RBMK-1000 reactors, and 200 L/h capacity for VVER-1000 reactors.

The first bituminization plant for liquid radioactive concentrates from the Leningrad site was put into commercial operation in 1984. Figure 5.1 shows a diagram of the Leningrad bituminization plant, and Figure 5.2 a detailed drawing of the bituminator. In 1987, a similar bituminization plant at the Ignalina site became operational. Data on plant operations at these sites is given in Table 5.1 (Nikipelov et al. 1990a).

The bitumen compound is directly transferred from a bitumator via a heated supply line into surface-reinforced concrete storage areas having a volume of 2500 m^3 each. For VVER-1000 reactors and the planned Gorky district heating reactors, bitumen is placed in 200-L steel drums which are transferred to a surface facility for temporary storage. The storage design provides for removal of these drums for placement into a regional repository (Nikipelov 1990a). A bituminization plant has also been stated to be operational at the Kalinin VVER reactor station (Nikiforov September 1990a). The Soviets have

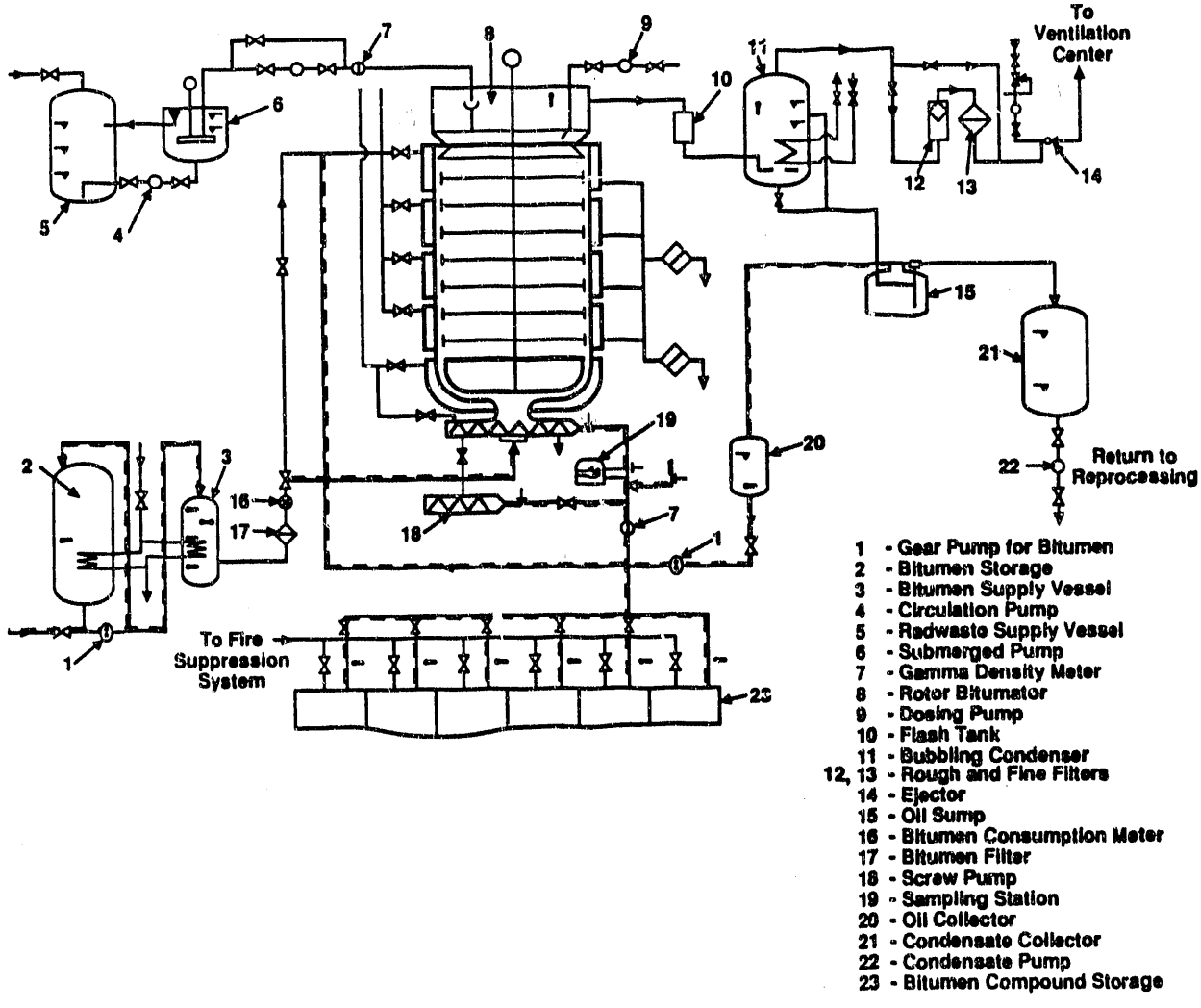


FIGURE 5.1. Liquid Radwaste Solidification by Bituminization at the Leningrad Reactor Site (Nikipelov et al. 1990a)

further stated that the bitumen is stored in above-ground concrete containers (with stainless steel liners) because the water table is essentially at the ground surface. They also indicated contamination problems due to rain entering storage vaults located at one of the state regional LLW sites near the Leningrad reactor (Falci 1990).

The resins and filters from air and water treatment at the Leningrad RBMK reactor site are incorporated into bitumen which is stored in concrete containers lined with stainless steel. There are 12 such containers in a building at the site, each with a capacity of 2000 m^3.

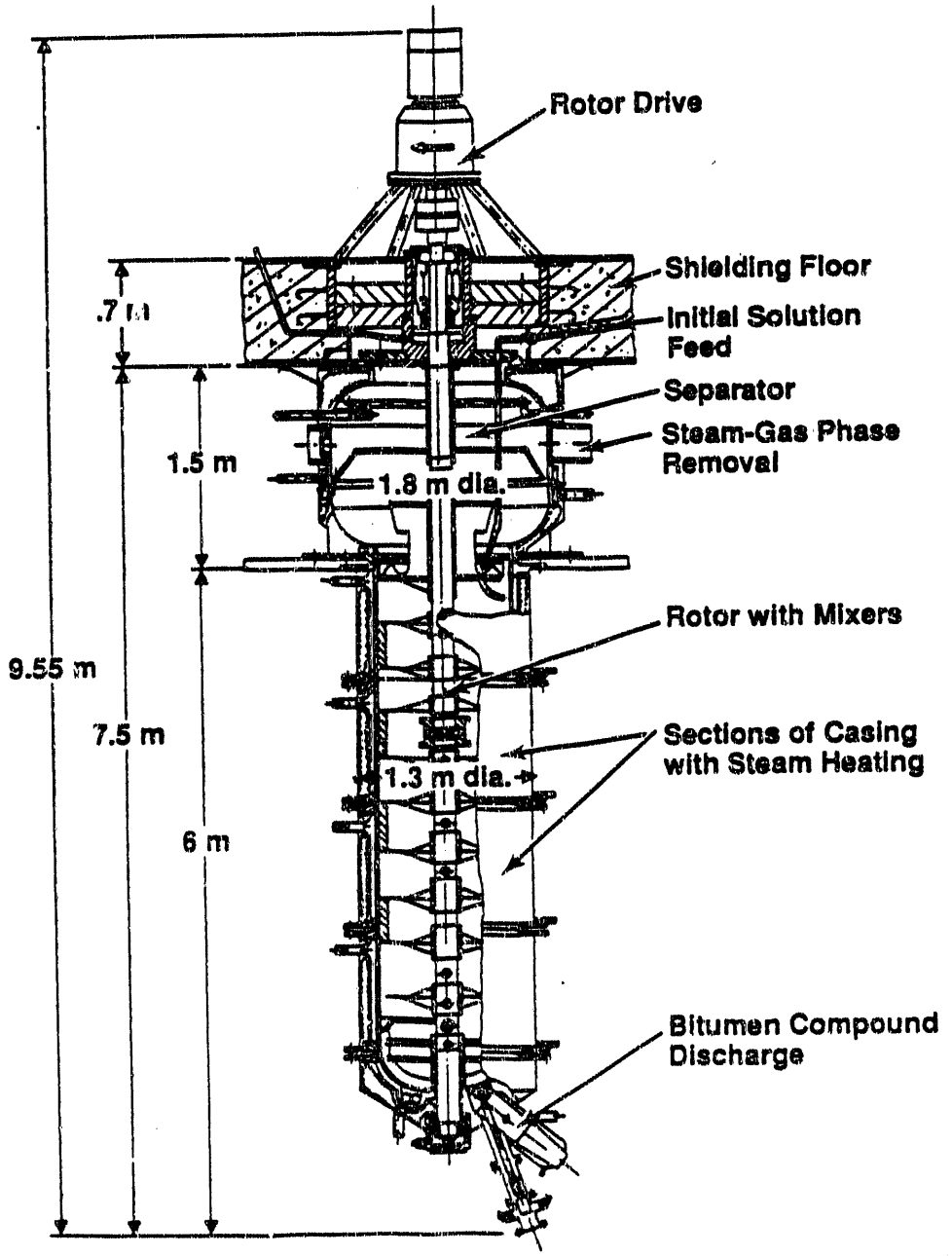


FIGURE 5.2. Bituminator with Built-in Extruder (Nikipelov et al. 1990a)

Liquid LLW from VVER reactor operations at Novovoronezh is evaporated to reduce the volume by a factor of 20, to a concentration of 900 to 950 grams of solids per liter of solution. The concentrated solution containing 1×10^{-5} Ci/L is then mixed with bitumen. The tanks into which the bitumen is

TABLE 5.1. Bituminization Plant Operational Data

	Leningrad RBMK Reactor Site	Ignalina RBMK Reactor Site
Quantity of LLW and ILW processed by 1/1/1990, m^3	~3 x 10^6	~0.7 x 10^6
Quantity of bitumen compound produced by 1/1/1990, m^3	6800	1542
Incorporation of solid components into bitumen, %	35-40	35-40
Average specific activity of bitumen compounds, Ci/L	10^{-4}	10^{-4}

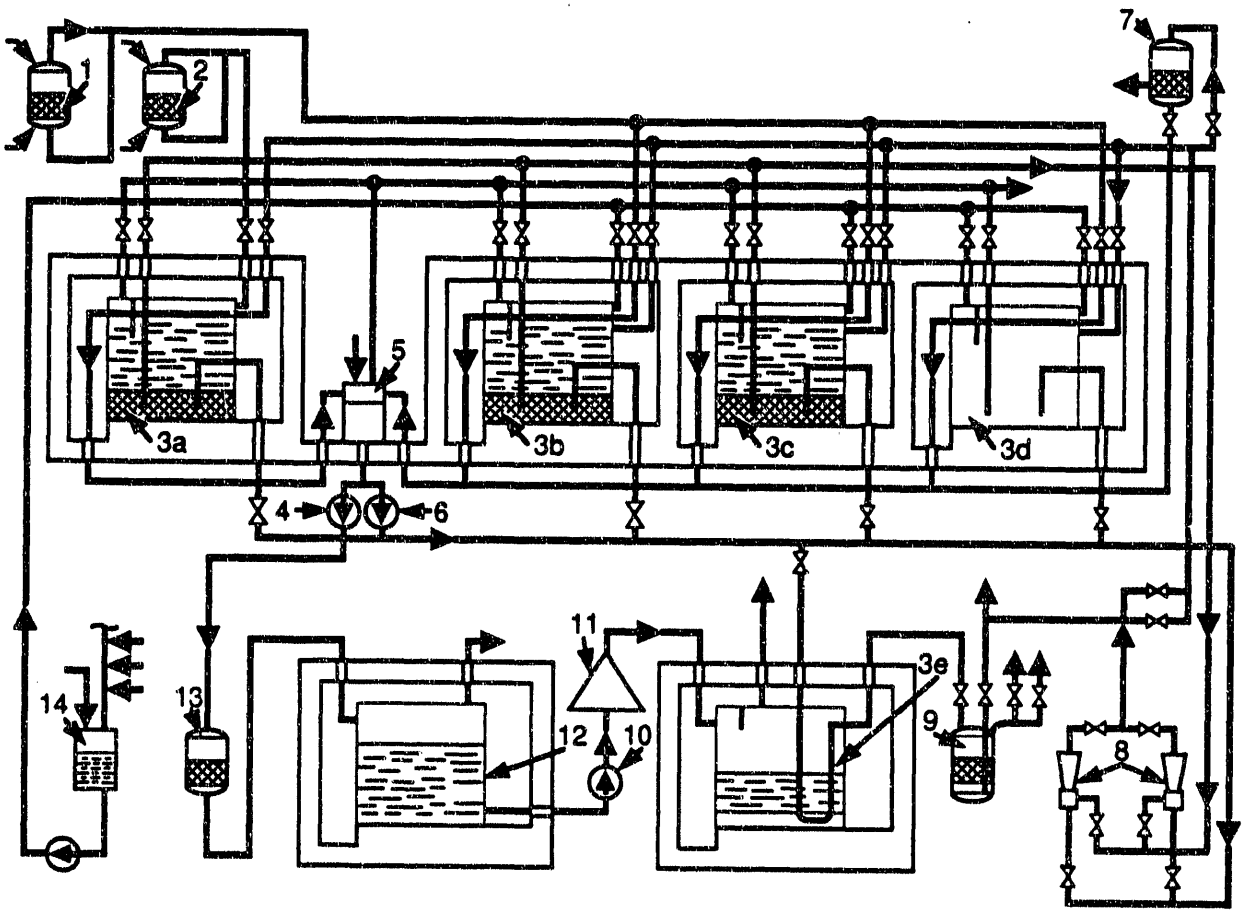
poured and hardened are designed to serve the 440-MWe units for 20 years and the 1000-MWe units for 5 years (Naticnal Academy of Sciences 1990).

The Soviets note that preference has been given to the bituminization method over cementation in the past because of the low water resistance and waste content of their cement-based waste forms. They indicate that studies have now shown that the use of Portland cement with a blast furnace slag content of 70 to 80% as a binding material has enhanced the mechanical strength when used to solidify waste solutions having a high alkali content. In addition, adding small amounts of bentonite clay (up to 10% weight), increases leaching resistance. To improve ductility, special plasticizing additives may also be added. Two types of cementation plants are being established: batch-operated cementation directly in a 200-L drum, and batch-operated mixing of a binder and a liquid waste concentrate in a small-volume mixer (Nikipelov et al. 1990a).

Radioactive gases formed in the RBMK reactors at Leningrad are released from solution in the turbine condenser and vented to the atmosphere after a 5-hour delay. Releases from the stack were reported to be less than 25% of the allowable concentration (National Academy of Sciences 1990).

Treatment systems for handling radioactive solutions, as well as resins and "sorbents," are available at Soviet nuclear power plants. Treated solutions are then apparently solidified using bituminization or cementation as

discussed above. Figure 5.3 shows a diagram of a typical processing system for resins, sorbents, sediments, and concentrates at a VVER-440 reactor. Figure 5.4 depicts the treatment and disposal of liquid radioactive wastes at VVER reactors (Nikiforov et al. 1985).



1. High Activity Ion Exchanger
2. Intermediate Activity Ion Exchanger
3a. Container for Low Activity Sorbents
3b. Intermediate Activity Neutralization/Clarification Tank
3c. High Activity Neutralization/Clarification Tank
3d. Standby Emergency Tank
3e. Tank for "Still Residues"
4. Pump
5. Tank for Clarified Solutions
6. Pump
7. Tank for Ion Exchange Resin
8. Ion Exchange Resin Hydraulic Pump
9. Air Lift Pump to Solidification Facility
10. Pump
11. Evaporator System
12. Tank for Trap Water
13. Mechanical Filter
14. Trap Water Receiving Tank

FIGURE 5.3. Process Flow Diagram for Treatment and Storage of Radioactive Ion Exchange Resins, Sorbents, Sediments and Concentrates at VVER-440 Reactors (Nikiforov et al. 1985)

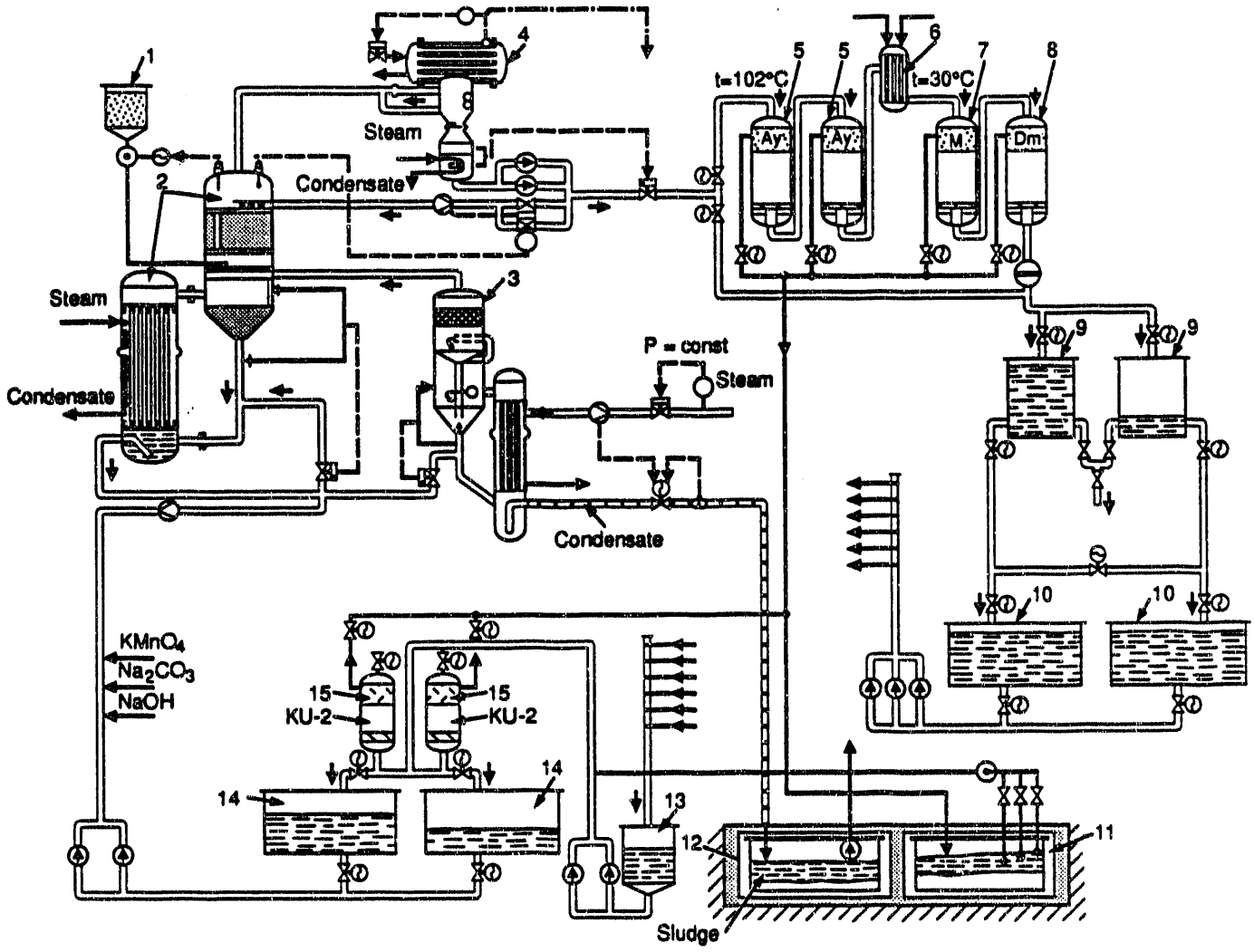


FIGURE 5.4. Process Flow Diagram for Treatment and Disposal of Liquid Radioactive Wastes at VVER Reactors (Nikiforov et al. 1985)

Solid radioactive wastes from nuclear reactor operations (decommissioned equipment, debris, filters, special clothes etc.) are disposed of in shallow-land repositories equipped with a "drain system, clay shields and concrete ceilings." Facilities are [being] established for decontamination, compaction, incineration and incorporation of solid wastes into a stable matrix. The Soviets are "paying much attention" to the development of radioactive

waste compaction and incineration equipment to help reduce the volumes of solid wastes to be disposed (Nikiforov September 1990a).

Another waste management problem related to Soviet reactor operations is the fate of steam generators. The general tendency at VVER reactors (VVER-1000s), each of which has four steam generators, is that when one fails all four are replaced, adding to costs, downtime and disposal problems. The cost of replacing the four generators is estimated at 25 million rubles plus another 40 million rubles for electricity loss from downtime. Design flaws in the generators have reduced their service life from a projected 30 years to an average of 2 to 3 years. It was reported that 26 steam generators have now failed. At the Balakovo power plant, waste management became an issue in dealing with its failed steam generators. Transportation workers refused to ship the generators offsite to be remelted, and metallurgists [presumably onsite] refused to remelt them for fear of radioactive contamination. The steam generators were then apparently left onsite in a shutdown condition (USSR Technology Update 1990).

Decommissioning and Decontamination

A new organization that is studying nuclear power plant decommissioning methods, and a nuclear spare parts factory are located in the town of Novovoronezh. The Soviets have stated they are using a decontamination method involving chelate complexing agents at reactor stations. The process has a low corrosivity, is reusable, and is competitive with "phosphorous" (National Academy of Sciences 1990).

6.0 SPENT FUEL MANAGEMENT

At the Leningrad RBMK reactor site, spent fuel elements are stored in the reactor building for 3 years. They are then moved by truck to an adjacent fuel storage building that has five pools, each capable of storing 4000 assemblies. The Soviets stated in a recent visit to the U.S. that all spent fuel generated at Leningrad has been stored there, and that next year will be the first year that spent fuel will be transported to Chelyabinsk subsequent to reprocessing (National Academy of Sciences 1990; Falci 1990). Spent fuel is reported to be stored in pools also for 3 years at the Novovoronezh VVER reactor site. The fuel from units 2-4 at Novovoronezh is shipped to Kyshtym, but it was not stated whether it was then reprocessed (National Academy of Sciences 1990).

The cooling pool for the BN-600 reactor at Beloyarsk was commissioned in 1980. The pool is made of monolithic reinforced concrete and lined with stainless steel sheet (3-mm sheet for the walls and 5-mm sheet for the bottom). It is filled with demineralized water to a depth of 7 m, and is designed to eliminate "self-dumping" resulting from pipe breaks or operator error. The pool liner integrity is checked by the use of "monitoring grooves" in seams under the concrete. The cooling pool is designed to contain 3885 spent fuel assemblies, for a design cooling duration of 3 years (Gorban et al. 1987).

All three bays of the Beloyarsk BN-600 cooling pool are united in normal operation; however, they can be separated from the others by a hydraulic gate. Two bays of the cooling pool store baskets containing spent fuel assemblies. The middle reception bay stores baskets as well and is also used for fuel transfer operations. The geometric volume and surface area of the bays are respectively (Gorban et al. 1987):

west - 976.15 m^3 and 139.45 m^2
reception - 392.00 m^3 and 56 m^2
east - 1503.25 m^3 and 214.74 m^2

The water purification system has a capacity of 120 m^3/h and maintains water quality to the following specifications:

transparency	- 95-96%
pH	- 6.5-7.5
conductivity	- 1.3-3.0 μS/cm
chloride content	- 50 g/kg
activity	- $4.5\text{-}5.0 \cdot 10^{-8}$ Ci/L

The cooling system controls the temperature in the fuel pool to 40°C, and is shut off if the water is under 35°C, with decay heat being removed by "natural processes."

Prior to 1984, spent fuel assemblies were stored in cans filled with demineralized water, in special baskets with 35 spent fuel assemblies each. Since 1984, spent fuel assemblies have been stored in similar baskets but without cans. Between spent fuel assembly "nests" the Soviets have placed components of a "control and protection system." Radiation monitoring of the cooling pool building is performed by three gamma-sensors, one aerosol, and two gas monitors (Gorban et al. 1987).

At the Zaporozhye site visited in 1989 by NRC inspectors, reactor spent fuel storage racks had a nominal capacity for 15 years of operation. It was also stated that a separate fuel storage facility was present at the site. Liquid radioactive wastes were evaporated and solidified (process unspecified) and stored onsite. It was noted that the site had sufficient storage capacity for its 30-year plant life, and that the radwaste building was nearly as large as one of the power blocks (Inside N.R.C. May 7, 1990).

Recent decisions by Boris Yeltsin, president of the Russian SFSR, may have a major impact on spent fuel shipment from, and waste management practices in, some CMEA countries. Yeltsin announced in June 1990 that "foreign wastes would no longer be welcome in Russia" after January 1. Although some spent fuel from VVER-440 reactors in Finland and Hungary has been shipped to the Mayak site, CMEA countries with these reactors have been asked by the Soviets to store their spent fuel "longer than the original 3 yr contract period." Czechoslovakia claims to have not shipped any spent fuel to Russia, and a moratorium on shipment of spent fuel back to the Soviet Union is expected to cause severe problems for Bulgaria, Czechoslovakia, Hungary and

the German Democratic Republic (Nucleonics Week July 12, 1990a). Additionally, it has been stated that the Russian SFSR would not allow the construction of new nuclear facilities on their territory after January 1, 1991, pending adoption of a program "for dealing with radioactive waste and spent nuclear materials and their utilization and burial in the USSR." (SOVETSKAYA ROSSIYA June 28, 1990).

In addition to announcements by the Russian SFSR, the Soviet Union has substantially raised the price it charges for return of CMEA country spent fuel. Effective July 1, 1990, the Soviets will cancel existing "spent fuel arrangements" and demand payment in hard currency at the rate of $1,200-$1,300 per kilogram of uranium for spent fuel returned to the Soviet Union. A Czechoslovakian official noted this translates to $16-$20 million for an average PWR core reload, or up to $160 million for all their reactors on line. Czechoslovakia is now "strongly considering" construction of a final repository for spent fuel in their country (Nuclear Fuel July 9, 1990).

7.0 FUEL REPROCESSING

A reprocessing plant at the Chelyabinsk-40 site (commonly referred to as the Kyshtym site, and more recently as "Mayak," see Chapter 11) was put into operation in 1949 to extract plutonium from natural uranium irradiated in uranium-graphite reactors. Later [reported to be 1978 (New Scientist July 22, 1989)], reprocessing of spent fuel from naval and VVER-440 power reactors was also performed at the Chelyabinsk-40 site. The Chelyabinsk-40 site now meets all demands for reprocessing of spent fuel from these reactors, constructed in the USSR and elsewhere (Drozhko 1990). It has also been reported that after 1978, spent fuel from the Chelyabinsk-40 site was being transported by rail to another reprocessing site located at Tomsk (New Scientist July 22, 1989). No further developments have been reported recently on the large reprocessing facility, stated to be 30% complete, for VVER-1000 fuel and "other reactors" near Krasnoyarsk (Nuclear Fuel October 16, 1989). Also, it should be noted that the Soviets have also been recycling uranium, obtained from the reprocessing of VVER reactor fuel and then re-enriched, into RBMK reactors (Nikiforov September 1990b). Although the reprocessing of RBMK reactor fuel has been continually delayed, the Soviets recently indicated that spent fuel from the Leningrad reactors would be shipped to Chelyabinsk-40 in 1991 for reprocessing at an unspecified time (Falci 1990).

The first reprocessing technology was based on plutonium and uranium extraction using "slightly" soluble sodium uranyl acetate precipitation from nitric acid solutions. During the first years of the radiochemical plant operation, acetate-nitrate solutions made up the bulk of high-level waste solubles. To "reprocess" the acetate-nitrate solutions, a "precipitation-crystallization-sorption technology" which used non-soluble compounds to precipitate radionuclides from fission product mixtures was used. Ruthenium and strontium were concentrated on nickel and chromium hydroxides; zirconium, niobium and protactinium on iron and nickel sulfides; and cesium was coprecipitated with nickel ferrocyanide. Concentrated fission product solutions were then placed in long-term storage, and the clarified solution after acidification by nitric acid was concentrated by evaporation. Sodium nitrate was obtained from distillation residues by crystallization (Drozhko 1990).

In the next stage, reprocessing based on precipitation technology was replaced by that of liquid extraction with tri-butylphosphate solution using an inert diluent as an extractant, in what appears to be the PUREX process used in western countries. The Soviets state that the "salinity" of their high-level radioactive wastes was thereby reduced several times (Drozhko 1990).

The Soviets have recently reported studies to determine better liquid extraction solutions for actinides from the first cycle of spent fuel reprocessing, evidently prompted by concerns over the limited solubility of plutonium-tributylphosphate in a "diluent of a saturated hydrocarbon type," and TBP's relatively high solubility in an aqueous phase which may result in product contamination with phosphorus. Their research led to the selection of triisoamyl phosphate (TIAP) with 15 carbon atoms and diisobutylisooctyl phosphate (DIBIOP) with 16 carbon atoms as the preferred extractants. Research has also been conducted on solvents to enhance extraction of transplutonium elements with phosphine oxides. They have determined that diphosphine oxides and carbamoyl phosphine oxides increase yields by one order of magnitude or more. These extractants, as well as TIAP and DIBIOP have been successfully tested with high burn-up short cooled fuel of 100 GW day/MTU and in VVER spent fuel reprocessing (Nikiforov et al. September 1990c).

At the reprocessing facility, spent fuel transportation casks are unloaded and the wrapped fuel assemblies are sent to a "buffer cooling pond." The bottoms of the fuel assemblies are cut off using a partially submerged electric circular saw to reduce the release of gases and aerosols. Cuttings and non-fuel-bearing components are sent for "disposal" and the fuel is sent to a shearing operation. Following nitric acid dissolution of the fuel, the structural material and insoluble residues are removed by an "air operated pulse," and sent for disposal with a pneumatic transport. The losses of uranium and plutonium were stated not to exceed 0.01 and 0.06%, respectively. The resultant dissolved fuel solutions ("suspensions") are "pretreated" with high molecular organic flocculants, and pearlite is used in the filtration process, which uses steel or titanium metal cartridges. In the extraction

process, the Soviets have stated that the losses of uranium, plutonium, and neptunium are 0.01, 0.025, and 0.5%, respectively (Nikiforov September 1990b).

The low-level wastes arising from fuel reprocessing operations constitute 98% of the volume of liquid wastes generated and only 0.01% of the radioactivity. Due to the large volumes, evaporation ("distillation") is not used for these wastes; rather they are sent to purification units where coagulation and ion-exchange are primarily used. The purified water, which contains "permissible concentrations of essentially all radionuclides," is discharged to the environment or reused. The concentrates of slurries resulting from these operations are categorized as intermediate-level wastes, and subjected to evaporation, usually in two stages. Following evaporation, concentrates and filter material slurries are stored in stainless-steel tanks, and ion-exchange resin slurries and concentrates containing ^{129}I may be solidified using bitumen (Nikiforov September 1990a).

In June 1990, it was reported that at Chelyabinsk-40, full scale experimental tests were nearing completion on a new method of reprocessing based on the use of a "metal carbomide" extractant, the cesium salt of cobalt dicarbolide. The Soviets remain interested in further processing of the transplutonium elements to include transmutation and space disposal (Drozhko 1990). The crown ether process, using Dicyclohexane-18-Crown-6, as well as the use of Tetraphenyl Borate, was stated to be being used for the extraction of strontium and cesium from high-level waste streams (Falci 1990). These studies were elaborated during a recent second visit by DOE specialists.

At the Khlopin Radium Institute laboratories in Gatchina, partitioning (liquid-liquid solvent extraction and purification) of elements from high-level waste streams is performed, and scientists are studying processes to incorporate the resulting waste fractions into various waste forms such as glass, ceramics, and glass-metal matrices. At Gatchina, work is starting on "SYNROC"-type materials, and in the next year they will put "hot equipment" into their laboratories to make them. The Moscow All-Union Scientific Research Institute of Inorganic Materials has studied vitrification of high-level wastes prior to any partitioning process (Bradley December 1990).

Dr. Lazarev, Chief Scientist for the Khlopin Radium Institute, recently stated that they started to study partitioning about 12 years ago using Diethyl phosphate. Due to a number of "drawbacks" they shifted to the dicarbolide process and more recently to the study of crown ethers. The Soviets recently ran a 3-month experiment to extract strontium and cesium from HLW in 3 molar HNO_3 acid solutions. The dicarbolide extractant was synthesized in the USSR for about 600 rubles/liter. The test included 260 cycles of dicarbolide extraction without significant dicarbolide degradation. Carryover of the dicarbolide was about 20-50 ppm in the raffinate, radiation exposure averaged 100 watts-h/cc up to a maximum of 1,000 watts-h/cc. Dr. Lazarev believes that dicarbolide degrades slowly and degradation products can be separated with settling. No fire or separation problems were uncovered in the test, and corrosion of the stainless steel containment was not visible. One laboratory at Gatchina, recently visited by U.S. DOE specialists, contained a conventional sieve-plate glass extraction column for process development. The Soviets are actively studying pulsed-columns, and their plan is to improve separation performance by vibrating the sieve-plate assembly and by deleting the traditional air pulse. This was demonstrated at a vibration rate of 2 to 3 cycles/sec with a 1/4" to 1/2" amplitude. They stated that a stainless steel container containing 18% chrome and 10% nickel was used in their nitric acid systems, and although they noticed no sign of corrosion, they plan to use more corrosion resistant material in the future (Bradley December 1990).

It appears that most pilot scale R&D was done at Gatchina with "industrial" trials performed at Chelyabinsk-40. At Gatchina, hot cells were built to test reprocessing of spent fuel from nuclear plants. A model of a small reprocessing plant was made and installed in eight hot cells which processed 100,000 curies. This was a small copy of the full-scale plant which is at Chelyabinsk-40. All the operations were tested in batch sizes of 2 to 3 kilos per day over a 2- to 3-year period. The Soviets then decided that operation of an experimental plant of this size was too costly and that there was no need for an experiment on a large scale, so they dismantled the plant to make the facilities available for work on various other problems. Part of the facility at Gatchina is for the "improvement" of the PUREX process to extract U, Pu, and Np in a single step, which is consistent with the earlier report

discussing better actinide extrant solutions, mentioned previously. Fully radioactive tests of the dicarbolide process were started at Chelyabinsk-40 about 5 years ago. The Soviets have tested at least two variants of the dicarbolide process there for extraction of TRU as well as Cs and Sr. It was stated that tests on the dicarbolide process had been done on both uranium metal and uranium oxide based spent fuels as well as naval spent fuels. They indicated that 500,000 Ci of Cs and Sr had been recovered at Chelyabinsk-40. In 4 to 5 months, new equipment for the dicarbolide process will be installed there which is to be operational in 1992. The Soviets indicated they will also try the crown-ether process for Sr extraction on an industrial basis at Chelyabinsk-40 (Bradley December 1990).

A recent article by Afonin et al. (1990) discusses the dicarbolide process, concentrating on a mathematical model they have developed to describe dicarbolide extraction processes in order to calculate individual cascades, overall process flowsheets, and develop automatic control systems. Distribution coefficients are also given for various elements in the dicarbolide - nitrobenzene system. The Soviets indicate that their present state of dicarbolide technology makes it possible to solve problems associated with this process in the past (Afonin et al. 1990).

8.0 HIGH-LEVEL WASTE TREATMENT, STORAGE AND DISPOSAL

8.1 HIGH-LEVEL WASTE TREATMENT AND STORAGE

The main method of high-level liquid waste storage at the Chelyabinsk-40 plant is in stainless steel tanks housed in underground concrete structures. After 1957, "solutions and suspensions" were stored in new tanks with a capacity of 280 to 1500 m^3. Tanks that were operated until 1957 were washed, decontaminated, and placed in "conservation" (Drozhko 1990). High-level liquid waste (>1 Ci/L) storage tanks are equipped with methods for cooling with permissible temperatures of 50 to 60°C, and blowdown to remove radiolysis products, of which hydrogen must not exceed 0.3% (Nikiforov September 1990a).

Further details of HLW storage were given during a recent visit by U.S. DOE specialists to the Soviet Union. It was stated that the tank characterization studies at Chelyabinsk-40 were now complete. The Soviets "decanted" the liquid phase from double-walled stainless steel storage tanks, indicating that they had taken steps to avoid precipitation. Part of this liquid waste has been vitrified using their first "industrial scale" melter at Chelyabinsk-40. By the first or second quarter of 1991, they hope to have a new vitrification facility operational, using the modified second single-stage ceramic melter at Chelyabinsk-40. With this facility in operation, they plan to empty their high-level waste storage tanks, allowing them to be reused for new wastes resulting from the continued reprocessing of VVER-440 reactor fuel. They do not plan to build any further HLW storage tanks at the Chelyabinsk-40 site (Bradley December 1990).

For "medium active" wastes stored in single-wall steel tanks [believed to be a 300 series stainless steel] containing liquids and solids, derived from chemicals "no longer used" which have been stored for up to 25 years, the Soviets stated that the wastes are incorporated into "cement" and/or "clays" for in-tank "final" disposal. They have solidified an unspecified number of these tanks which they state is feasible when the radioactive contents are <5 Ci/L. No significant problems have been encountered with gas generation in

their tanks because of the use of air flow-through systems. Temperature measurements, both radially and vertically in tanks containing solids, showed a variation from 20 to 30°C.

The Soviets felt their most important problem is what is to be done to those double-shell tanks made of stainless steel, which have a limited [undefined] durability. They are developing technology and methods to take out "remnants" and reprocess them. In those cases where radiation levels are not high [i.e., no large heat release is expected during solidification], in-tank solidification, as with the older tanks, may be considered (Bradley December 1990).

The Soviets only discuss two high-level waste streams at the Chelyabinsk-40 site. The wastes from power reactor fuel reprocessing are low in "salt" content, but contain a large quantity of long-lived fission products and transplutonium elements, whereas the wastes from reprocessing of submarine and research reactor fuel contain a large quantity of salts, but few transplutonium elements. The solutions from power reactor fuel reprocessing are concentrated by evaporation and then stored in tanks, with nitric acid being recycled. Part of the evaporated HLW solutions are processed at the "fractionation" facility, and then used for making radiation sources. All high-level wastes from submarine and research reactor fuel reprocessing will be vitrified, along with the majority of intermediate-level wastes (Drozhko 1990).

Some aspects of the history of vitrification in the USSR were given during a recent visit to the USSR by a DOE fact-finding delegation. Their first work was done on silicate glasses with a radioactivity content ranging from 1-1000 Ci/ℓ. They did not build a large-scale model of this process. In the 1970s, natural gas was used as a heating source for a single-stage vitrification facility with water-cooled walls. Oxygen was introduced to decrease the volume of off-gases but a working facility was not completed. The design for a working facility was finally based on glass tube manufacturing plants in the USSR (Bradley December 1990).

The Soviets have reported further details of the high-level liquid waste vitrification facility at Chelyabinsk-40. Equipment is placed in two

buildings connected by a "technological scaffold" bridge. The first building contains equipment for feed materials preparation (fluxing), HLLW concentration by evaporation, and offgas cleaning systems. The second building contains two 500-L/h [feed rate] electric glass melters (Nikipelov et al. 1990a) that achieved a maximum processing rate of 450 L/h of solution and 90 kg/h of glass (Medvedev 1990, Nikiforov et al. 1990d). The building also contains a unit for pouring glass into cans, a system for can transportation, a chamber for welding canisters containing three cans of glass, tools for remote operation, and air-cooled bays for canister storage. Figure 8.1 shows a diagram of the 500-L/h feed rate ceramic melter, Figure 8.2 shows the high-level waste canister, and Figure 8.3 shows the waste canister transport shielded container (Nikipelov et al. 1990a).

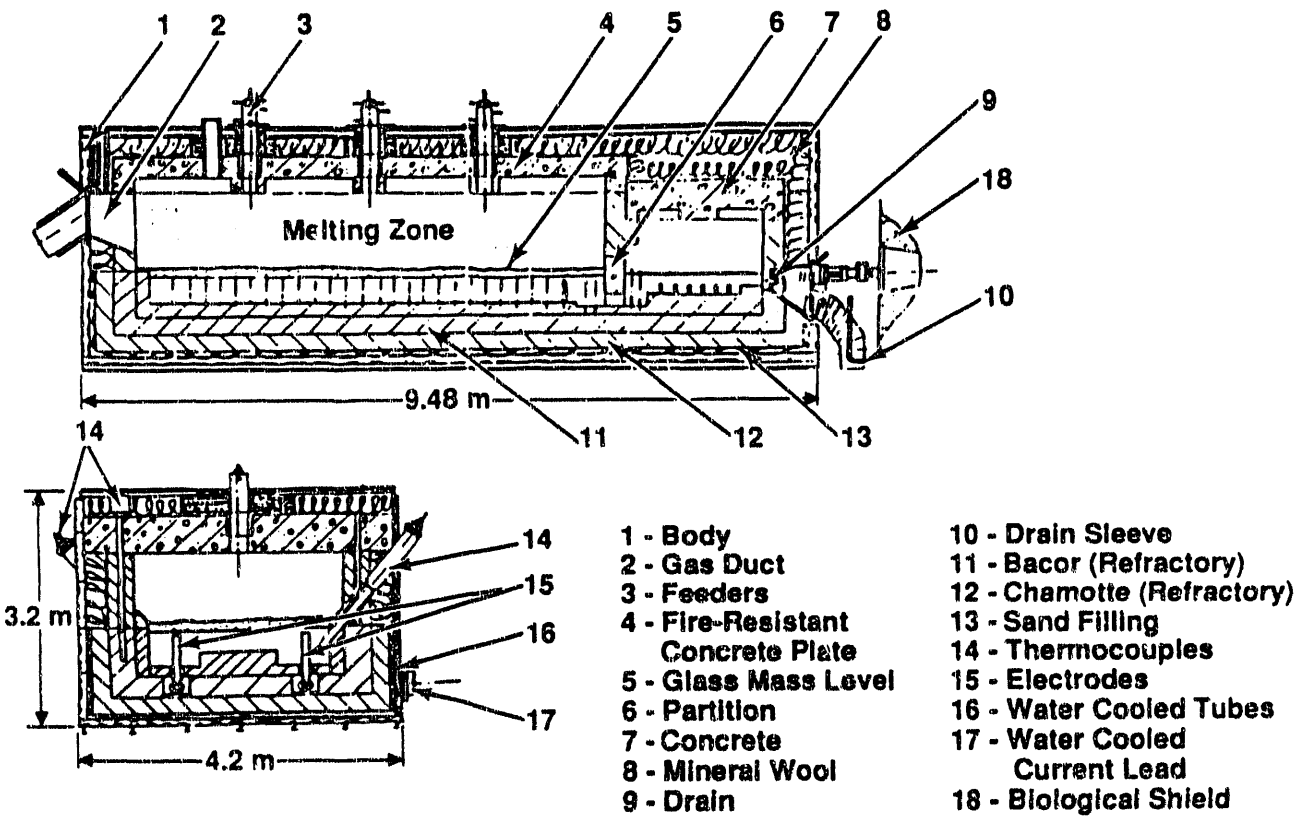


FIGURE 8.1. Ceramic Melter - 500 L/h Feedrate Capacity (Nikipelov et al. 1990a)

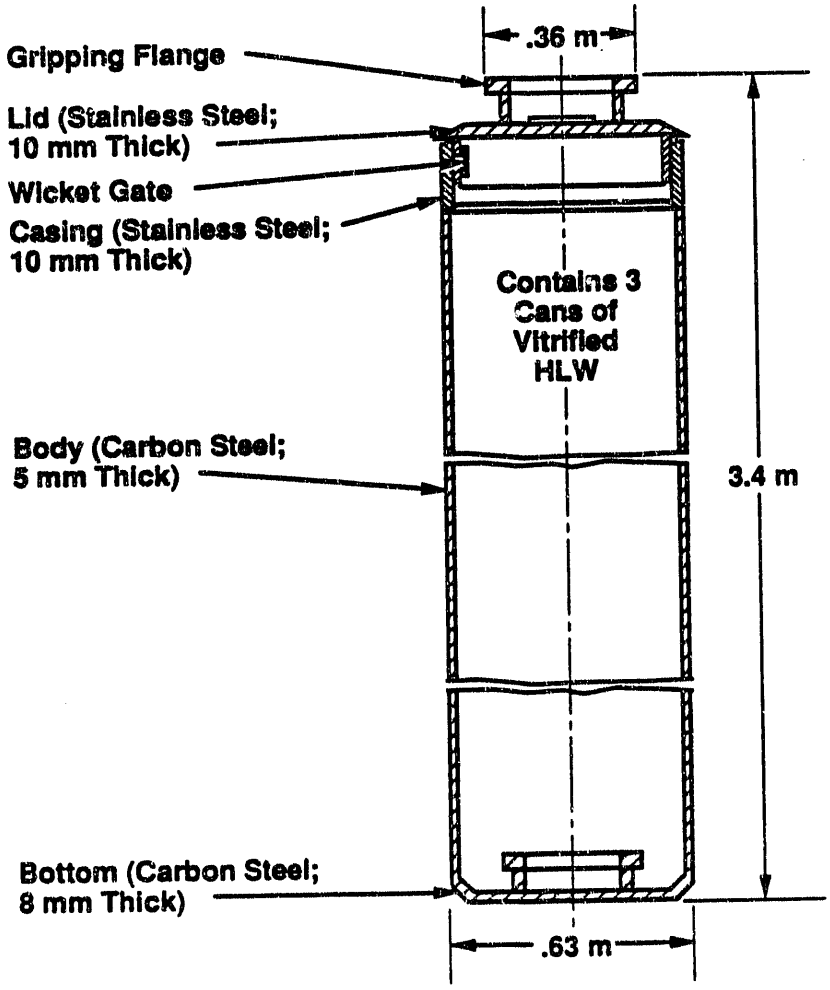


FIGURE 8.2. Canister for Vitrified High-Level Wastes (Nikipelov et al. 1990a)

Solidified wastes with an activity of ~5.5 x $10^3 W/m^3$ are placed in forced-air-cooled storage which consists of concrete bays containing equally spaced concrete tubes (shafts). Two canisters are welded into a "three-seat" shielded container and then placed into one of the concrete shafts. It was noted that the storage design also allows the use of natural air circulation, if required, using a tall stack. Figure 8.4 is a drawing of the forced-air-cooled storage facility. After the specific decay heat decreases to 1.0 to 1.5 x $10^3 W/m^3$, the HLW glass canisters are taken out from the forced-air-cooled storage bays and transported in a shielded container to another storage

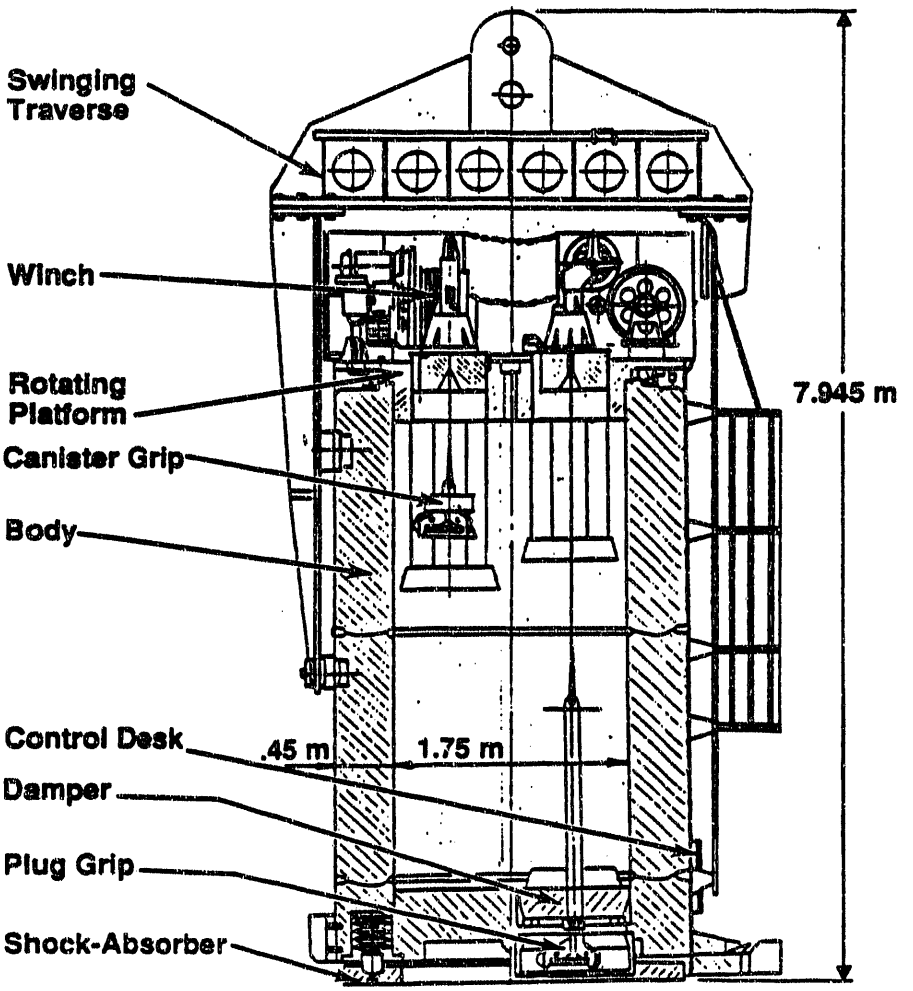
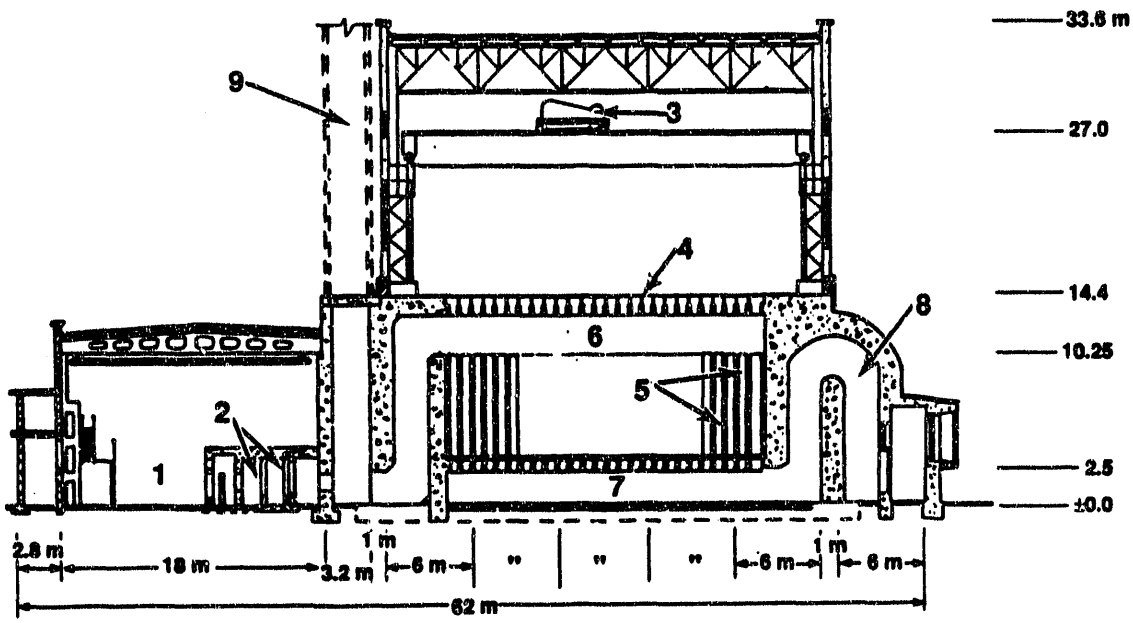


FIGURE 8.3. Shielded Container for Transferring Waste Canisters to the Forced-Air-Cooled Storage Area (Nikipelov et al. 1990a)

area where heat removal is accomplished by natural air circulation. This storage area consists of reinforced concrete bays and shafts designed to hold four canisters for long-term storage. Figure 8.5 shows a drawing of the natural-circulation-cooled storage facility (Nikipelov et al. 1990a).

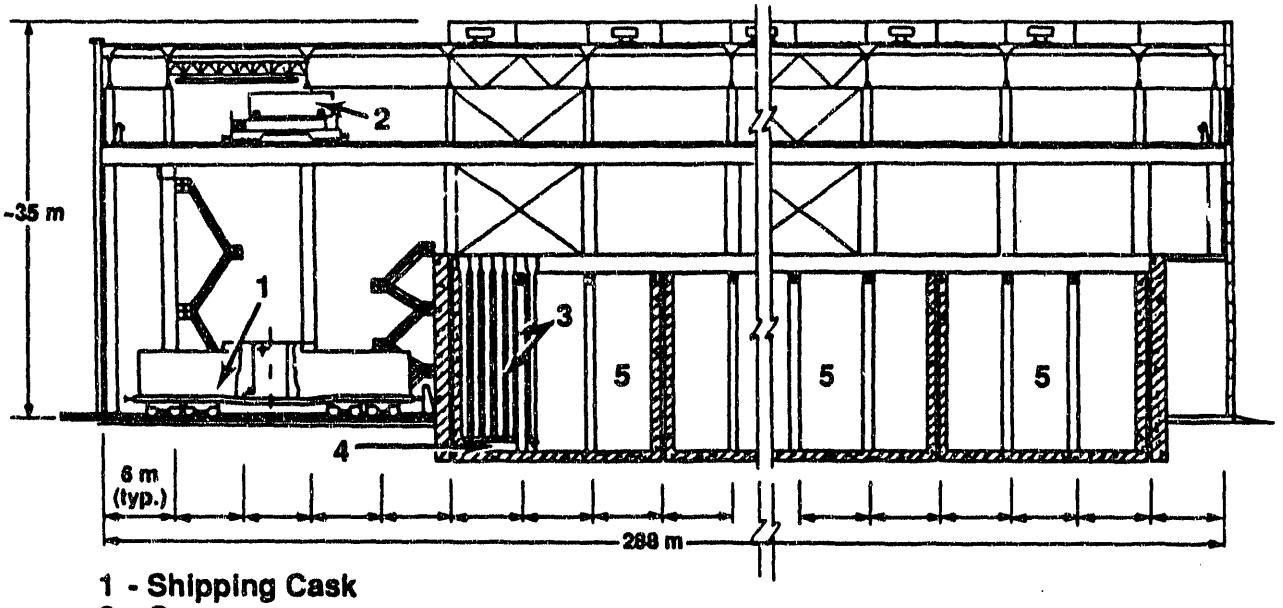
The first of the two electric melters in the vitrification facility was used to produce high-level waste phosphate glass starting in 1987 (Nikipelov et al. 1990a). After 13 months operation (Falci 1990), "the furnace [melter #1] was decommissioned" because of "loss of tightness" [corrosion] of the water cooling system used to cool the current leads to the melter electrodes



1 - Fans
2 - Gate Valves and Filtering Station
3 - Crane
4 - Knock-Down Ceiling
5 - Reinforced Concrete Shafts for Cans
6, 7 - Air Ducts
8 - Air Intake
9 - Stack

FIGURE 8.4. Forced-Air-Cooled Storage Facility for Vitrified Wastes (Nikipelov et al. 1990a)

(Nikipelov et al. 1990a). They shut down the "oven," leaving the HLW glass to solidify in the melter. Alterations have been made to the other identical melter in their facility, and they are now heating the melter to "dry the ceramic liner." Following an inspection, equipment modifications will be made, after which they will decide whether or not to initiate glass production. They stated that they were forced to speed up completion of this vitrification facility since they lack tanks for waste storage and are not planning to build any more. The Soviets further stated that they must "clear out" existing tanks to make room for wastes from VVER-440 fuel reprocessing, which is ongoing at Chelyabinsk-40 (Bradley December 1990). This second melter is "hard piped" in place and cannot be removed if it fails. Because of this design, the Soviets are developing a smaller two-stage melter system which is more amenable to repair and remote operation (Falci 1990).



1 - Shipping Cask
2 - Crane
3 - Reinforced Concrete Shaft for Cans
4 - Air Duct
5 - Storage Bays

FIGURE 8.5. Natural-Circulation-Cooled Storage Facility for Vitrified Wastes (Nikipelov et al. 1990a)

Further details on the two-stage vitrification process were given in a recent paper by B. V. Nikiforov. The process revolves around a method to drythe liquid waste and then melt the waste in a second stage using a high-frequency induction melter with a so-called "cold wall" or "cold crucible" design to help contain the melt and decrease corrosion of the melter materials. The expected design capacity of the system is 100 L/h of feed solution and 25-35 kg/h of solidified product. For the first stage, fluidized bed, spray and rotating horizontal calciners as well as a once-through evaporator have been studied. It appears that only the once through "tube in tube" evaporator meets their engineering and capacity requirements. Experiments with the once-through evaporator have showed satisfactory operation with up to 100 L/h feed rate of solutions with salt contents up to 350 g/L (Nikiforov et al. 1990).

The performance of the inductive melting process has been experimentally demonstrated in the cold crucible at temperatures from 1200°C to 2300°C. This

process may be used to produce glassy-crystalline and "mineral-like" materials such as pyroxene and pyrosilicates, titanates and titano-silicates, ferrogarnets and ferrosilicates, and Synrock-C.

All these materials have been prepared using the induction melting process at a temperature of 1250°C to 1550°C, and then treated at 650°C for two hours to simulate annealing, and irradiated to 10^{10} rad to determine their radiation resistance. Chemical stability was determined by an "express" [rapid] method under "contact with distilled water fraction 0.16-0.25mm" at a temperature of 60°C during 1 hour (Nikiforov et al. 1990). Tentative results showed that sphene, ferrogarnet, and a complex type of glassy-crystalline pyroxene have high chemical stability, jadeite, aegirine-augite and andradite were the most stable, and synroc "type" materials were "intermediate" in durability.

The Soviets have developed "cold crucibles," made of stainless steel and "sealed" by refractory materials, with a tank area of 0.05-0.12 m^2. At a mean temperature of 1500°C, operating in the "continuous mode," they have demonstrated production of silicate materials at 12-18 kg/h. Details of their design are given in Table 8.1. Figures 8.6 and 8.7 show a general hot cell arrangement for the two-stage vitrification process and concept of the induction-heated cold crucible melter, respectively (Nikiforov et al. 1990). It should be noted that two-stage vitrification processes have been under development since the 1970s in the Soviet Union. A diagram of the KS-KT-100 two-stage vitrification process is shown in Figure 8.8 (Nikiforov et al. 1985).

The principle of transmutation, as stated by the Soviet scientists, is to separate actinides, fission products, and/or isotopes of long half-life and subject these isotopes to high fluxes of thermal neutrons, protons, or lasers. It was indicated that heavy water reactors will be used to produce neutrons which will bombard a mixture of Lithium and waste (with an approximate composition of: ^{237}Np - 35%, ^{243}Am - 27% and Cm - 44%). Approximately 500 to 1000 kg per year of actinides will be "burnt" (National Academy of Sciences 1990). Work along these lines has recently been reported by the Ukrainian Academy of Sciences Institute of Physics and Technology in Kharkov. Scientists have installed "several new 100 MeV accelerators" at an unspecified

TABLE 8.1. Specifications of the Two-Stage Vitrification Process Using a Spray Calciner and Induction Melter with a Cold Crucible

Spray Dryer-Calciner (RS-100)

1.	Diameter, m	0.7
2.	Height, m	3.5
3.	Material,	Ch18NIOT (Stainless Steel)
4.	Furnace Power, kW	240
5.	Electrical Consumption, kWh/L	0.9
6.	Working Temperature, °C	750
7.	Production Based on Feed Solution, L/h	100

Induction Melter with Cold Crucible (IPCht)

1.	Inductor Power, kW	160
2.	Operating Frequency, MegaHz	1.76
3.	Crucible Material	12Ch18NIOT (Stainless Steel)
4.	Dimensions of "Cold" Crucible, mm	600x300x600
5.	Operating Temperatures, °C	900-2300
6.	Production Based on End Product (Glass or Mineral-Like), kg/h	30

nuclear station to bombard isotope targets with electrons. Full-scale "experiments" are scheduled to begin later in 1990 (Nuclear Waste News May 10, 1990).

The Khlopin Radium Institute is conducting research on partitioning of HLW using the organic compound cobalt dicarbolyl anion in HNO_3 acid solutions. This reagent is especially effective for large ions, and the process separates Sr, Cs, REE and TRU with efficiencies up to 99%. Cs and Sr were reported to

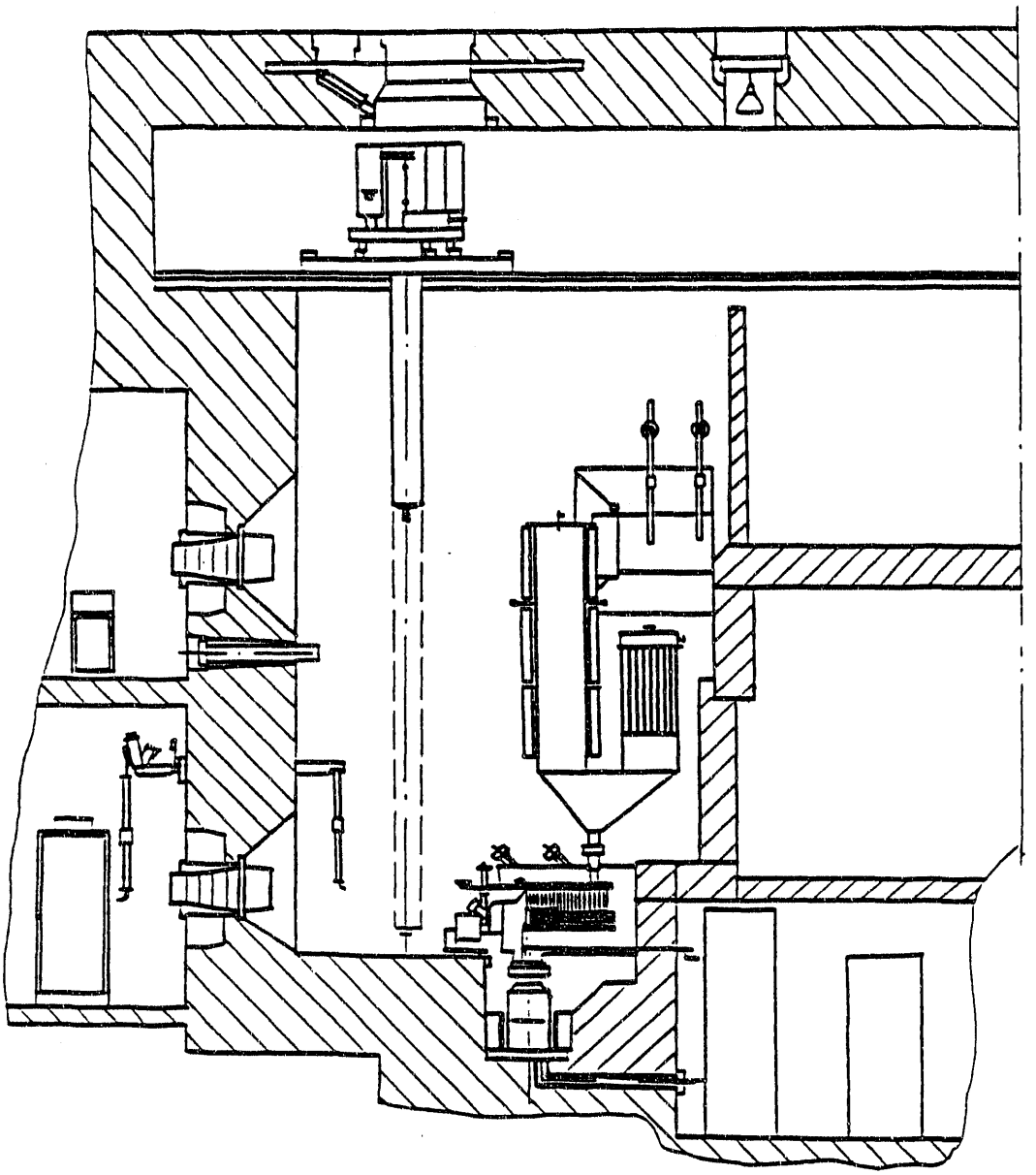


FIGURE 8.6. General Hot Cell Arrangement for the Two-Stage Vitrification Process (Nikiforov et al. 1990)

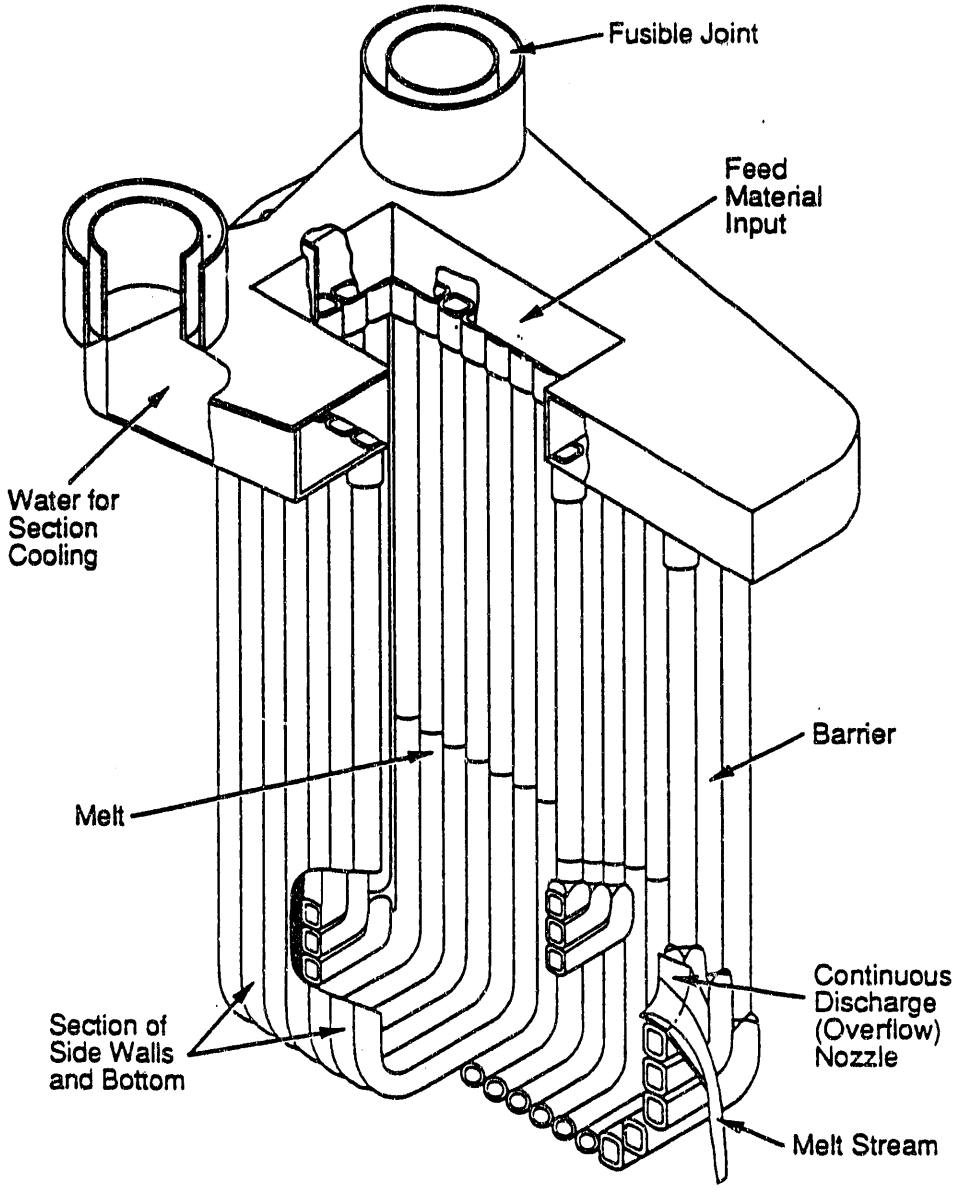


FIGURE 8.7. Drawing of the Induction-Heated Cold Crucible Melter Concept (Nikiforov et al. 1990)

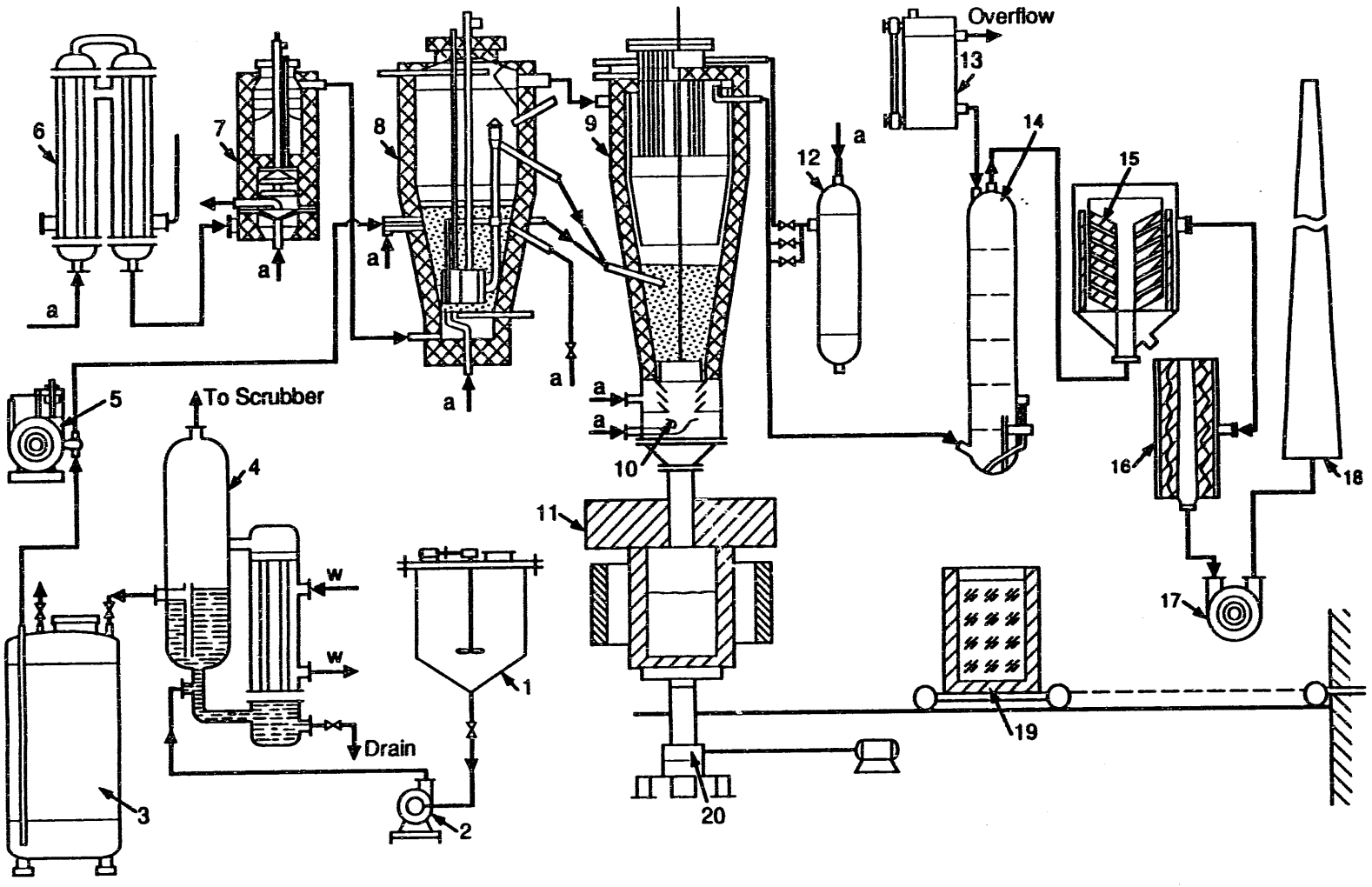


FIGURE 8.8. Drawing of the KS-KT-100 Two Stage Vitrification Unit (Nikiforov et al. 1985)

be concentrated by a factor of 10 in a single extraction cycle with the process being automatically controlled. See Section 7.0 for further information (National Academy of Sciences 1990).

8.2 HIGH-LEVEL WASTE DISPOSAL

The Soviets recently indicated that they are continuing to look at several sites for HLW disposal in crystalline and salt rock. They are considering using an area at or near the Chelyabinsk-40 site for an underground laboratory as well as potentially a disposal site. They were not overly optimistic on making progress quickly in this area (Bradley December 1990).

The Soviets have also reported that the Khlopin Raduium Institute has been studying geological disposal "for twenty years," in three principal areas:

- role of barriers
- stability of wastes
- characterization of regional and central disposal sites (waste repositories).

Field samples of the various rock types are collected by the Institute staff and sorption properties of the rocks and migration of plutonium, cesium, strontium, and americium radionuclides are being studied. Salt mixtures with carbonates and clays have been studied for use as a backfill material. Gaseous and liquid inclusions in salt have also been studied, probably to age date the candidate salt repository formations. There appear to be no studies underway on rock mechanics. Scientists at the Khlopin Radium Institute also indicated that for HLW disposal in deep boreholes, the borehole diameter considered as optimum is 0.63 m at a depth of 600 to 1000 m, or deeper. The canisters will be stacked in vertical columns 500 to 600 m long in bedded rock formations. It was stated by the Soviets that disposal of LLW, ILW, HLW, TRU, and iodine wastes in vertical boreholes in salt formation has been considered for many years. The primary impurities in the bedded salt formations considered ranged from 0.5 to 3%, and were comprised of dolomite and "sulphate impurities." Dr. Shishchits was indicated to be the principal researcher in

this area. A systematic integrated repository program is not in place in the USSR. Other than these studies on rock types and the following site location studies authored by Kedrovski, little work appears to have been done. It was stated that a program to assess physical and chemical properties of waste forms and engineered barriers is being "developed" (National Academy of Sciences 1990).

The Soviets have noted that the following types of repositories would be necessary (Kedrovski et al. 1990):

- municipal storage facilities for disposal of non-industrial wastes
- final disposal storage facilities for spent fuel and wastes from nuclear plant decommissioning
- high-level wastes containing long-lived radionuclides.

Their concepts for geologic disposal are:

- geological and geohydrological conditions are the main isolation barriers
- the waste form, whose mechanical, physical and chemical properties can be changed by treatment processes, constitutes the second most important barrier
- engineered barriers provide additional isolation, mainly in the pre-closure period
- engineered barriers function as the main isolation barrier for low-level waste and for waste containing short half-life radionuclides.

The following concepts of geologic disposal have been, or are being evaluated (Kedrovski et al. 1990):

- deep boreholes in salt and hard rock formations
- special underground facilities in salt formation, where wastes are emplaced in mine workings, or into relatively short boreholes bored from these mine workings
- specially mined salt and potassium mines
- underground cavities mined in salt formations
- specially mined openings in hard rocks.

Figure 8.9 shows an overall concept of a Soviet geologic repository, Figure 8.10 gives details of various concepts for three different types of geologic media. Figures 8.11 through 8.13 are drawings of various underground facilities (Kedrovski et al. 1990).

Figure 8.14 shows a map of the Soviet Union with salt and crystalline formations and the general location of eight candidate repository sites. The Soviets focused their initial attention for geologic repository site characterization on the "Pricaspian" lowland, which is famous for its salt domes (Kedrovski et al. 1990). The primary period of salt accumulations in the Pricaspian Basin originated about 250 million years ago and continued for about 10 million years. The Soviets have looked at what they consider are two key problems with respect to disposal in these salt formations: characteristics of radionuclide migration and the development of a procedure for

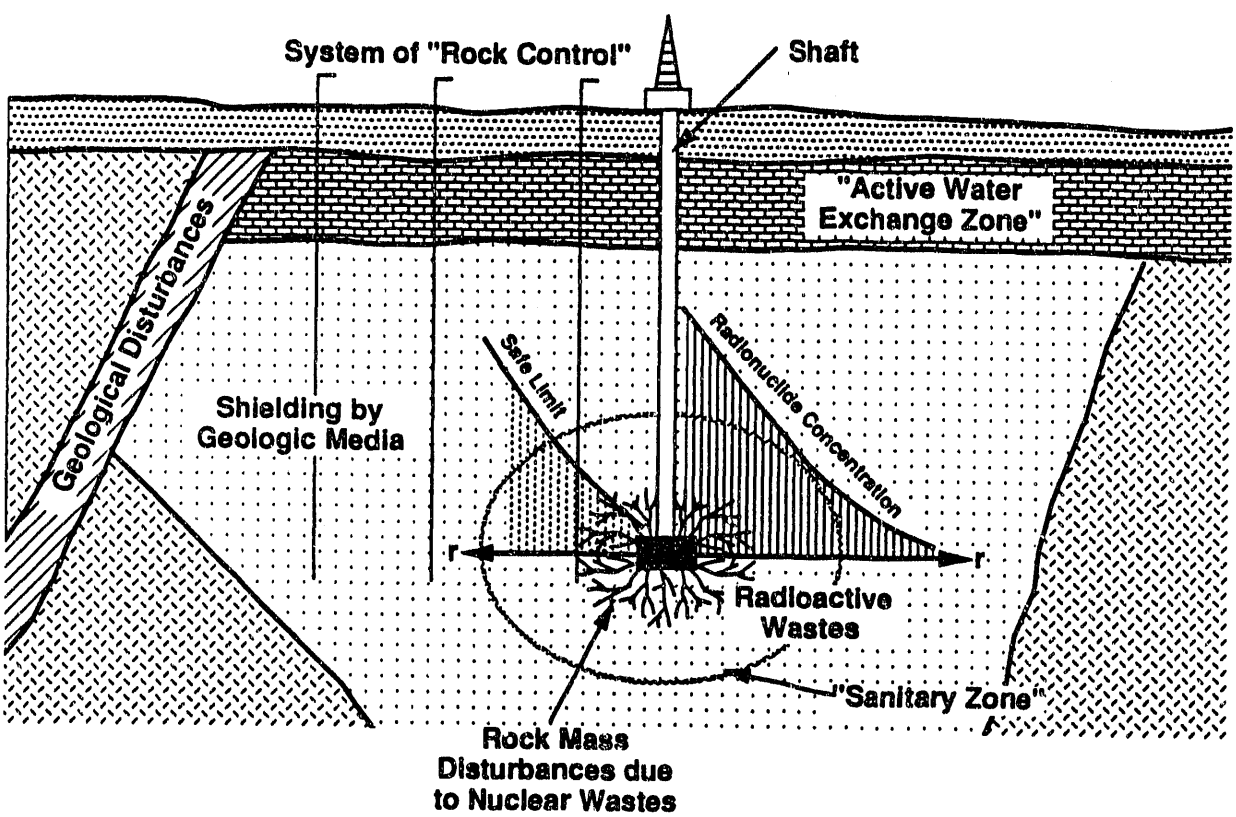


FIGURE 8.9. Soviet Geologic Repository Concept for Radioactive Wastes (Kedrovski et al. 1990)

Type of Geological Formation	Geological Formation Features	Waste Types*		
		HLW and α-Bearing Waste	ILW	LLW
Halite	Halite deposits 500 m and more in thickness		Underground Cavities • Emplacement of packed waste	• Emplacement of packed waste, pressed garbage, and piles of construction materials and solidifying mixtures
		Deep Boreholes • Emplacement of packed solidified waste		
	Layered deposits of limited thickness (not less than 80-100 m)	Special Underground Structures (Complexes)* • Emplacement of containers in short bore holes or along excavations	• Emplacement of packed waste in excavations or rooms; orderly or in piles • Emplacement of solidifying mixtures in rooms	• Emplacement of packed waste, pressed garbage and construction materials in rooms; orderly or in piles • Emplacement of solidifying mixtures in rooms
			Open Spaces in Abandoned Mines and Other Underground Structures • Emplacement of packed waste in excavations or rooms; orderly or in piles • Emplacement of solidifying mixtures in rooms	• Emplacement of packed waste, pressed garbage and construction materials in rooms; orderly or in piles • Emplacement of solidifying mixtures in rooms
Clays	Deposits more than 400-500 m	Deep Boreholes • Emplacement of packed solidified waste		
	Other deposits not less than 80-100 m	Special Underground Structures (Complexes)* • Emplacement of waste containers in short bore holes or along excavations	• Emplacement of packed waste in excavations	• Emplacement of packed waste or construction materials in excavations
Hard Rock	Thick deposits of hard rock	Deep Boreholes • Emplacement of packed solidified waste		
		Special Underground Structures (Complexes)* • Emplacement of containers in short bore holes or along excavations	• Emplacement of packed waste in excavations or rooms; orderly or in piles • Emplacement of solidifying mixtures in rooms	• Emplacement of packed waste, pressed garbage and construction materials in rooms; orderly or in piles • Emplacement of solidifying mixtures in rooms
		Specially Designed Shafts • Orderly emplacement of packed waste and heat removal by air, water, etc. • Disorderly arrangement and heat removal into the ground • Discharge of molten glass into the structure	• Disorderly arrangement and heat removal into the ground	
			Open Spaces in Abandoned Mines and Other Underground Structures • Emplacement of packed waste in excavations or rooms; orderly or in piles • Emplacement of solidifying mixtures in rooms	• Emplacement of packed waste, pressed garbage and construction materials in rooms; orderly or in piles • Emplacement of solidifying mixtures in rooms

*Special underground structures should be built for emplacement of different activity waste at various sites,not for HLW alone.

FIGURE 8.10. USSR Geologic Repository Concepts for Different Waste Types (Kedrovski et al. 1990)

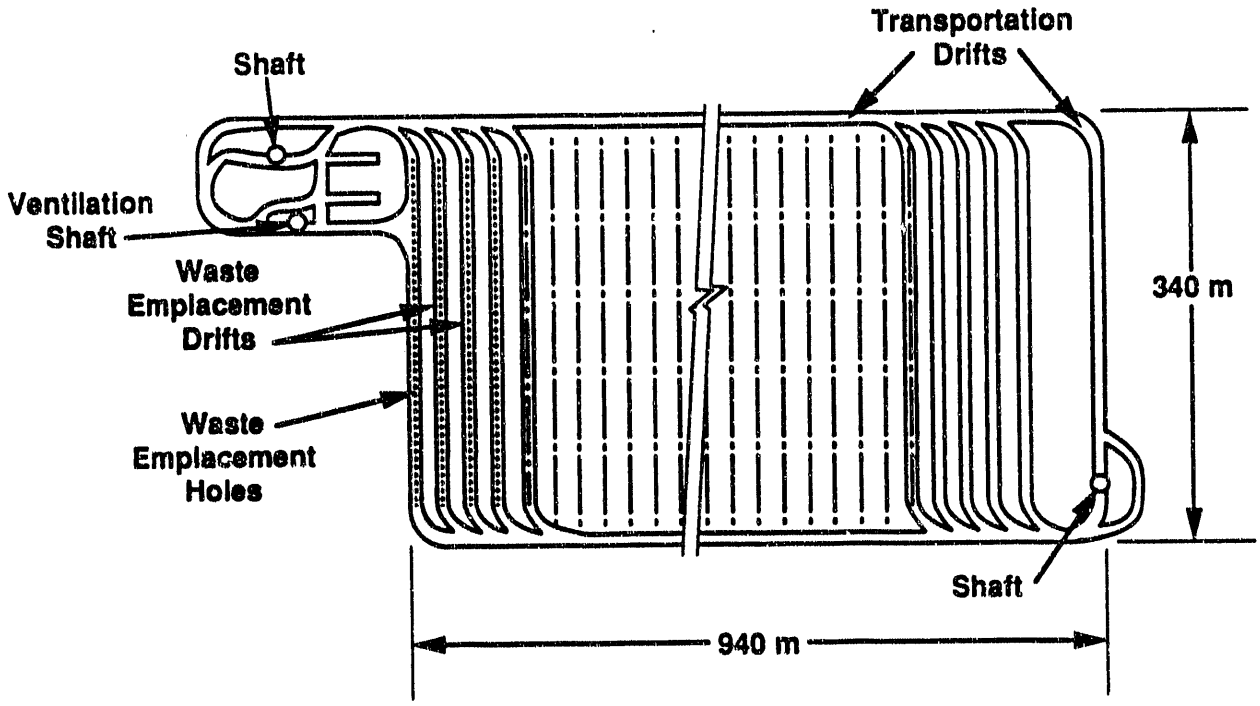


FIGURE 8.11. Soviet Geologic Repository Concept: Underground Facilities - Version 1 (Kedrovski et al. 1990)

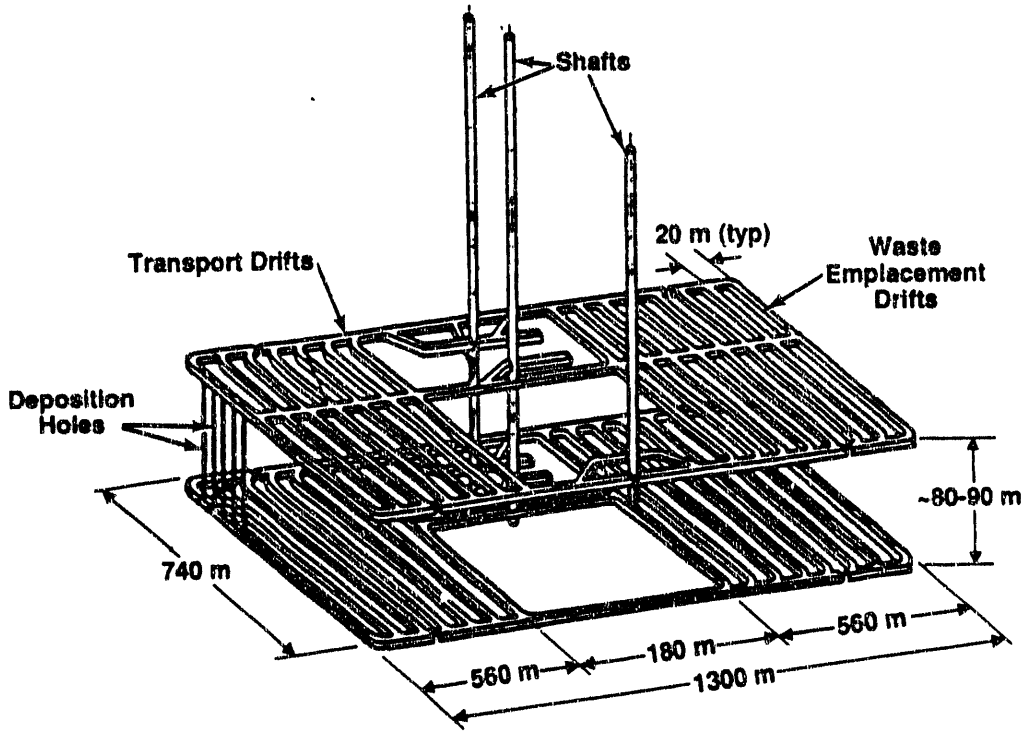


FIGURE 8.12. Soviet Geologic Repository Concept: Underground Facilities - Version 2 (Kedrovski et al. 1990)

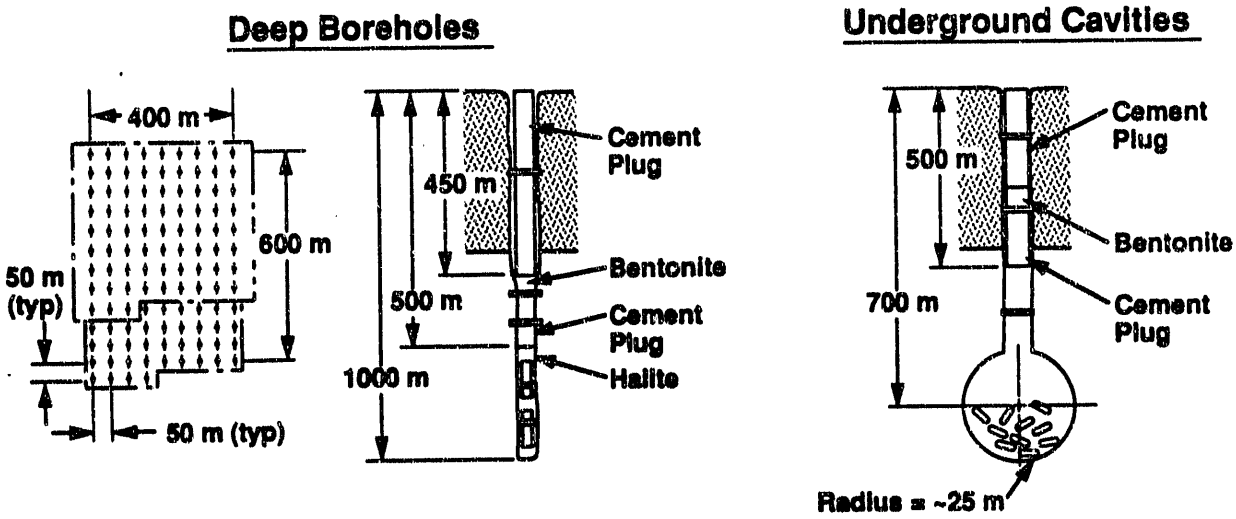


FIGURE 8.13. Soviet Deep Borehole and Underground Cavity Concepts for Geologic Repositories (Kedrovski et al. 1990)

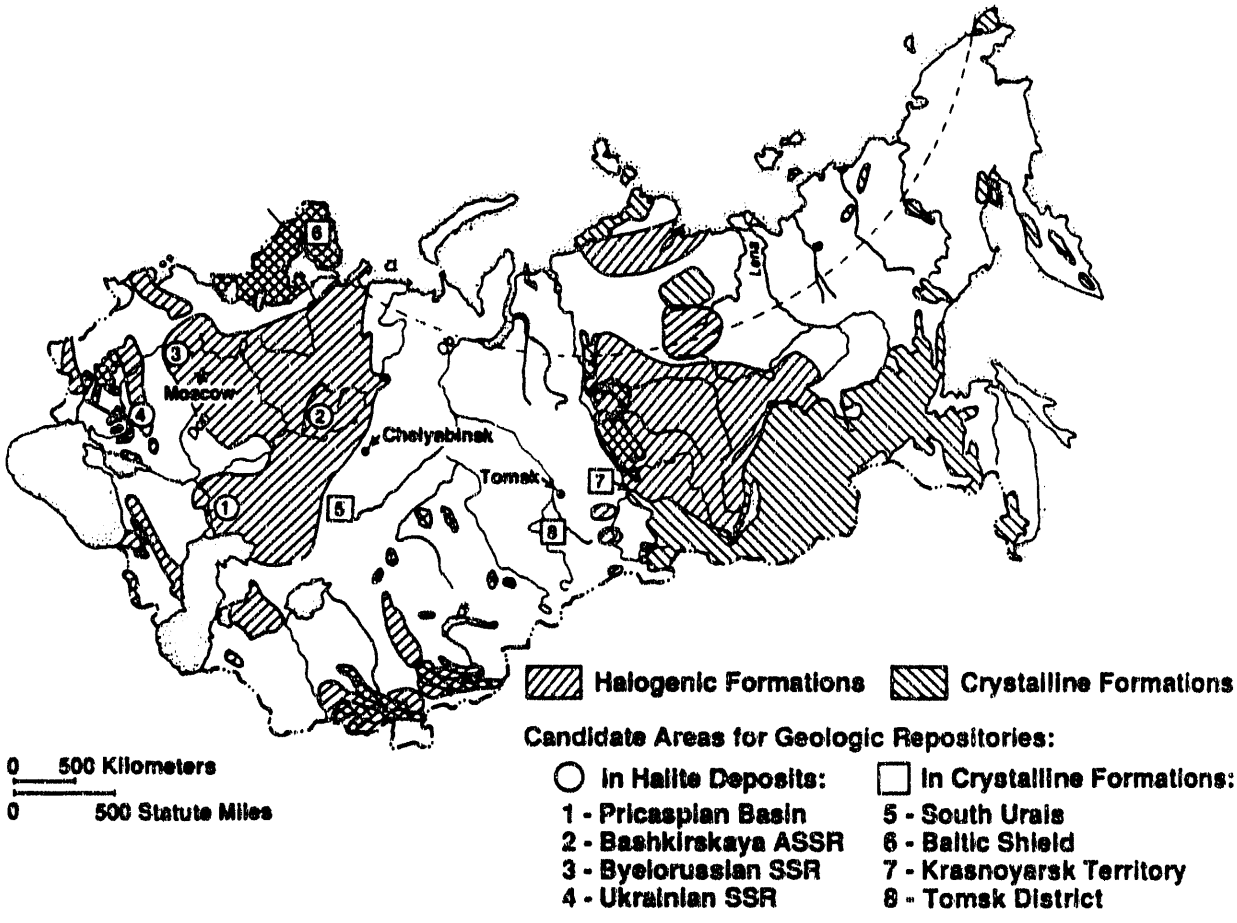


FIGURE 8.14. Map of Halogenic and Crystalline Formations in the USSR (Kedrovski et al. 1990)

estimating the stability of salt dome structures. To date they have concluded that the volume of intercrystalline inclusions is much greater than intracrystalline inclusions, and that the main pathway for radionuclide migration will be via intercrystalline pores. The are also studying the age of the salt formations using radiogenic methods such as argon/potassium ratios (Anderson et al. 1990). The Soviets have found abnormal diapirism in some salt domes located in the southern part of the Pricaspian Basin. Analysis of the region made by "space geological survey" showed a very complicated tectonic structure with centers of recent earthquakes. For these reasons, the Pricaspian salt formations are now regarded as potentially suitable for disposal of radioactive wastes having only "short life periods" (300-500 years). Figure 8.15 shows details of a geologic sequence of a candidate site in the Pricaspian Basin near Orenburg.

The Soviets report that more attention was then paid to bedded salt formations, one of which is located in the Bashkirian republic. Analysis reportedly showed that this formation may be suitable for high-level wastes. Another rock salt deposit, situated in the region of Bachmut hollow in the Ukraine, apparently was abandoned since it is used as a source of table salt (Kedrovski et al. 1990).

Some formations in Byelorussia are regarded as possible candidates for waste disposal, including some wastes from the Chernobyl accident (Kedrovski et al. 1990). In this regard, an underground repository for Chernobyl wastes was stated as being considered at the Gorky nuclear power station (National Academy of Sciences 1990).

The use of crystalline rocks for underground repositories is also being considered. In the South Urals region, there are large formations of tuff and tuff-breccia, and porphyrite at a depth of 200 to 300 m under the surface having a thickness of more than 1.2 to 1.5 km. The Soviets indicate that the rocks are minimally fractured and have a low permeability (having a "filtration coefficient" about 10^{-4} to 10^{-5} m/24 hours), although they indicate that some zones have a higher permeability (10^{-3} m/24 hours). The whole region is located in a tectonically stable zone. Figure 8.16 shows geologic cross-sections of the South Urals candidate repository site (Kedrovski et al. 1990).

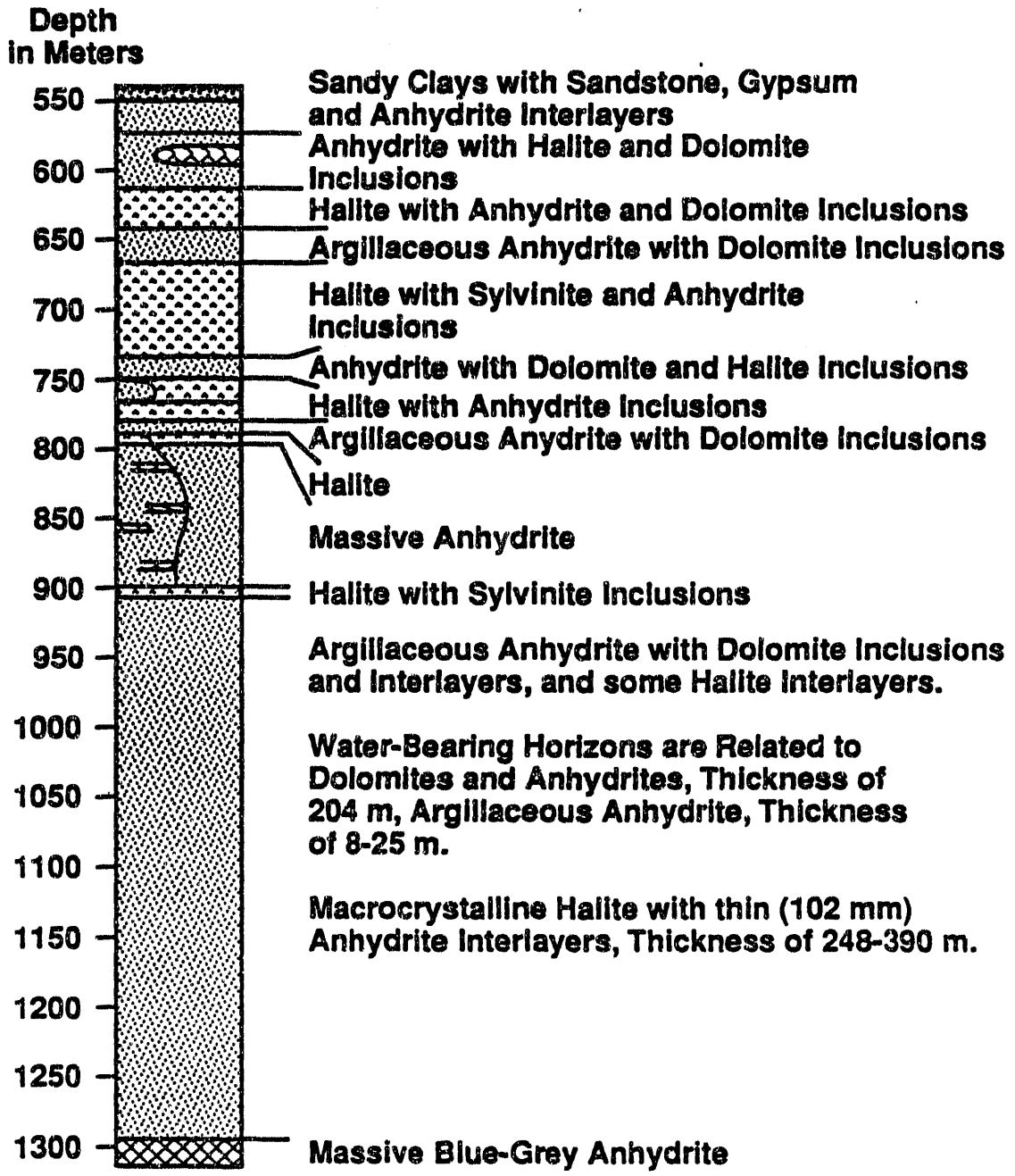


FIGURE 8.15. Geologic Sequence of a Candidate Repository Site in the Orenburg District (Kedrovski et al. 1990)

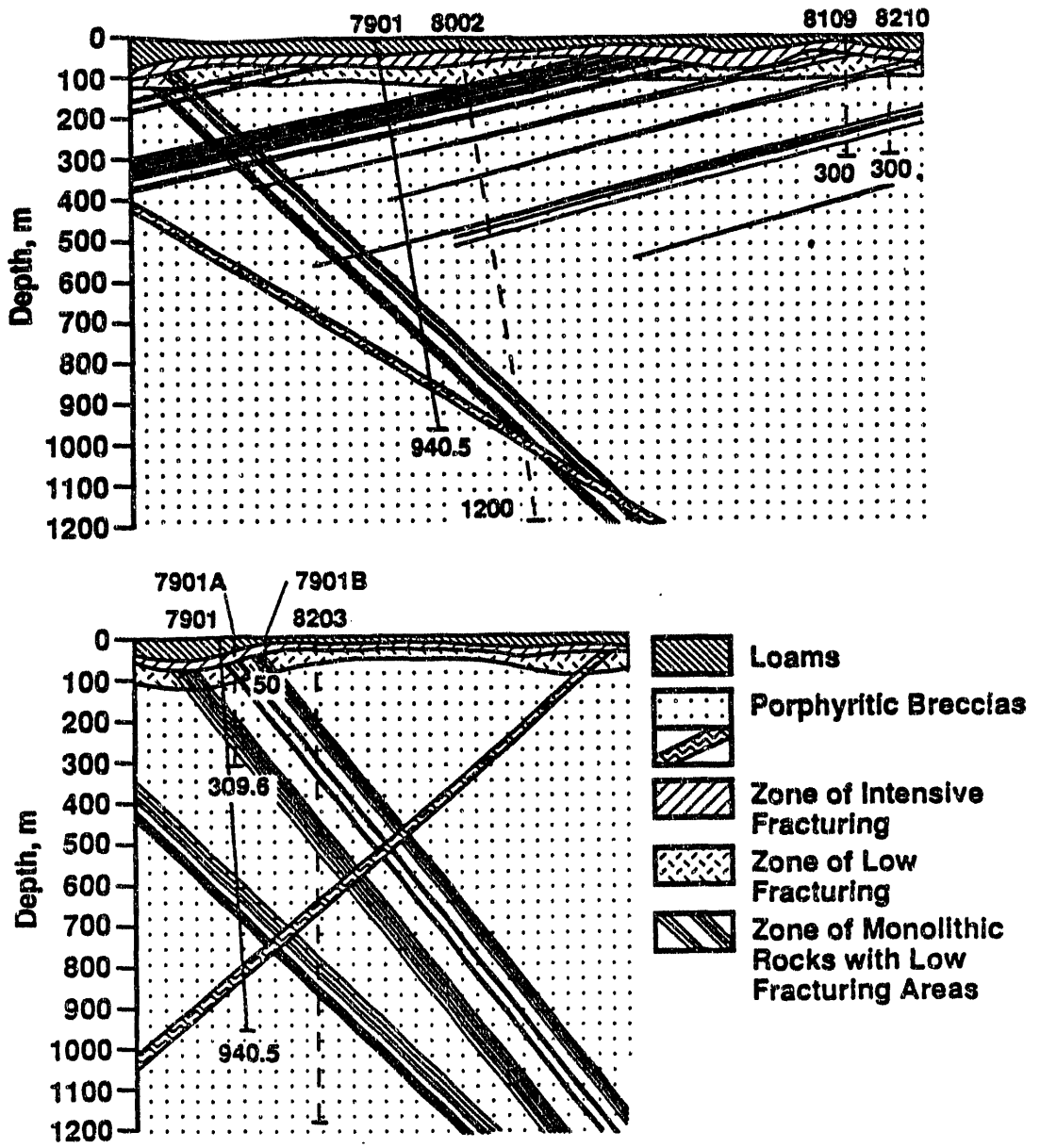


FIGURE 8.16. Geological Cross-Section of a Candidate Repository Site in the South Urals (Kedrovski et al. 1990)

The Soviet Union has vast territories occupied by permafrost from the Kolsk Peninsula to Chukotsk and Kamchatka. The low permeability and tectonic stability of this area have led to its consideration as an emplacement medium for disposal of low- and intermediate-level waste that do not generate heat and have relatively short decay periods. Shallow buried and underground

repositories are being considered. For emplacement of long-lived and heat generating waste the Soviets state they intend to consider different underground facility designs that use permafrost rocks as a barrier (Kedrovski et al. 1990).

Another potential repository site area, which the authorities in Soviet Karelia say has been abandoned, is in the Kuhmo area close to the Finland border. The local Karelia press reports that Soviet engineers are continuing feasibility studies aimed at building a nuclear power plant 45 miles from the Finland border near Rukajarvi, and also claim that the Soviets are considering a waste repository in the Romuvaava area, 12 miles from the border (Nucleonics Week April 26, 1990). In June 1990 it was reported that the Soviets stated they have dropped plans for the reactor [and repository site] in favor of building two new VVER-1000 reactors at the Kola site (Nucleonics Week June 7, 1990).

The Soviets state that the most important scientific and technical problems for the future, with respect to waste disposal, are the following (Kedrovski et al. 1990):

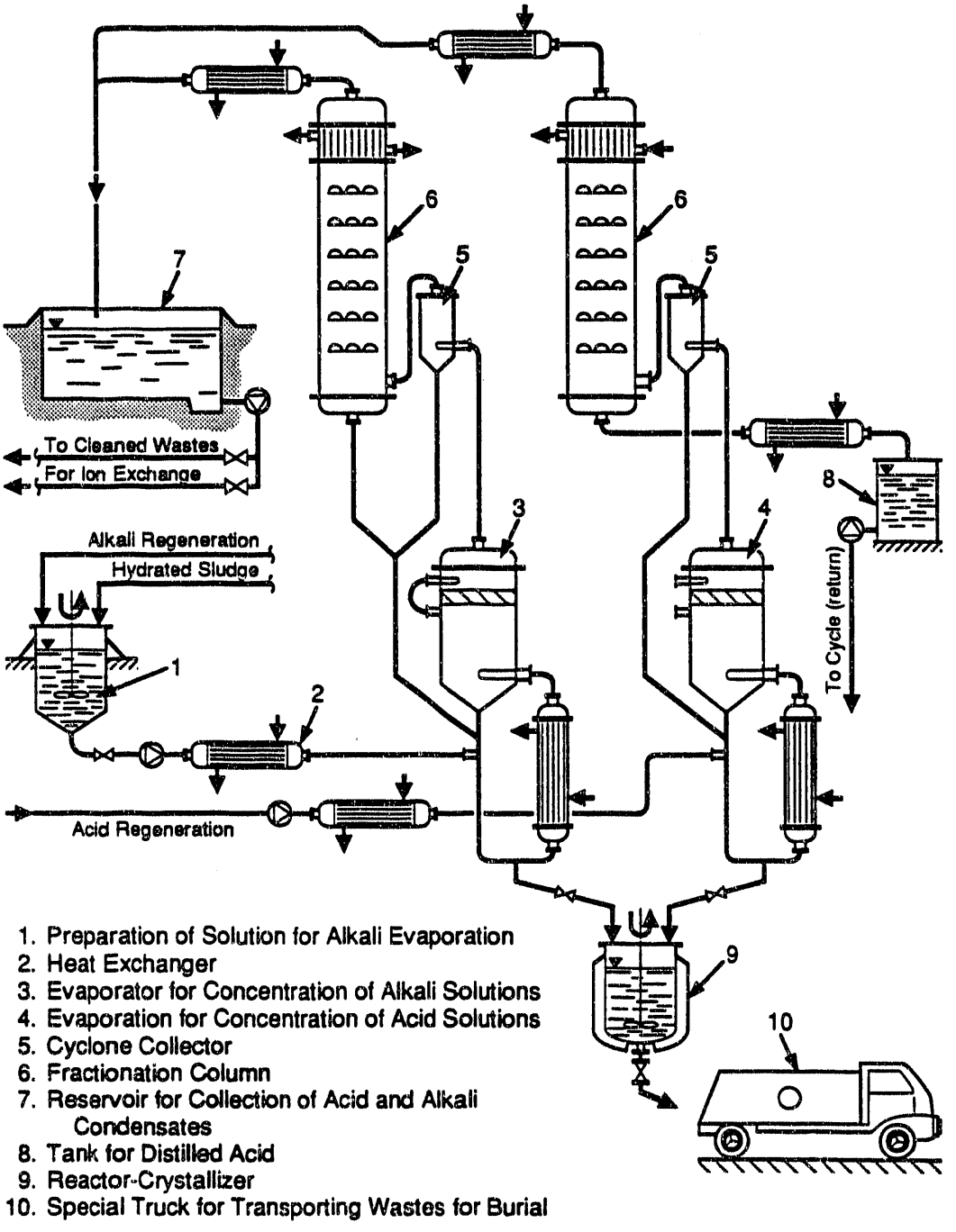
- development of waste preparation techniques that could provide minimization of high-level waste volume via waste partitioning
- development of repository design analysis and selection of the optimal combinations of the waste and host rock system
- development of reliable models of waste behavior in a geologic environment, risk and safety assessments, and monitoring methods control over the storage period.

9.0 LOW- AND INTERMEDIATE-LEVEL WASTE TREATMENT STORAGE AND DISPOSAL

Recently, feasibility and demonstration studies have been conducted at the Radon facility on the vitrification of low- and intermediate-level wastes. Radon, one of 34 [or 35] regional shallow-land disposal facilities in the Soviet Union, receives solid and liquid wastes, including LLW and ILW, from the Moscow area. Liquid wastes are transported to the facility as liquids in tank trucks (National Academy of Sciences 1990). The radioactive wastes received at Radon, 35,000m^3 per year, are generated from medical and research centers and test reactors, and are treated and disposed of onsite. The Radon facility also serves as the central management site for all the regional waste sites in the USSR State disposal system, and performs developmental work on LLW and ILW. Radon is not part of the Ministry of Atomic Power and Industry (MAPI), which is responsible for defense and nuclear power wastes, but does work jointly with it and the Kurchatov Institute on development work for treatment of LLW and ILW. Radon is also testing a small "cold crucible" melter (see Section 8.1).

The Radon facility began using cementation for low-salinity wastes in 1965, bitumen for high-salinity wastes in 1969, vitrification in 1978, and compaction in 1979. Wastes originating as solids or solidified from liquid wastes are placed into shallow-land burial sites which are then covered with a meter of reinforced cement and clay layers and planted with vegetation. So far 80,000 m^3 of wastes have been disposed of. Solidified wastes are also stored in canisters in above-ground vaults inside a storage building. The Soviets are planning for a storage life of 500 years. Site geology consists of mixed layers of clay and sand from the surface to the water table. These layers are the "basis for containment" of contaminants from the site, which has marshes on all sides. Groundwater at Radon is located between 25-70 meters depth, and drinking water wells in the area are generally located at a depth of I80-230 meters.

The Soviets state that population growth is encroaching on the Radon facility where 1,800 people work, with another 300 located in Moscow. The nearest community is about 6 km away (Falci 1990). Figure 9.1 shows the



1. Preparation of Solution for Alkali Evaporation
2. Heat Exchanger
3. Evaporator for Concentration of Alkali Solutions
4. Evaporation for Concentration of Acid Solutions
5. Cyclone Collector
6. Fractionation Column
7. Reservoir for Collection of Acid and Alkali Condensates
8. Tank for Distilled Acid
9. Reactor-Crystallizer
10. Special Truck for Transporting Wastes for Burial

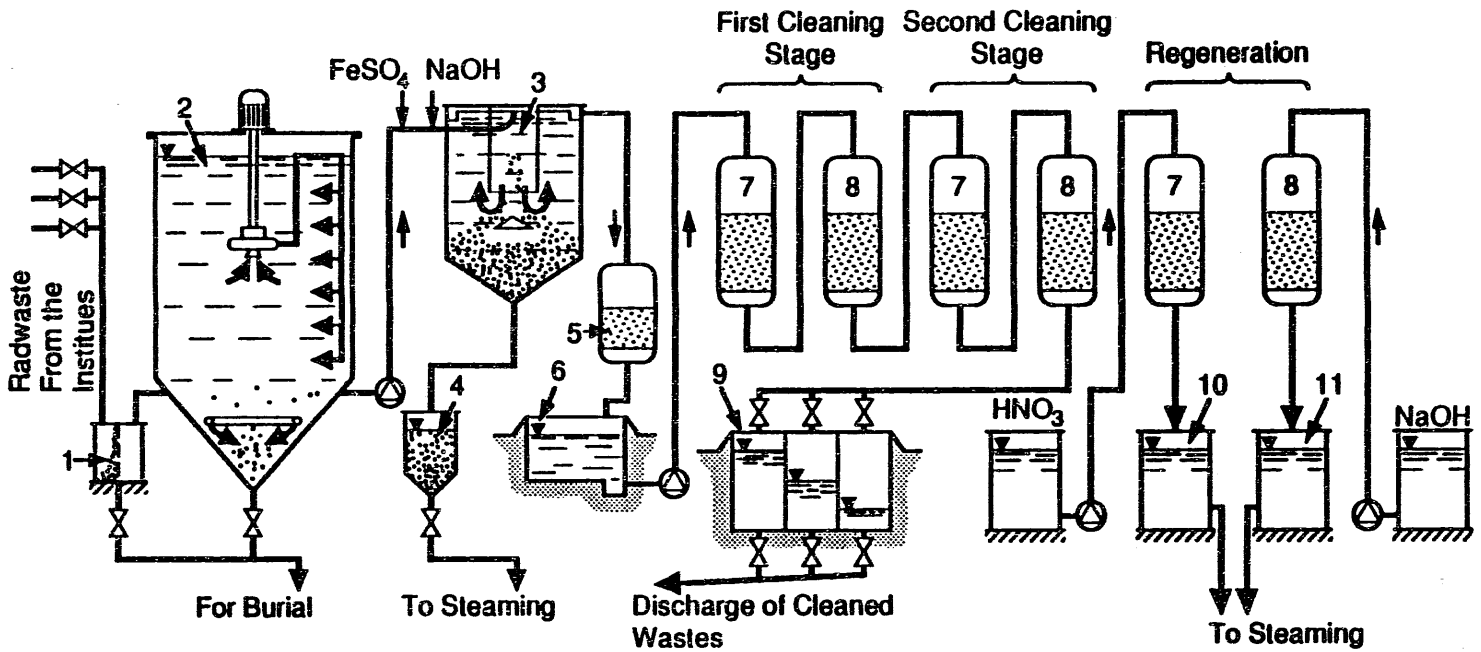
FIGURE 9.1. Liquid Radioactive Waste Evaporation at the Radon Facility (National Academy of Sciences 1990)

process at Radon for liquid radioactive waste evaporation, and Figures 9.2 and 9.3 show decontamination by ion exchange and electrodialysis, respectively, also at Radon. It is not clear that the electrodialysis process is still being used.

Solid wastes below 30 $\mu r/h$ are considered non-radioactive in the Soviet Union and do not require any special treatment or handling. They are disposed of at municipal dumps. [It is noted that beta- or alpha-emitting radionuclides are not monitored according to this procedure. Further, the packaging of the waste influences the surface activity and the criteria could be met by simply increasing the shielding provided by the container.] The Soviets indicate that although not much attention had been paid to monitoring in the past, it is now considered absolutely indispensable (National Academy of Sciences 1990).

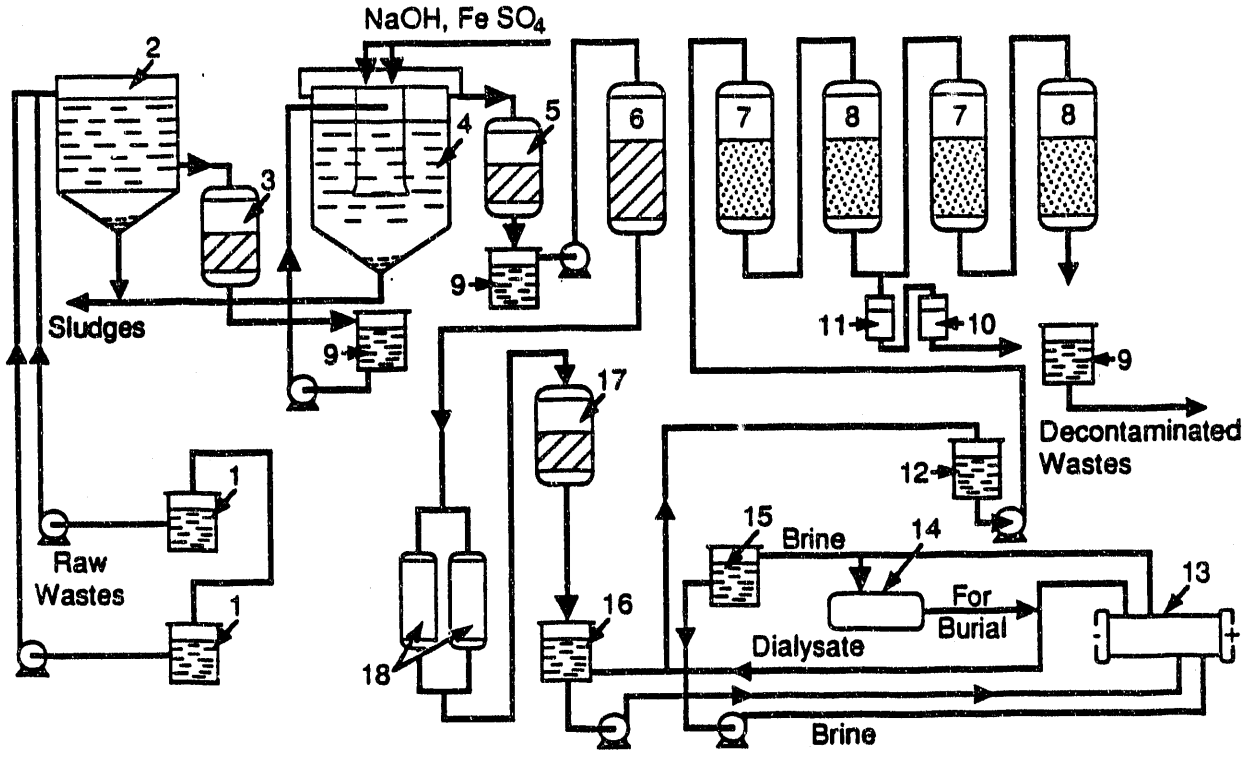
The Soviets have indicated that some irradiation sources (such as radium) were placed in municipal dumps upon which housing was later built. Some source materials even showed up in apartment units, and helicopter surveys were initiated to locate other such materials. The Radon facility now transports and disposes of 10^5 Ci of sources and 10^3 Ci of nonsources annually, with the cost of waste management essentially borne by the Soviet government; only approximately one percent is paid by the facility generating the waste. It was stated that if a higher percentage were assessed, more waste generating facilities might engage in "midnight dumping" (National Academy of Sciences 1990).

The Soviets have stated that processes including both ceramic and induction melters were initiated at Radon in mid-1989 for vitrification of intermediate-level wastes (National Academy of Sciences 1990). Additional information was provided in a recent article which described a pilot-scale vitrification unit that had been operated for 3 months by the Radon Production Association in Moscow, processing actual intermediate-level wastes from the Kursk [RBMK reactors] and Kalinin [VVER reactors] power stations. Radioactive wastes from these reactors were added to datolite [a calcium-boron silicate mineral that was only added to the wastes from the Kursk reactors that did not contain any boron], and quartz and argillaceous sands to produce a



1. Screen Filter for Coarse Radwaste Cleaning
2. Reservior-Neutralizer
3. Vertical Setting Tank
4. Tank for Hydrated Sludge
5. Clarifying Sand Filter
6. Reservior of Clarified Radwaste
7. Cation Exchange Filter
8. Anion Exchange Filter
9. Monitoring Reservior of Cleaned Radwaste
10. Acid Solution from Regeneration of Cation Exchange Resin
11. Alkaline Solution from Regeneration of Anion Exchange Resin

FIGURE 9.2. Decontamination of Low-Level Liquid Wastes by Ion Exchange at the Radon Facility (National Academy of Sciences 1990)

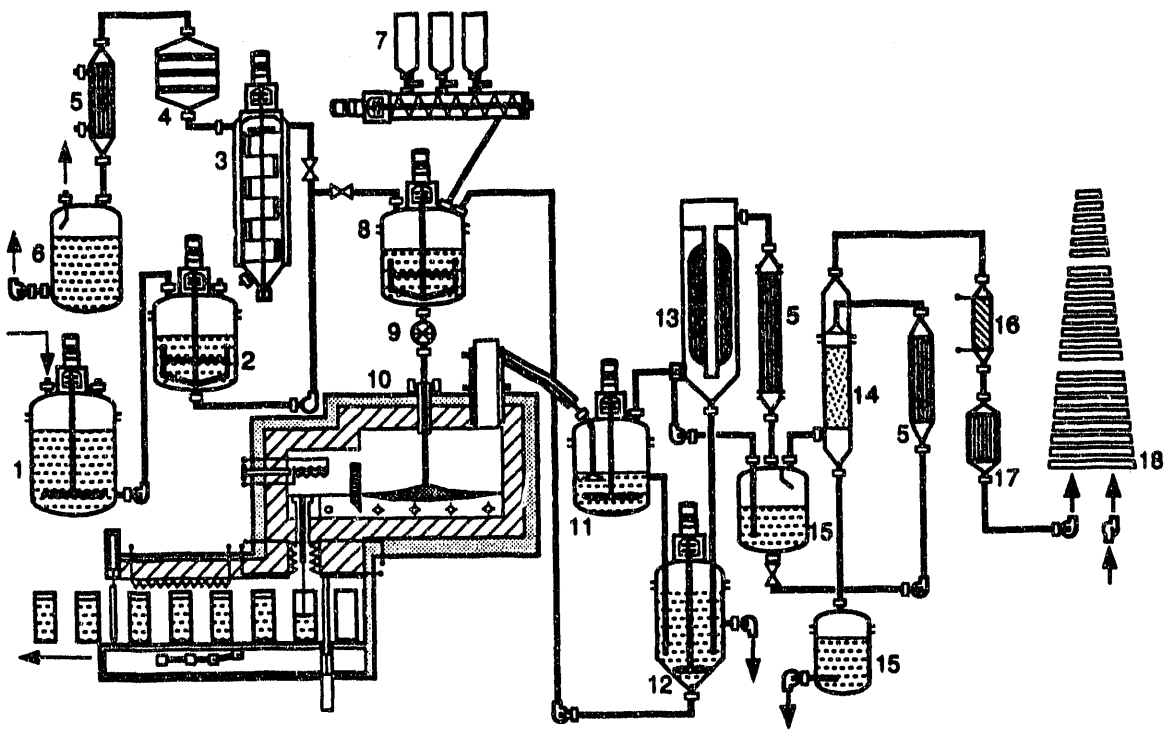


1. Container
2. Oil-and-Gasoline Trap
3. Sawdust Filter
4. Clarifier
5. Sand Filter
6. Filter Containing ABC (activated birch charcoal)
7. Cation Exchange Filter
8. Anion Exchange Filter
9. Storage Tanks, 50 m^3
10. Experimental Ion Exchanger
11. Experimental Ion Exchanger
12. Diluate Storage Unit
13. Electrodialysis Unit (EDU-50)
14. Concentrate Collector
15. Condensate Brine Tank
16. Diluate Tank
17. Filter Containing Thiocarbonate
18. Metal-Ceramic Filters

FIGURE 9.3. Decontamination of Radioactive Waste Water by Electrodialysis at the Radon Facility (Nikiforov et al. 1985)

borosilicate waste glass. The vitrification unit has a furnace divided into melting and pouring zones of 1,500 mm x 400 mm, and 600 mm x 200 mm, respectively, and is composed of a "Bakor-33" refractory liner, and then a layer of "fireclay," which is cooled using water in tubes. This joule-heated type of melter uses three molybdenum electrodes in the melting zone and one in the pouring zone, all 24 mm in diameter, and has a power consumption of 100 kW. Waste glass was discharged into containers via a bottom drain in the pouring

section of the melter. Figure 9.4 shows a drawing of the pilot-scale melter. The Soviets noted several problem areas during the melter's operation: the need to replace the molybdenum electrodes once a month, phase separation in the glass melt due to the presence of sulfates and chlorides, and acid condensation formed by thermal decomposition of nitrates in the presence of water. In 1988, the Soviets also began work at the Radon Production Association in Moscow on a "pilot installation" which would have a capacity to produce waste glass at a rate of 100 kg/h with a feed rate of 350 L/h of waste solutions. This installation is to have an automatic process control system and was scheduled for "prestart" tests in 1990 (Atomnaya Energiya October 1990).



1. Temporary waste storage tank
2. Intermediate waste storage tank
3. Rotary evaporator
4. Water vapor filter
5. Heat exchanger
6. Condensate storage tank
7. Storage hoppers for melter additives
8. Melter feed mixing tank
9. Melter feed meter
10. Joule-heated ceramic melter
11. Off-gas sparger
12. Low-salt condensate tank
13. Spray separator
14. Contact separator for oxides of nitrogen
15. Storage tank
16. Heater
17. Off-gas fine cleaning filter
18. Stack

FIGURE 9.4. Pilot-Scale Melter for Vitrification Tests Using Intermediate-Level Wastes from Power Reactors (Atomnaya Energiya October 1990)

Also at Radon, scientists stated that a plasma jet fuel burner based on an electric arc plasmatron was a promising method for waste solidification. Relatively high temperatures (i.e., 1500°C) are used during processing to obtain highly stable mineral slag. High temperatures also make it possible to incinerate unsorted wastes and wastes with up to 30% metal and 10% concrete (National Academy of Sciences 1990).

In Dimitrovgrad, where well injection of ILW and LLW was done, exploratory boreholes penetrate Meso-Cenozoic and Paleozoic sedimentary deposits having a total thickness of 2270 to 2300 meters and overlying the crystalline rock foundation of Archean age. The Paleozoic section contains Devonian and Permian systems of 2100 m thickness composed mainly of carbonate rocks. Mesozoic sediments are represented by Triassic and Jurassic clays of 100 to 110 m thickness. The upper complex is composed of quaternary alluvial sand and clay deposits of 60 m thickness. Both the permeable zones include strongly mineralized water (200 to 250 g/L), with a natural flow rate of 0.1 to 1.0 m/year. The Soviets have apparently been studying radionuclide migration at the Dimitrovgrad site, with results indicating containment within a "secondary protective" zone about 6000 m square (Kedrovski et al. 1990).

The Soviets are studying specialized waste forms for the immobilization of iodine-129, carbon-14, and tritium wastes. For iodine-129, the Soviets have studied cement and bituminous compounds, glasses, epoxide compositions, dense polycrystalline and "chemically modified" materials based on slightly soluble iodates. Dense polycrystalline waste forms produced by cold and hot isostatic pressing of powdered iodine compounds have been studied, based on lead iodide and copper iodide. In addition, successive chemical precipitation from aqueous solutions is being considered In this process, microgranules of materials containing iodine are coated with inorganic modifier materials such as lead iodide and lead-silicate. Characteristics of these waste forms are given in Table 9.1 (Kalinin et al. 1988). It appears that PbI_2 or CuI waste forms are preferred, since the Soviets state that they have prepared a flow diagram for producing these wastes forms for storage or burial (Lazarev et al. 1990).

TABLE 9.1. Characteristics of Waste Forms for Immobilization of Iodine-129

Matrix (process)	Initial Form of Iodine Fixation	Iodine Leaching Velocity, cm/day	Waste Volume for Fixation of 500 kg of Iodine, m^3	Mass Fraction of Iodine in Waste Form, %
Portland cement brand 500	$Ba(IO_3)_2$, $Pb(IO_3)_2$ $Cu(IO_3)_2$ PbI_2, CuI	$2\text{-}4 \times 10^{-5}$ 2×10^{-4}	9.0	4-5
Bitumen	$Ba(IO_3)_2$, $Pb(IO_3)_2$ PbI_2, CuI	$2\text{-}3 \times 10^{-6}$	2.0	22-31
Lead-borate glass	KI, BaI_2	$3\text{-}6 \times 10^{-5}$	1.2	15 (KI) 10(B_aI_2)
Epoxide resin	PbI_2	$2\text{-}5 \times 10^{-6}$	0.6	28-42
Isostatic Pressing	PbI_2 CuI	2×10^{-4} 3×10^{-5}	0.2	(not reported)
Chemical modification with silicate	PbI_2	3×10^{-7}	0.3	(not reported)

At present, the Soviets state that slightly soluble carbonates formed in a "double alkaline process" seem to be the most convenient form for carbon-14 fixation, but for storage or "burial conditions" cement may be the preferable waste form. Compounds of Portland cement and calcium, strontium, and barium carbonates have been studied. Test results show that carbon-14 is incorporated in calcium carbonate within the cement matrix (Kalinin et al. 1988).

Aqueous tritium waste solidification has been studied by treating wastes with calcium oxide and then producing a dry powder of tritiated calcium hydroxide which is then incorporated into bitumen or other binders such as epoxide resin, paraffin, ceresin and polystyrene. The Soviets report that epoxide resin waste forms have the lowest tritium leaching "velocity," but they are still looking for new matrix materials (Kalinin et al. 1988).

Intermediate-level wastes at Chelyabinsk-40 are evaporated with the concentrated wastes stored in tanks, and the condensates discharged into the Karachai reservoir "to maintain its level." Low-level wastes are processed by

the ion-exchange facility at the water treatment plant. The filtrate is discharged into the recycling water supply basin, with the remaining wastes combined with intermediate-level waste solutions. Some low-level waste solutions are also discharged into the Karachai reservoir. It was stated that this was necessary since condensates from ILW evaporation were not alone sufficient to maintain the "reservoir level" (Drozhko, June 1990).

The majority of solid radioactive wastes from the Mayak plant are to be disposed of since the plant lacks appropriate processing facilities. Some solid high-level wastes are stored in "permanent" ferroconcrete facilities. Intermediate- and low-level solid wastes are placed in specially prepared trenches. Some solid waste treatment processes (such as scrap decontamination and organic waste incineration) have been tested, and may be used in a solid waste treatment complex that is scheduled for operation in 1998 (Drozhko, June 1990).

10.0 TRANSPORTATION

BN-600 reactor spent fuel assemblies are transported using the Soviet TK-11 railroad container-car designed for maximum permissible fuel burnup with a three-year cooling. The TK-11 railroad container-car consists of three compartments--one freight compartment and two working compartments. In the freight compartment a cask is fixed to a supporting frame and has the following specifications (Ogordov et al. 1987):

- inside diameter - 1485 mm
- outside diameter - 2195 mm
- thickness of the cask lid - 320 mm
- cask mass is not over 86,500 kg.

The working compartments of the TK-11 container-car house electrical equipment, instrumentation, hydraulic drive controls, and ventilation systems. The outer surface of the cask has fins to provide convective heat transfer efficiency. The fins are coated with epoxy to facilitate decontamination operations. The lid is made of stainless steel. Spent fuel assemblies are transported in 35-cell baskets. Since the spent fuel assemblies have insufficient strength to provide for their integrity under emergency conditions, they are inserted into cans which are reused. Nitrogen is used as a coolant for the cans as well as in the container-car (Ogordov et al. 1987).

Liquid wastes, at least those destined for regional solidification and disposal facilities such as Radon, are transported as liquids in tank trucks (National Academy of Sciences 1990).

11.0 ENVIRONMENTAL RESTORATION AND WASTE MANAGEMENT AT CHELYABINSK-40 AND CHERNOBYL

11.1 OPERATIONS AT CHELYABINSK-40

11.1.1 Early Site Contamination and Techa River Restoration

The Production Association Mayak has carried out military-industrial nuclear activities since 1948 at the Chelyabinsk-40 site, which has been commonly referred to in the past as the Kyshtym site. The site, referred to as Chelyabinsk-40 in this report, is located near the towns of Kyshtym and Kasli and is 70 km north of the city of Chelyabinsk. Chelyabinsk-65, which refers to a town of 83,000 built to house the Mayak staff, is located 12 km from the site (Nucleonics Week July 26, 1990a).

The facilities at Chelyabinsk-40 have had a long history of releases of radioactivity to the surrounding environment. According to recent Soviet estimates, a total of about 1 billion curies have been released to the environment at Chelyabinsk-40 between 1949 and 1960. The factors contributing to the release are given as disposal of solid wastes at the reactor site, disposal of wastes to Lake Karachai and subsequent dispersal by wind from the lake shore, the 1957 HLW tank explosion, and discharge to the Techa River from the reprocessing plant from 1949-1951 (Nucleonics Week March 21, 1991). The Techa River was severely contaminated from the discharge of "intermediate-level waste" effluents, with a stated specific activity [location unspecified] up to 10^{-4} Ci/L in 1949-1951. In the summer of 1951, a radiation survey at the Chelyabinsk-40 site revealed an "excessive" contamination of the flood lands and bed of the Techa River and an "increased irradiation effect on the inhabitants of the banks." In September 1951, the discharge of radioactive effluents into the river was stopped. The Soviets state that the major portion (99%) of the radionuclides were deposited in the upper region of the Techa, as far as Muslyumovo. As a result of the contamination, the Techa River was withdrawn from economic use, some settlements were evacuated [8,000 people were re-located, according to PRAVDA July 17, 1989], and the remainder were supplied with water from sources other than the Techa. Since the contaminated upper flood lands of the Techa constituted about 80% of the area of

its entire flood lands, the Soviets built a cascade of four reservoirs to contain the contamination. The first reservoir was erected in 1951, and the last in 1964. The Soviets state that the reservoirs made it possible to isolate about 98% of the radionuclides deposited in the flood lands. Today, work is under way to increase the capacity of the reservoirs, and their influence on the contamination of groundwater is being studied (Nikipelov et al. 1990c).

In the past, the level of the reservoirs was regulated by using the contaminated water as a heat sink for the five plutonium production reactors at Chelyabinsk-40. With these reactors shut down, the Soviets are concerned about the steadily increasing water levels in the reservoirs. There is 80 million m^3 in Reservoir #10 alone, where fish are reported to be 100 times more radioactive than normal (Nucleonics Week July 26, 1990a).

11.1.2 Personnel Exposure

The Soviets recently published information relating to radiation doses to workers at Chelyabinsk-40 from early operations through 1974. The dose information was for workers at two different facilities, a uranium-graphite channel-type reactor commissioned in June 1948 (now closed and "conserved"), and a fuel reprocessing plant commissioned in December 1948 (now closed and dismantled). The Soviets state that in 1948-1952, the radiation technology was studied and dose reduction techniques were looked for. The active implementation of these measures began in 1953-1959, and in 1960-1973, radiation doses fell to within international standards. A more detailed historical development of radiation protection procedures was given as follows (Nikipelov et al. February 1990):In August 1948, the Ministry of Medium Machine Building (Minsredmash) and the Ministry of Health prepared the "General Sanitary Standards and Regulations for Health Care of the Employees at the facilities A and B" [the reactor and reprocessing facilities, respectively]. The daily maximum dose was fixed at 0.1 rem for 6 working hours (about 30 rem during the year), with a provision for a one-time irradiation dose not to exceed 25 rem in case of an accident. Individual monitoring of external gamma irradiation was performed with film dosimeters which could measure the dose from 0.05 to 3 rem in the energy range 0.4-3.0 Mev with an accuracy of 30%.

- In 1949, "Regulations of the Health Control of the Employees" were introduced and installation managers were required to report to the physicians every case of irradiation exceeding ten daily norms (i.e., more than 1 rem).

- In 1952, a new norm was introduced which limited the irradiation dose to 0.05 rem during 6 working hours, or 15 rem per year. These regulations still allowed a single emergency irradiation not exceeding 25 rem.

- In 1954, new directions were issued that allowed for some employees to get doses up to 100 rem, provided that they would then be transferred to other jobs excluding their contact with ionizing radiation. The Soviets state that this directive resulted from their practice of using the most qualified workers on facility repairs to reduce exposure time, and that they only had a limited supply of such workers.

- A special order was issued in 1954-1955 for the Minsredmash which established the procedure of transferring workers into "clean" conditions for 6 months after their total irradiation dose exceeded 45 rem for the last year or 75 rem for the last two years.

- In 1960, the "Sanitary Regulations for the work with Radioactive Substances" became effective in the USSR. The upper weekly dose of external irradiation was set at 0.1 rem and 5 rem for the year. However, even these regulations allowed, if necessary, to increase the yearly dose up to 15 rem for persons 30 years or older.

- Starting in 1970, the "Norms of Radiation Safety" (NRB-69) were introduced in the Minsredmash which placed an upper limit of 5 rem on the yearly dose. This requirement is continued in the norms NRB-76/87 that are effective now.

At the reactor installation at Chelyabinsk-40, the main contribution to personnel dose came from irradiation in the central hall, in the fuel storage pools-depositories, and during transportation of the irradiated products. However, in many rooms, the irradiation doses were "practically nil." At the reprocessing plant, however, the equipment was located in such a way that practically all the locations were subject to radioactive contamination.

In 1949, about 30% of the workers at the Chelyabinsk-40 reactor received doses of between 100-400 rem; at the reprocessing plant in 1950 and 1951, 36% and 43% of the workers, respectively, received doses between 100-400 rem. Table 11.1 gives further information on average external doses received by workers at these two facilities from 1948 to 1974.

TABLE 11.1. Average External Gamma Doses at Chelyabinsk-40 Facilities from 1948 to 1974

Time Frame	Employees at Reactor Commissioned in June 1948	Employees at Reprocessing Plant Commissioned in December 1948
1948 - 1952	35.4 rem	--
1949 - 1952	--	80.3 rem
1953 - 1959	7.9 rem	18.7 rem
1960 - 1974	1.8 rem	3.8 rem

Reactor personnel received the highest doses in 1949 and the first cases of chronic radiation disease were diagnosed at the same time. At the reprocessing plant, the maximum level of external gamma radiation was noticed in 1950-1952 with chronic radiation disease being noted a year later than at the reactor facility. A clear increase in the worker mortality was found for irradiation levels more than 100 rem during the whole worktime combined with a maximum dose of 25 rem during any year. The Soviets state that due to the high background of the external irradiation received by the workers at the reprocessing plant, it was "impossible to reveal the role of internal irradiation." Table 11.2 provides data on chronic radiation disease and dose received by Chelyabinsk-40 workers at the reactor and reprocessing plant (Nikipelov et al. February 1990).

TABLE 11.2. The Occurrence Rate of Chronic Radiation Disease and Doses Received by Chelyabinsk-40 Workers

Facility	% of Workers with Chronic Radiation Disease	Average Worker (gamma dose, rem)	
		Total for Worktime	Maximum for a Year
Reactor	5.8 ± 0.5	264 ± 14	127 ± 11
Reprocessing Plant	22.5 ± 0.6	340 ± 5	150 ± 4

11.1.3 High-Level Waste Tank Accident in 1957

In 1957, a high-level waste storage tank at Chelyabinsk-40 exploded, expelling about 2 million curies into the atmosphere and surrounding environment out of about 20 million curies contained in the tank. The tank was one of the 16 250-m^3 stainless-steel tanks that were enclosed in a buried rectangular concrete vault with 60-cm-thick walls (McNeece 1990) having cells for the storage tanks which were put into operation in 1953 (Falci 1990). The tanks, which contained high-level waste solutions with up to 100 g/L sodium nitrate and 80 g/L of sodium acetate, were cooled by water "flowing through an annulus between the walls of the tank and the canyon." Deterioration of monitoring equipment eventually occurred that evidently was impossible to repair. Reports indicate that since the tanks were "entirely immersed in water, they gradually rose as the solutions evaporated, leading to a loss of seal in the lines for reception and discharge of radioactive material." Due to inadequate capacity at the site to clean up the resulting contaminated cooling water, only periodic cooling was used, which eventually led to overheating of the dried explosive salts (Nikipelov and Drozhko 1990). The Soviets have stated that the liquid wastes were kept slightly acidic at a pH of 4, and that the tank did not contain any ferrocyanides (Falci 1990). The stainless steel tank had a concrete cover 1.5 m thick, and weighed 160 MT. A video of the accident, shown recently to a U.S. visitor, shows no visible explosion crater, only one of the 160-MT tank covers laying on the ground. The location of the tank accident was shown to be between the vitrification and the VVER reactor fuel reprocessing plants at the Chelyabinsk-40 site (McNeece 1990). It was also stated that the Chelyabinsk-40 site had about 60 single-wall tanks for containing HLW (Falci 1990).

A portion of the reactor site in the northeast sector [of the Chelyabinsk-40 site] became contaminated due to the explosion. Contamination was either covered with clean soil or removed and buried, and decontaminating solutions were used for washing asphalt roads. Altogether, 350,000 m^3 of contaminated soil was removed and 400,000 m^3 of clean soil was deposited (Nikipelov et al. 1990c). Further details on the tank accident are summarized by Bradley and Schneider (1990).

Due to high levels of contamination from the tank explosion, some territories were decontaminated using road-building machines. Up to a 100-m radius of the explosion crater, the dose rate was more than 400 R/hour, within a 1-km radius it was 20 R/hour, and within a 3-km radius it was 3 R/hour. It appears that significant contamination has been spread by winds from "bare" parts of Karachai reservoir to parts of the Chelyabinsk-40 site, and has overlapped the contamination zone from the 1957 accident. A total of 600 Ci, mainly of ^{90}Sr and ^{137}Cs, has been stated to have been spread due to winds (Nikipelov et al. 1990c).

Approximately 20 million Ci of activity was involved in the explosion, of which ~10% was scattered in the surrounding environment following the movement of the explosion cloud, which initially rose to a height of up to 1 km. Formation of the radioactive "track" on the ground was stated to be completed within 11 hours after the accident. For a radioactive isopleth of 0.1 Ci/km^2 of ^{90}Sr, the dimensions of the contamination track reached 300 km by 30-50 km; for a radioactive isopleth of 2 Ci/km^2, the track was 105 km by 8-9 km (Nikipelov et al. 1990). The total area of contamination was 23,000 km^2 (EKONOMIKA TEKHNIKA EKOLOGIYA, January 1990). In the first 10 days after the accident, it was stated that winds had caused the boundaries of the minimum contamination density to shift "several kilometers" into previously "clean" territory (Nikipelov et al. 1990). Figure 11.1 shows a map of the radioactive contamination "track" from the 1957 accident at Chelyabinsk-40 (U.S. DOE 1990).

The maximum radioactive contamination density on the track's axis near the source reached 15 x 10^4 Ci/km^2 of total activity or 4 x 10^3 Ci/km^2 of ^{90}Sr. In the areas of maximum contamination, the initial exposure dose was as high as 0.6 R/h. After 25 years, the total radiation activity has decreased by 34 times and has decreased by 1.8 times for ^{90}Sr activity. The present contamination is 99.3% from ^{90}Sr + ^{90}Y, and 0.7% from ^{137}Cs (Nikipelov et al. 1990). Tables 11.3 and 11.4 indicate soil activities and distributions of ^{90}Sr contamination (EKONOMIKA TEKHNIKA EKOLOGIYA, January 1990).

In 1957, about 270,000 people lived in the contaminated zone [0.1 Ci/km^2 for ^{90}Sr], 10,000 lived in a contamination zone of $\geq$2 Ci/km^2 of ^{90}Sr, and

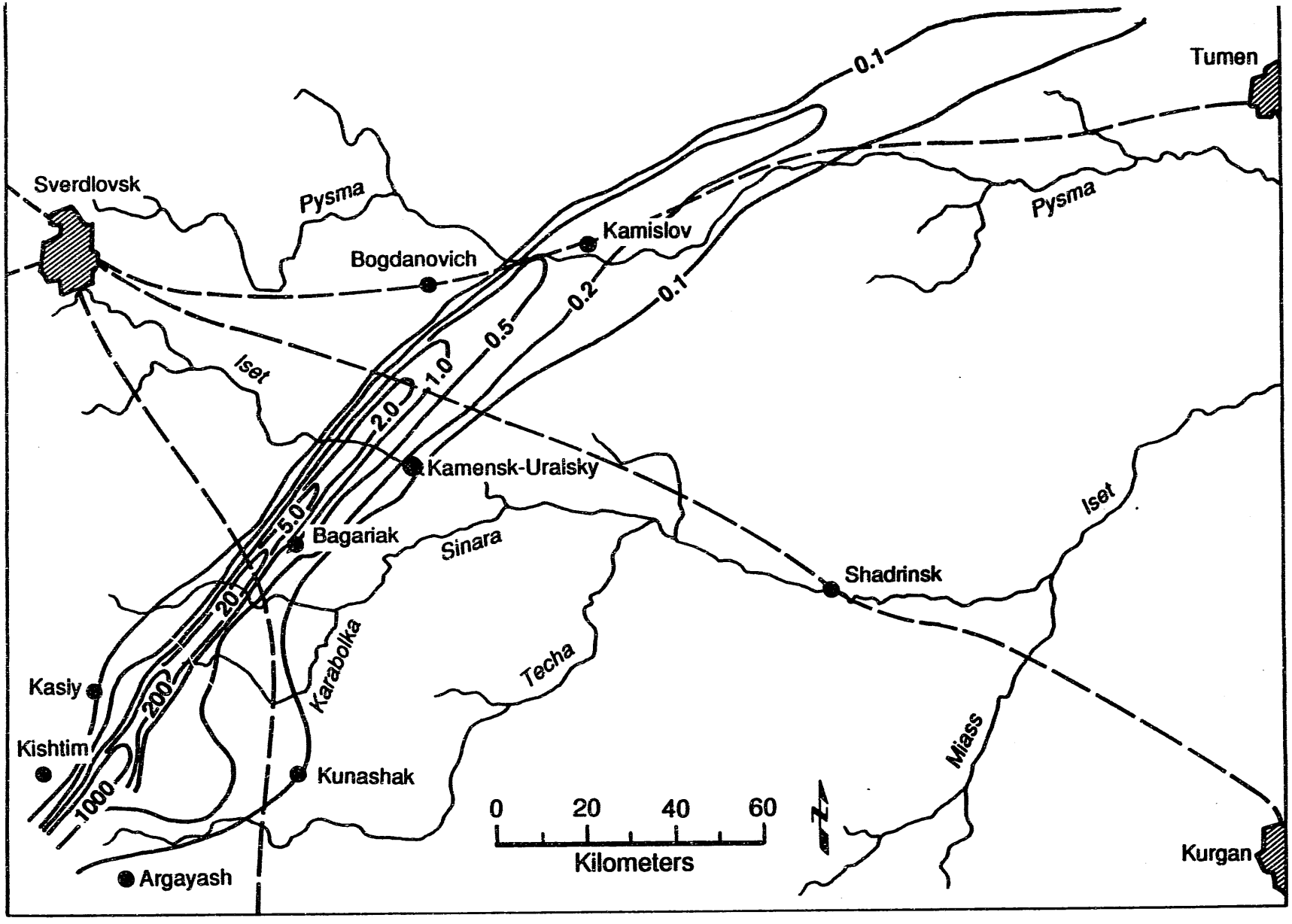


FIGURE 11.1. Map of the Radioactive "Track" from the 1957 Accident at Chelyabinsk-40, Ci/km^2 (U.S. DOE 1990)

TABLE 11.3. Soil Activity and the Dimensions of the Radioactive "Track" from the 1957 Accident at Chelyabinsk-40

Soil Activity, Ci/km^2	Length, km	Width, km
140,000	1-2	0.5-1
14,000	12	1.5
1,400	10	3.5
280	65	--
28	75	7

TABLE 11.4. Distribution of Strontium-90 Contamination from the 1957 Accident at Chelyabinsk-40

Indicator	Level of Contamination, Ci/km^2			
	100	10	1	0.1
Area of track km^2	200	400	1,400	23,000
Number of populated areas	3	13	71	217
Number of people, 000	1.5	5	17	270

2,100 people lived in a contamination zone of more than 100 Ci/km^2 of ^{90}Sr. In the first 7-10 days immediately after the accident, 600 people from the most contaminated inhabited areas were resettled, and in the subsequent 1.5 years, about 10,000 people (Nikipelov et al. 1990). Further evacuation of the population was conducted 1-1.5 years after the accident for areas with a strontium-90 contamination level exceeding 4 Ci/km^2, which totaled about 700 km^2. The population of this region effectively used contaminated foods for 3 to 6 months in an "unrestricted manner." Only after the second evacuation 1-1.5 years after the accident, was the intake of contaminated food halted (EKONOMIKA, TEKHNIKA, EKOLOGIYA, February 1990). A total of 10,180 people were evacuated. The average maximum radiation dose received by the 600 people before evacuation was 17 rem of external radiation, 160 rem as the internal radiation dose to the digestive tract, and 52 rem as the effective dose equivalent (Nikipelov et al. 1990).

Only one radiological laboratory was operating the first days after the accident; another seven went into operation later. Since the accident

occurred during harvest time, a great deal of attention was stated to be spent on monitoring the radioactive content of grains, potatoes, and forage. The separation of food and forage into clean and contaminated groups was done 3 months after the accident, and withdrawal and destruction of discarded food was begun 5 to 6 months after the accident (EKONOMIKA, TEKHNIKA, EKOLOGIYA, February 1990).

Between 1957-1959, approximately 10,000 tons of various kinds of agricultural produce were withdrawn from use and 200 km^2 of agricultural area was "decontaminated" by ploughing. In 1960-1961, deep ploughing was implemented on an area of 62 km^2, along with burial of some contaminated soils to a depth of more than 50 centimeters (Nikipelov et al. 1990).

After the evacuation was completed in 1959, access to areas with a contamination density of more than 2 Ci/km^2 of ^{90}Sr was restricted. By 1962, the area of this zone was reduced to 220 km^2 with a maximum contamination density of 100 Ci/km^2. The remainder of the territory was turned over for agricultural usage. In 1958, land areas of 590 km^2 in the Chelyabinsk region and 470 km^2 in the Sverdlovsk region were withdrawn from agricultural use. In the Sverdlovsk region, agricultural production was established in 1961. In the Chelyabinsk region, the restoration of land to agricultural usage was "complete" by 1978, and by 1989 about 67% of the land had been brought back into use (Nikipelov et al. 1990).

The Soviets experimented with grazing young cattle (about 1500 head) on hayfields with contamination levels of 4-100 Ci/km^2 of strontium-90. After grazing on the contaminated fields, the cattle were placed on clean feed for 2 months before slaughter. Analysis of the radioactivity of the meat showed that its strontium-90 content did not exceed 100 pCi/kg.

Soldiers in the military unit that was on guard duty at the time of passage of the radioactive cloud sustained a dose of about 100 rad. The Soviets contend that neither they, nor some 2,767 people tested under outpatient conditions 2 to 5 years after the accident, showed any "pattern of radiation sickness." The only effects of radiation appeared to be a correlation with bronchial asthma (EKONOMIKA, TEKHNIKA, EKOLOGIYA, March 1990).

U.S. officials recently visited the laboratory, referred to as ONIS, established in 1958 to oversee the efforts to study and mitigate the effects of the HLW tank explosion in 1957. Located 10 miles from Chelyabinsk-40 in an agricultural area near the zone of the worst radioactive contamination, the purposes of the laboratory are to (Falci 1990):

- study the migration of radioactivity in the environment
- study the biological effects and influence of radioactivity on ecology
- develop measures to eliminate adverse consequences resulting from the contamination
- reclaim contaminated areas and return them to the economy.

A recent visitor to the proposed South Urals power plant site near Chelyabinsk-40 was told that a nearby lake, Kasha-Kul, was contaminated to "300 times normal background" due to the 1957 explosion (McNeece 1990).

11.1.4 Restoration of the Karachai Reservoir

Work is under way to eliminate contaminated water basins, primarily the Karachai reservoir where "medium activity waste" was dumped starting in 1951. The reservoir has accumulated about 120×10^6 Ci of ^{137}Cs and ^{90}Sr distributed between the aqueous phase, the bottom loam soil, and deposits in the ratio 1:7:12. Contamination is evidently migrating to the groundwater from the reservoir, which the Soviets state became known in the 1960s, and has now migrated 2 to 3 km from the reservoir (Nikipelov et al. 1990c).

The Soviets started reducing the size of the Karachai reservoir in 1967 when its surface area was 0.45 km^2, reducing it to 0.35 km^2 by 1976. After 1976, work was slowed down or stopped, due to large amounts of natural silts and "artificial" deposits, "primarily from hydroxide sludges from spent fuel reprocessing," which occupied up to 30% of the reservoir volume. A large amount of sludges accumulated in the northeast section of the reservoir in the discharge line region. Of the stated 120×10^6 Ci accumulated in the reservoir, ~35% is located in the loam deposits in the reservoir, 60% in the "mobile deposits," and ~5% in the aqueous phase, which has a specific activity of about 1.0 to 1.5×10^{-2} Ci/L. The specific activity of the deposits was up

to 2 Ci/L in the discharge line region and up to 0.3 Ci/L in remote regions. It appears that the work was then stopped in 1976 due to exposure rates and wind-blown contamination (Nikipelov et al. 1990c). During a visit to Chelayabinsk-40 and Lake Karachai by U.S. DOE officials in June 1990, radiation levels were reported to have reached 80 mr/h on their bus within a distance of a few hundred feet of the water, and were told that the reservoir surface radiation level was 3-4 R/h (Falci 1990). Other sources have reported dose rates in the region of the discharge line, or at the lake surface, from 600 R/h to greater than 700 R/h (Nucleonics Week August 23, 1990b).

In 1985, a "special engineered machine" was developed to work on highly contaminated parts of the reservoir. To immobilize contaminated lake deposits, reinforced concrete hollow blocks were used. By 1989, the northeast sector had been closed and the reservoir surface area was reduced to 0.29 km^2, then to 0.25 km^2 by 1990. The reservoir was packed with 1.5 x 10^6 m^3 soil (of which 0.4 x 10^6 m^3 is rock) and about 6,000 hollow concrete blocks. In 1990, the Soviets plan to divide the reservoir into sections using dikes, possibly to minimize further airborne contamination. The Soviets further state that by 1991 the reservoir will have been reduced to 0.20 km^2, and be completely eliminated before 1995. After that they plan to stop contaminant migration, and although no solution to this problem has been determined, they are considering "a sorption treatment of underground water," and a "ground and surface drain separation." The final choice is to be made in 1993. A system of engineered barriers is planned by the year 2000 to prevent further migration of contaminants and stop the discharge of contaminants into the Mishlyak river (Nikipelov et al. 1990c).

11.1.5 Long-Term Waste Management Program

The 15-year program of waste management at Chelyabinsk-40 includes the following four main sections, and is illustrated in Figures 11.2 and 11.3 (Drozhko 1990):

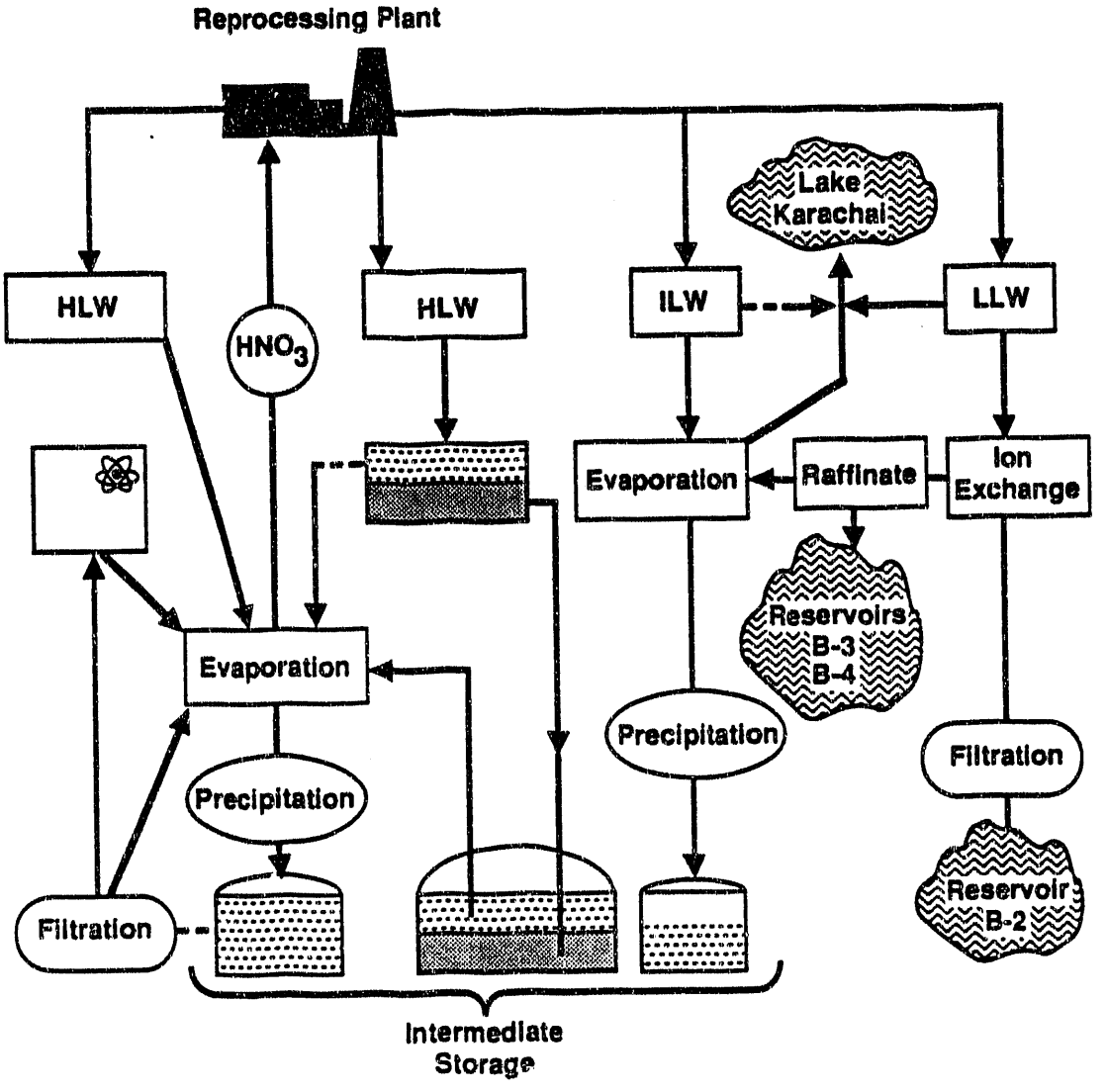


FIGURE 11.2. Radwaste Treatment at Chelyabinsk-40 Prior to Start-up of the Single Stage Vitrification Facility (Drozhko 1990)

1. Facilities operation and design to provide safe processing and storage of all waste streams:

   - solidification of liquid high-level wastes and some intermediate-level wastes by means of single-stage vitrification in 1990-1991

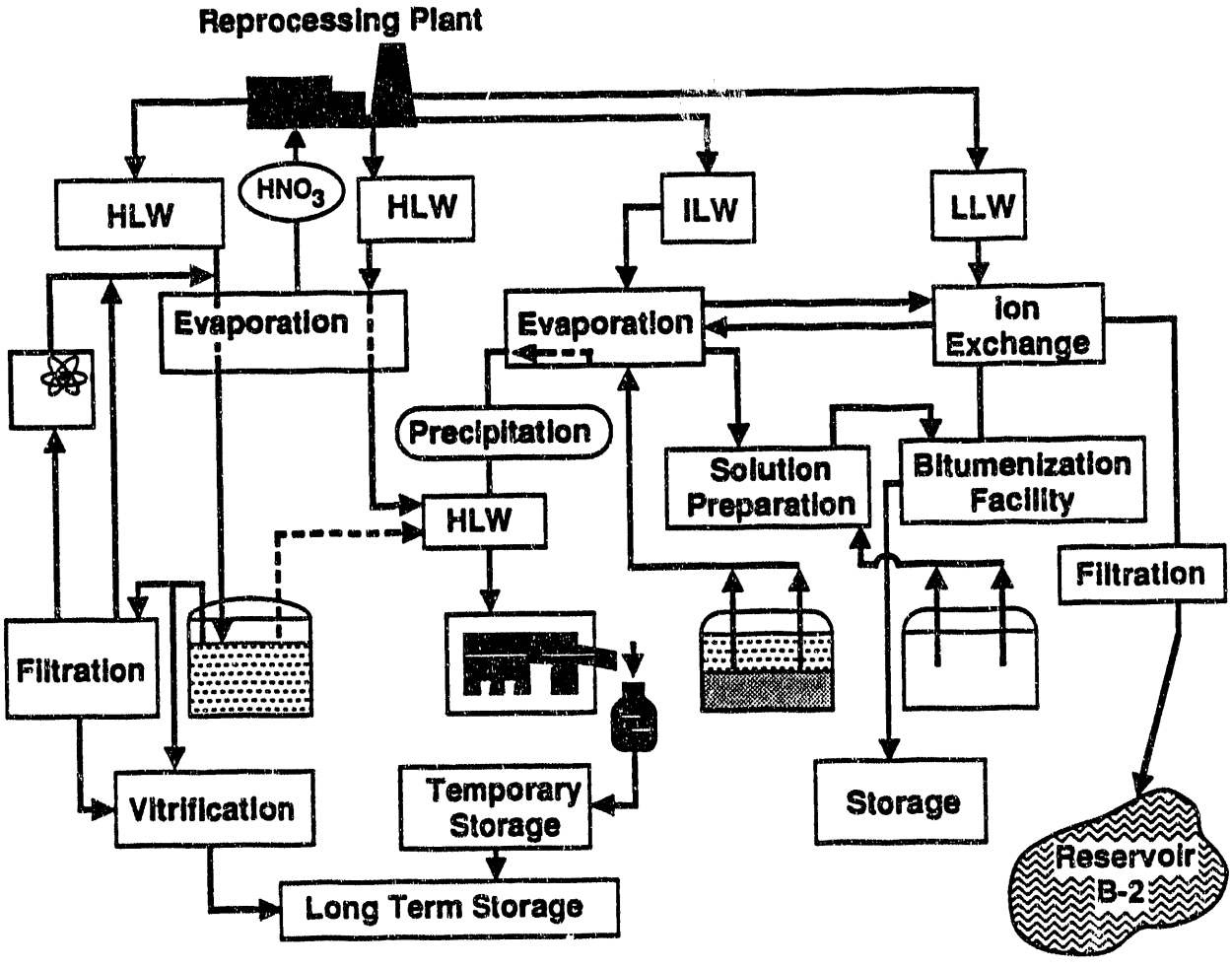


FIGURE 11.3. Radwaste Treatment at Chelyabinsk-40 After Start-up of the Bitumization Facility (Drozhko 1990)

- transfer of low- and some intermediate-level liquid wastes in 1993-1994 for their solidification at the bituminization plant, scheduled for operation in 1994. After the plants start, the discharge of all liquid wastes categories will be stopped, except for filtrates from the ion-exchange facility.
- operation of a single-stage "removable" melter
- design and construction of a solid waste reprocessing complex.

2. Restoration, to include "recovery" of contaminated areas, and "localization" of contamination sources:

- implementation of process to regulate the level of the Techa Reservoir Cascade - 1991-1992

- "liquidation" of the Karachai reservoir by 1994
- restoration of the contaminated Techa River flood-plain, Vurs, and Techa Reservoir Cascade - 1998.

3. Decommissioning:
   - decontamination of ground wastes [surface sites]
   - decontamination of surface reservoirs such as the Techa-Cascade
   - decontamination of metal wastes and solid waste treatment; two-stage solidification
   - evaporation of low-level wastes and contaminated surface waters
   - site selection for solid waste disposal
   - recultivation of contaminated areas
   - development of a mathematical model of the influence of plants on groundwater [contamination], and determination of "hydro-dynamic and hydrochemical parameters"
   - long-term waste storage conditions studies.
4. Research and development to support the above areas.

11.2 OPERATIONS AT CHERNOBYL

11.2.1 Status of Destroyed Unit #4

The Soviets recently stated that their data and models indicate that the damaged Chernobyl reactor is currently too hot and that gas pressures are too great to turn the reactor block into a "monolith." There is apparently agreement that the present status of the damaged reactor is not satisfactory regarding containment of radionuclides, although the treatment to be applied has not been determined (National Academy of Sciences 1990). In addition, Andrei Gagarinski, deputy director of the Kurchatov Institute, recently noted that the 1000-metric ton upper plate of Chernobyl #4 will be strengthened to prevent it from "falling down inside the reactor vault." It was also stated that it has been decided to add a steel cover over the concrete sarcophagus. Gagarinski also noted that the sarcophagus building is not hermetically sealed, and that aerosols produced inside could escape through "many slots and

holes" and although he added that this posed no health hazard, the Soviets will be discussing an "advanced confinement system" (Nucleonics Week 5/17/90). Further information on more permanent "disposal" options for the destroyed Unit #4 was provided during a recent visit by U.S. DOE staff (Falci 1990). The Soviets stated that options included building another engineered structure over the sarcophagus, filling the present structure with sand, and pouring a concrete monolith. They felt that the current sarcophagus was adequate to contain radionuclide migration for 100 years (Falci 1990).

Nearly all of the radioactive noble gases and "the main part" of iodine were released from the reactor as a result of the accident. The Soviets state that about 13% (±7%) of the cesium and 3.5% (±0.5%) of the fuel was also released.

Large amounts of fuel "masses" are located in the destroyed central hall of unit #4, as well as under the northern wall of the confinement system, in the spent fuel storage pool, and in the "under reactor rooms." The fuel is believed to exist in three main forms: fragments of reactor core, dispersed fuel lines and dust, and incorporated into black vitreous masses, of which one was found with a mass of "some cubic meters." The gamma dose rate near this large mass [found in 1986] was about 8,000 R/h, and had a composition of 95-96% SiO_2, 2-3% fuel, and small amounts of graphite, iron and construction materials. Similar fuel masses came through the steam discharge lines and oozed like "lava" from steam discharge valves or formed a pumice-like material upon contact with water.

About 50 boreholes have been made into the reactor core area, from which the Soviets have determined that not only the cover plate, but the "reactor bottom lid" was thrown away by the explosion, crushing the metal work beneath and dropping down about 4 meters (Borovoy 1989).

11.2.2 Contamination Measurement and Restoration Activities

An Industrial Association was organized in October 1986 to remediate the Chernobyl site and to be responsible for all operations except running the Chernobyl reactor. Their work is being done in five areas:

- monitoring and predicting migration of radionuclides

- medical and biological consequences of the accident
- decontamination and radioactive waste management
- study and prediction of the radionuclide situation in the control zone
- radioecological monitoring of the control zone.

The area of medical and biological consequences of the accident includes developing early diagnostic standards for those evacuated from the 30-km zone, and developing standards, automatic dosimeter and biological dosimetry systems. The Soviets are also looking into treatment of exposed personnel with food additives such as potassium ferrocyanide, natural herbs, and they are studying activated charcoal. Through 1991, they are focusing on monitoring those people who formerly lived in the control zone and expanding this at a later time to other populations. They expect to monitor about 600,000 people. More than 80 Soviet research organizations are working in this area, with the leading ones being the Biophysics Institute in Moscow and the All-Union Research Center of Radioactive Medicine in Kiev. The decontamination and waste management function includes the development of new decontamination methods, as well as nontraditional technologies for extracting radionuclides from soils (Falci 1990).

Following the Chernobyl accident on April 26, 1986, the Soviets placed more than 800 "containers" of high-level wastes, with a surface gamma dose rate >300 mr/h, within the sarcophagus of unit #4 (Strakhov et al. 1989). The Soviets also made unlined trenches ("makeshift disposal sites") near the reactor site for the disposal of 3×10^6 m^3 of equipment, trees, etc. These burial trenches were located about 4 meters above the water table. In addition, they have buried another 3×10^6 m^3 of soil, which in some cases was removed to a depth of 1 meter. Wooden houses were torn down and masonry houses had their roofs removed. The Soviets state that a primary task is to remediate these waste trenches and they are looking at a variety of options, including the use of sorbents and in situ burning (Falci 1990). During 1988-89, about 240 holes were drilled around the makeshift waste burial sites to monitor the radionuclide migration from these sites. It was reported that

the soil surface remains contaminated with cesium-137, strontium-90, and plutonium-239. The "territory" is contaminated by cesium-137 up to 1000 Ci/km^2, and by strontium to more than 600 Ci/km^2. The total inventory [in the 30-km zone], excluding waste disposal sites, is cesium-137 - 110,000 Ci; strontium-90 - 100,000 Ci; and 800 Ci of plutonium-239 + 240 (Nikipelov et al. 1990b).

Data from monitoring studies on the amount of radioactive material within various areas surrounding the Chernobyl station are given in Tables 11.5, 11.6, and 11.7. The Chernobyl accident released about 50 MCi, including about 3-4% of the fuel from the reactor, and contaminated an area of 200,000 km^2 with surface gamma dose rates ≥0.2 mr/h. The contamination in the "near zone" was reported to be 1.1 x 10^7 Ci, with a total activity deposited on "USSR territory" of 3.1 x 10^7 Ci (Strakhov et al. 1989).

In January 1987, the Soviets established a new disposal site 15 km west of the reactor site that is located 20 meters above the water table with an annual precipitation of 50 cm/yr (Falci 1990). In 1988-1989, two types of radioactive waste repositories [trenches] were built and put into operation within the 30-km protection zone at Chernobyl. Chernobyl wastes from the 30 "makeshift disposal sites" were then relocated into these repositories (Nikipelov et al. 1990b):

TABLE 11.5. Radioactivity Surrounding the Chernobyl Site (total activity in Ci) (National Academy of Sciences 1990)

Soil: Annulus (km)	Approximate Area (km^2)	Cs-137	Sr-90	Pu
0 to 1	3	3,100	3,000	7
1 to 3	25	13,200	14,000	30
3 to 5	50	22,600	30,000	63
5 to 15	628	47,100	63,000	260
15 to 30	2,120	24,000	17,000	440
Trees:				
1 km^2		5,280	5,600	12
9 km^2		4,070	5,400	11
300 km^2		22,600	30,240	125
990 km^2		11,280	8,000	210
Interim Storage:		110,000	100,000	800

TABLE 11.6. Territory Contaminated with Cesium-137 from the Chernobyl Accident, Excluding the Evacuation Zone, km^2 (PRAVDA April 17, 1990)

Republics	Level of Contamination (Ci/km^2)		
	5 to 15	15 to 40	Over 40
Byelorussia	9,830	3,640	1,160
Ukraine	540	350	200
Russian Federation	5,760	2,060	310
Total	17,130	6,050	1,670

TABLE 11.7. Territory Contaminated with Cesium-137 from the Chernobyl Accident, Evacuation Zone Included, km^2 (PRAVDA April 17, 1990)

Republics	Level of Contamination (Ci/km^2)		
	5 to 15	15 to 40	Over 40
Byelorussia	10,160	4,210	2,150
Ukraine	1,960	820	640
Russian Federation	5,760	2,060	310
Total	17,880	7,090	3,100

- "Buryakovka" - for wastes <5 R/h--30 trenches (with a capacity of 450,000 m^3) with clay "screens" and a system of observation holes.
- "Podlesny" - for wastes >5 R/h--8 reinforced concrete compartments with a capacity of 50,000 m^3.

More detailed information on these "repositories" has been provided by Strakhov et al (1989). Low- and intermediate-level wastes are placed in trenches. The trenches are 136 m long, 52 m wide, 4 m deep, and have a 12° (angle of) slope. The trench floor and walls are covered with a 1-m water-proof layer of "locally procured clay" and a protective 0.6-m layer of ground. The filled trenches are smoothed out with a 0.6-m ground layer, covered with 1-m-thick layers of clay and ground, respectively, and then grass is planted on top. High-level wastes are stored in a facility which may be multi-layered, with the walls built in concrete blocks, and the base floor made of road slabs, placed in a pad of water-tight material. The free space in the compartments is concreted to fill voids and form a protective layer of 800 mm

thickness under the containers. Then, the compartments are covered with an asphalt layer. In perspective, the whole complex will be covered with earth, a water-tight layer, and then planted over with grass (Strakhov et al. 1989). The Soviet goal is for 300-500 years of isolation (Falci 1990). Figures 11.4 and 11.5 show diagrams of the low- and intermediate-level waste disposal facility and high-level waste disposal facility, respectively (Strakhov et al. 1989).

Recent U.S. DOE visitors to this disposal site were told that thirteen trenches containing 15,000 m^3 each have been used, for a total of about 200,000 m^3 of LLW and ILW buried waste so far. Wastes in these trenches have a surface dose rate of less than 1 R/h. Elsewhere onsite they also have stored 11,000 m^3 of wastes having a surface dose rate of greater than 1 R/h. Future plans for disposal of metals, concrete and construction materials in 2.5-m cubic cells buried in the ground with a 1 m clay cover was also mentioned. The Industrial Association plans to remediate the improperly disposed of waste near the reactor site and process the rest prior to disposal. The first stage (with work plans expected to start during July 1990) will identify storage methods and processing of the waste; the second stage will involve construction (Falci 1990).

In 1986-1988, a survey of the agricultural lands taken out of service was carried out. Special measures, aimed at the reduction of radionuclide uptake, were deemed necessary on 35 to 40% of the lands. The main uses for these lands were stated to be (Nikipelov et al. 1990b):

- growing of seeds and trees with a specialized tree-farm planned for 1990
- breeding of cattle and fur-bearing animals, fodder production, bee-keeping
- the joint development and testing of decontamination equipment and radiobiological investigations.

The Soviets are interested in identifying "channels" for migration of radionuclides away from the Chernobyl site via the Pripyat River as well as groundwater routes to the river. Groundwater flow to the Pripyat is about 75,000 m^3y^{-1}. Transport in the river system (Pripyat River to the Dneiper

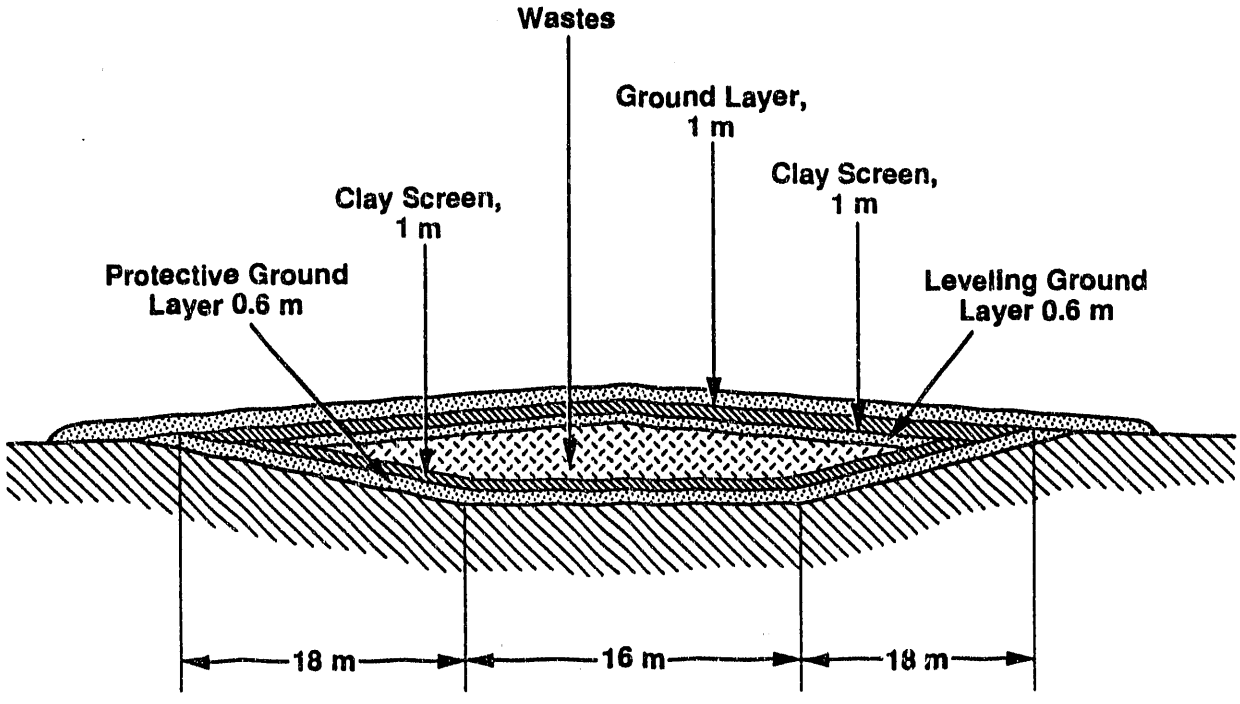


FIGURE 11.4. Diagram of Low- and Intermediate-Level Waste Disposal Facility Near Chernobyl (Strakhov et al. 1989)

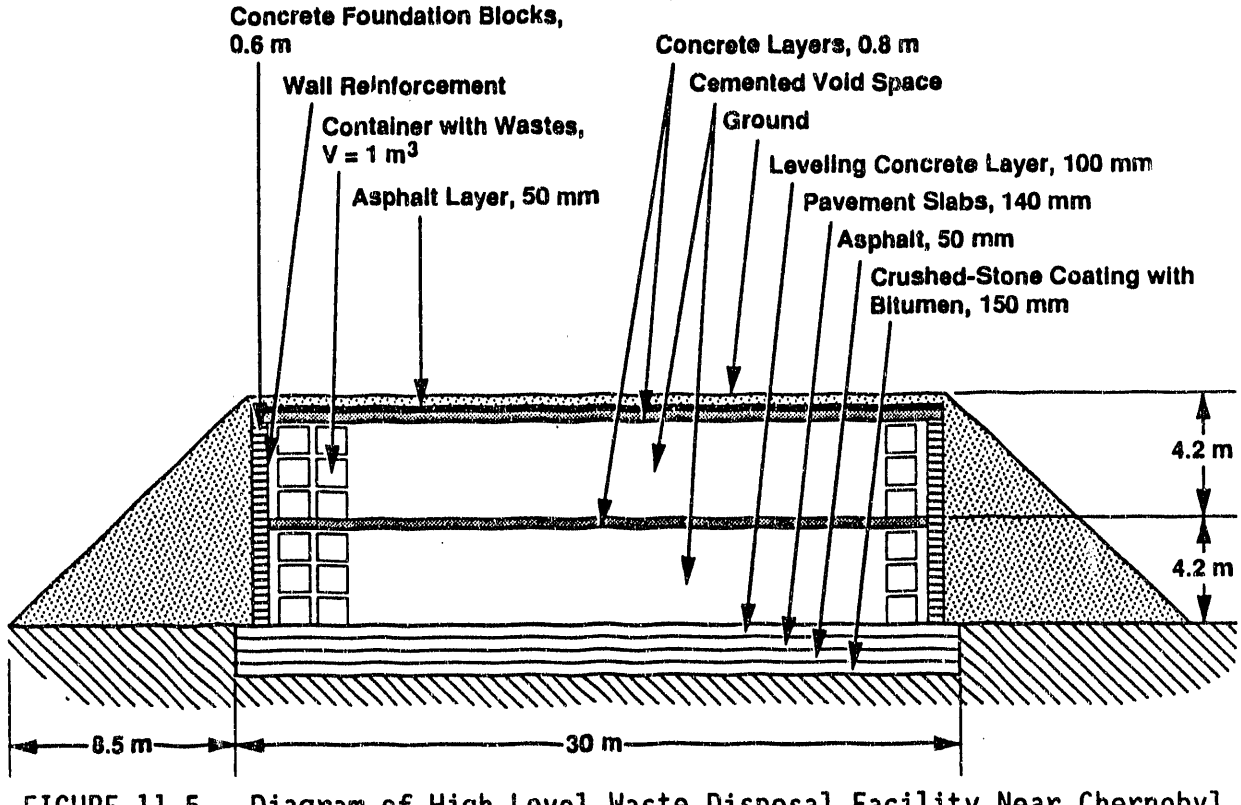


FIGURE 11.5. Diagram of High-Level Waste Disposal Facility Near Chernobyl (Strakhov et al. 1989)

River and ultimately to the Black Sea) was stated to have been measured. The second major pathway for release of radionuclides is via airborne dust. It was reported that polymers and grass seed were being sprayed over the area to stabilize the soils and to limit airborne transport. The Soviets have stated that the Hydrometeorology service has mapped cesium, strontiaum, and plutonium contamination in soils. Khlopin Institute staff also have been involved in studying radionuclide distributions in the air and water from the Chernobyl accident. Their modeling efforts were found not to be adequate to predict the observed radionuclide distributions (National Academy of Sciences 1990).

Due to the scale and difficulty of removing contaminated soil from the Pripyat river flood lands, radionuclides are being immobilized by selective planting of shrubs or grassy vegetation. In 1990, this is expected to be completed on 10 km^2. For intraflood land reservoirs, the removal of contaminated ground deposits, using special mobile equipment, is being developed with cooperation from APD, an American company. Simultaneously, the Soviets are working on immobilization of radionuclides using water plants such as reeds, canes, etc. (Nikipelov et al. 1990b).

The Soviets indicate that an urgent task is to reduce the radionuclide release from contaminated territories of the 30-km zone into water sources feeding the Kiev storage pool. Within this zone the Pripyat River, whose left-bank flood lands are heavily contaminated, is the main water source. Approximate inventories of strontium-90 in this area are reported to be up to about 5,000 Ci as well as 20,000 Ci of cesium-137. The station coolant pond (at Chernobyl) is reported to contain 4,600 Ci of cesium-137, 700 Ci of strontium-90 and 20 Ci of plutonium-239. To prevent radionuclides from entering from the coolant pond, a system of drain holes between the pond and the river was put in place to "intercept waters returning into the coolant pond" (Nikipelov et al. 1990b). A representative of several Soviet ecological organizations recently estimated that the Kiev reservoir contained 30,000 Ci of radionuclides, and serves as the drinking water source for 30 million people (Nucleonics Week May 10, 1990).

These concerns were amplified during a visit by a U.S. scientist who recently spent about three weeks in the vicinity of Chernobyl, participating in studies as a part of the U.S./USSR Joint Coordinating Committee on Civilian Nuclear Reactor Safety. The area of specific interest was environmental radionuclide transport, and the areas of expected joint research are as follows (Onishi 1990):

- radionuclide characterization, especially adsorption/desorption mechanisms,
- field collection of geo-hydro-radiochemical data for determination of major mechanisms controlling radionuclide migration and mathematical modeling,
- development and validation of mathematical models for overland and surface waters, and
- evaluation of remediation techniques and effectiveness of remediation of overland and surface waters.

The key USSR organizations involved in this study are:

- The Institute of Experimental Meteorology, which is a Soviet Union institute (approximately 300 staff members) and is officially responsible for determining distributions of radionuclides on the land and for predicting radionuclide migration over land surface, and in the Pripyat River and its tributaries.
- The Ukrainian Institute of Hydrometeorology, which is both a Ukrainian institute (approximately 350 staff members), as well as a part of the Soviet Union's Institute of Hydrometeorology. This institute collects water and soil samples used for future predictions of radionuclide migration over land surfaces and in the Pripyat and Dnieper Rivers (including reservoirs) and their tributaries.
- The V. Glushkov Institute of Cybernetics, which is both a Ukrainian (approximately 7,000 staff members) and a Soviet Union institute, and conducts computer simulations of radionuclide migration in the Dnieper River from the Kiev Reservoir to its mouth at the Black Sea.
- The Pripyat Research and Industrial Association, which is believed to be a Soviet Union organization, is responsible for (among other things) the 30-km restricted zone.

A brief summary of information learned while visiting and studying environmental issues in the Chernobyl area is as follows (Onishi 1990):

- The Ukrainian Institute of Hydrometeorology, along with other Soviet institutes, conducted cloud-seeding 150 km upwind from Chernobyl after the accident to avoid precipitation around the site.

- Within 5 days after the accident, there were rapid increases of radionuclide concentrations in the flood plains and the rivers. The Soviets built dikes, dams, and sediment traps around and in the rivers and flood plains to control the migration of the radionuclides in the Pripyat and Dnieper Rivers, which in many cases were not effective. The Dnieper River has a series of large reservoirs created by locks and dams, and is supplying drinking and irrigation water to about 40 million people (mostly Ukrainians) before it reaches the Black Sea, approximately 1000 km away.

- The radionuclides of current concern are ^{90}Sr and ^{137}Cs. There are three large hot areas (one near the Chernobyl plant, the second about 120 km away, and the third another 100 km away) resulting from the transport of radionuclides in different physical forms (i.e., fuel particles or condensed forms originally emitted as a vapor, most likely to be Cs_2CO_3, in the case of Cs), precipitation patterns and other factors. For ^{90}Sr, most of the hot areas are near the Chernobyl plant, partially due to ^{90}Sr being associated with fuel particles.

- A special characteristic of radionuclides in the environment from the Chernobyl accident is the existence of fuel particles. They are now disintegrating in the environment and releasing radionuclides in land surfaces and in rivers. Only 10 to 20% of the ^{90}Sr was exchangeable in 1986 and 1987, while now more than 60% is exchangeable.

- The current average radiation levels on the land, based on observed measurements, are 150 to 300 $\mu R/h$ at the reactor site, 200 $\mu R/h$ at Pripyat Town and 40 to 60 $\mu R/h$ at Chernobyl Town, respectively. At Pripyat Town, ^{90}Sr and ^{137}Cs concentrations on the ground are 40 and 100 Ci/km^2, respectively. At Chernobyl Town, the highest reading observed was 10,000 $\mu R/h$, but (as an average) the level is about 2 to 3 times the background level.

- Dissolved concentrations of ^{90}Sr and ^{137}Cs in the Pripyat and Dnieper Rivers are now 1 to 10 pCi/L. The USSR drinking water standard for ^{90}Sr is 400 pCi/L, while in the U.S. it is 100 pCi/L.

- Changes in concentrations of ^{137}Cs and ^{90}Sr in the Pripyat River near Chernobyl over the last four years are shown in Figure 11.6, together with associated river water discharge. Since a major potential source of ^{90}Sr is the flood plain across from the Chernobyl plant, and subsequently the Kiev Reservoir, these two locations are the primary candidates for cleanup activities. Although

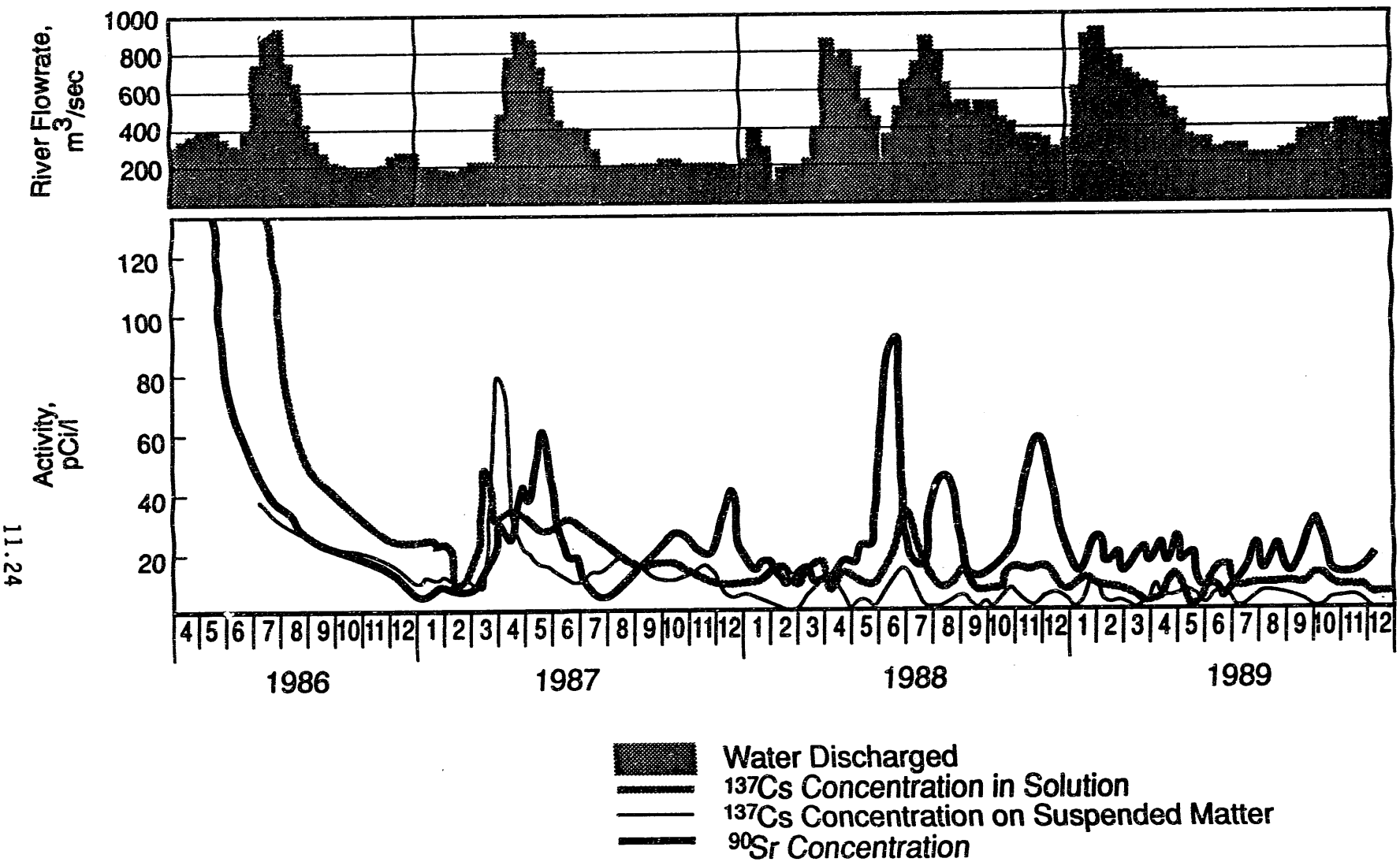


FIGURE 11.6. Changes in Radionuclide Concentrations in the Pripyat River (Onishi 1990)

a 5- to 10-year flood can cover most of the flood plain across the Chernobyl plant, no major flood has occurred during the last 4 years.

- The sources of ^{90}Sr and ^{137}Cs, respectively, flowing from the Pripyat River into the Kiev Reservoir are as follows:

  - 43% and 12% from the flood plain across the Chernobyl plant
  - 1% and 7% from the Chernobyl cooling pond
  - 22% and 4% from the tributary, the Uzh, and other water sources near the Chernobyl plant
  - 24% and 77% upstream of the Chernobyl plant.

- Unlike ^{90}Sr, most of the ^{137}Cs comes from upstream areas of Chernobyl in roughly equal amounts from the Pripyat and Dnieper Rivers into the Kiev Reservoir. Most of the radionuclides found in the flood plain are still near the surface; 90% of them are within 1 cm of the ground surface. About 73% of the radionuclides flowing into the Kiev Reservoir are trapped there.

- Although radionuclide concentrations in the Pripyat and Dnieper Rivers are one to two order magnitudes lower than the USSR or USA drinking standards, an irrigation pathway for radionuclide transport and uptake has not been considered to date.

Following a request by the Soviet government in October 1989, the International Atomic Energy Agency (IAEA), with the participation of the Commission of the European Communities (CEC), the United Nations Food and Agricultural Organization (FAO), the U.N. Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), and the World Health Organization (WHO), is organizing a major project to evaluate aspects of the Chernobyl accident. The study [expected to be available in 1991] will assess the radiological consequences within the USSR of the Chernobyl-4 accident. The survey will include health and environmental effects, and will evaluate the protective measures taken by Soviet authorities (Nuclear News June 1990b).

The Soviets have reported that a contract was signed by the USSR Ministry of the Atomic Power Industry and the West Berlin firm, Recytech, to install a pilot decontamination facility at Chernobyl. The plant, to be operational in late 1990, will decontaminate materials and equipment, of which 165,000 MT has accumulated at the site. The pilot facility can handle up to

5 MT of metal per day, and the contract with Recytech includes building a commercial plant of larger capacity in the Chernobyl area (TASS April 25, 1990).

Beginning in 1991 the Soviets expect to increase the environmental restoration of the Chernobyl contaminated zone, with emphasis on designing special mobile equipment for decontamination, along with construction of sarcophagus-2 for the destroyed fourth unit. The main direction of work in the 30-km contaminated zone is stated to be (Nikipelov et al. 1990b):

- creating a proving ground for testing equipment and technology for decontamination
- organizing an international center under the aegis of the IAEA to enlist the cooperation of foreign scientists
- using natural and agricultural lands for the development of production technology of various kinds of commodities.

11.2.3 Health and Environmental Effects

Authorities in Byelorussia continue to report statistical trends of diseases in the wake of the Chernobyl accident and recently reported that there is a clear link to thyroid disease, but it is not yet possible to link Chernobyl to leukemia and similar diseases (Nucleonics Week 1990a). As part of this effort, some 60,000 people are being continuously monitored (Nuclear Waste News April 26, 1990). In addition, it has been reported that 150,000 people have been "seriously affected" by radiation doses (Multinational Environmental Outlook May 1, 1990), that of 600,000 people who worked for 5 months at Chernobyl, 7,000 have died (IAEA May 4, 1990), and that the first five cases of thyroid cancer in infants have been identified (Nucleonics Week May 3, 1990).

Byelorussian Deputy Prime Minister Alexander Kichkailo has indicated that 2.2 million people (one-fifth of the Byelorussian population) were exposed to radioactive contamination, there has been a loss of 4 million acres (20%) of its farmland, and about 2.5 million acres (15%) of its forests have been affected (Nucleonics Week 1990a). According to PRAVDA, 14,000 people would be evacuated this year from areas contaminated by the Chernobyl accident (Washington Post April 24, 1990). The Soviets then stated in a session of the

Supreme Soviet on April 25, 1990, that at least 300 people had died from nuclear-related causes due to the Chernobyl accident, and an emergency program costing 16 billion rubles was proposed. As part of this program, 200,000 more people could be evacuated (Independent April 26, 1990; Times April 26, 1990). Further details of the evacuation were given in June 1990. The basis for evacuation comes from a policy (adopted more than a year ago) of resettling people who might incur a dose of more than 35 rem over the next 70-75 years. A cesium ground contamination level of 15 Ci/km^2 was established to define areas where this limit might be reached if there were no special controls, and a 40 Ci/km^2 level was used to define areas where the doses could be kept below the limit if there were restrictions on the eating of local produce. Details of the further evacuation of people are given in Table 11.8 (Nuclear News June 1990a).

11.2.4 Economic Impacts

A Soviet study by the chief economist of the R&D Institute of Power Engineering, Yuri Koryakin, has concluded that the cost of the Chernobyl accident may be about 20 times higher than previously estimated, and has contributed to the country's worsening economic problems. Koryakin estimates that by the year 2000, the accident may cost 170 to 215 billion rubles in direct and indirect costs, as shown in Table 11.9. The study also notes that the estimated net economic contribution of nuclear power since the first power reactor started in 1954 has been 10 to 50 billion rubles (Wall Street Journal March 29, 1990. It was also reported that the accident so far had cost 9 billion rubles and was projected to cost between 100 to 200 billion rubles by 1995 and 2000, respectively (Times April 26, 1990).

11.3 OTHER CONTAMINATED SITES AND ENVIRONMENTAL RESTORATION-RELATED ACTIVITIES

The Soviets discussed studies of monitoring radionuclide contamination in water bodies during a U.S. National Academy of Sciences visit to the Soviet Union. They stated that 30 areas have been looked at, including the Pripyat River, the Kiev Water Reservoir, and the Baltic Sea and rivers flowing into

TABLE 11.8. Planned Evacuation of People from Areas Contaminated by the Chernobyl Accident

Stage	Completion Date	Affected Area Contamination Level	People Affected	Affected Population Centers	Number of People Evacuated
1	1990	>15 Ci/km^2 of Cs >40 Ci/km^2 with administrative controls	Families with children <14 years old, pregnant women	---	20 to 23,000
2	1990 to 1991	Same as above	Same as above	306 in Byelorussia 22 in Ukraine 67 in Russian SFSR	38 to 40,000[a] 19 to 20,000[a] 15 to 18,000[a]
3	1991 to 1992	<40 Ci/km^2 not to exceed 35 rem per individual over the next 70 to 75 years	Families with children and pregnant women	Byelorussia Ukraine Russian SFSR	90 to 94,000 40 to 43,000 50 to 80,000

(a) Includes those evacuated from stage 1.

TABLE 11.9. Chernobyl Reactor Accident Costs

Area	Cost (billions of rubles)
Loss of Agriculture Production on Contaminated Land	57.5 - 94.5
Loss of Electrical Production	66.8
Decontamination/evacuation, cleanup	35-45
Installation of new reactor safety equipment	3.9 - 5.1
Loss of capital invested in closed reactors	5.0
Total	~215

it. This work was done in collaboration with Canada, Poland, the Federal Republic of Germany, and the German Democratic Republic (National Academy of Sciences 1990).

Radiation up to 20 times normal natural background was recently reported outside the city of Marioupol in the Azov Sea coastal area. Storms and land slides have exposed deposits of monazite sands apparently containing thorium-232. Work to map the sources and then possibly to cover them is to begin soon (TASS May 25, 1990).

A recent survey of radioactive contamination in Leningrad revealed 150,000 spots with above-normal radiation levels, and 5.3 million cubic feet of contaminated soil. The only radioactive waste disposal site was also found to be leaking radioactive material into the soil and groundwater (Nuclear Waste News August 16, 1990). Also near Leningrad, in an area known as Lake Logoda where islands in the lake were used to test military equipment, a ship containing radioactive materials was "beached during the 1960's." It has been reported that the ship contains about 2,000 MT of water contaminated with strontium-90, causing concerns of radioactive contamination due to corrosion of the old ship. It is expected that "salvaging" operations are to begin in the summer of 1991 (Moscow Television Service 1990).

Izvestia has reported that 38 residents of Tomsk had higher internal radiation levels after eating meat and fish caught locally, and four adults

and three children had to be hospitalized. The contamination is attributed to wastes from a nuclear installation, Tomsk-7, built in the 1950s (IZVESTIA) May 3, 1990). Environmental contamination has also been observed at a "chemical isotope factory" located near Krasnoyarsk, the location as well for an underground disposal site for liquid radioactive wastes via a tunnel underneath the Yenisey River. Referred to as "Site-27", a Soviet journalist reported that two research expeditions of specialists from Leningrad, the Krasnoyarsk Scientific Center, and the State Committee for the Protection of Nature confirmed radioactive contamination of the Yenisey River. The level of radioactivity [supposedly at "Site 27"] was reported to exceed background by a factor of "six to eight" and is still up to 100 μR/h more than 400 km down the Yenisey River (where the natural background is 10 to 15 μR/h). Silty radioactive deposits were mentioned downstream from the site having an activity level greater than 1,000 μR/h. The article also mentions that industrial reactors at the site have used once-through cooling, discharging directly into the Yenisey River, for more than 30 years. Two of these reactors were expected to be taken out of service by 1995, and a third by the year 2000. The mining and chemical plant at the site has been "converted" to the production of fuel for nuclear power plants (Vozdushnyy Transport 1990).

Radioactive contamination has been reported at the Ulbinskiy Metallurgical Plant in Ust-Kamenogorsk, where an explosion at a beryllium plant recently took place. It was stated that uranium and thorium tailings piles and "radioactive gypsum" piles have accumulated to about 100,000 tons of material since 1949. Tailings piles were reported to be giving off readings in excess of 1,000 μR/h (KAZAKHSTANSKAYA PRAVDA 1990).

The Soviets have recently published a map of the city of Moscow that shows areas of radioactive contamination. The map, shown in Figure 11.7, indicates areas where the contamination has "spread over an area" and that which is "local in character" [both of which are undefined]. The radioactivity is reported to range from 0.12 mR/h up to 1 R/h. Apparently, part of the radioactive contamination is due to disposal at numerous dump sites and then subsequent use of material from these dump sites as fill material, thereby spreading the contamination further (Rabochaya Tribuna January 30, 1991).

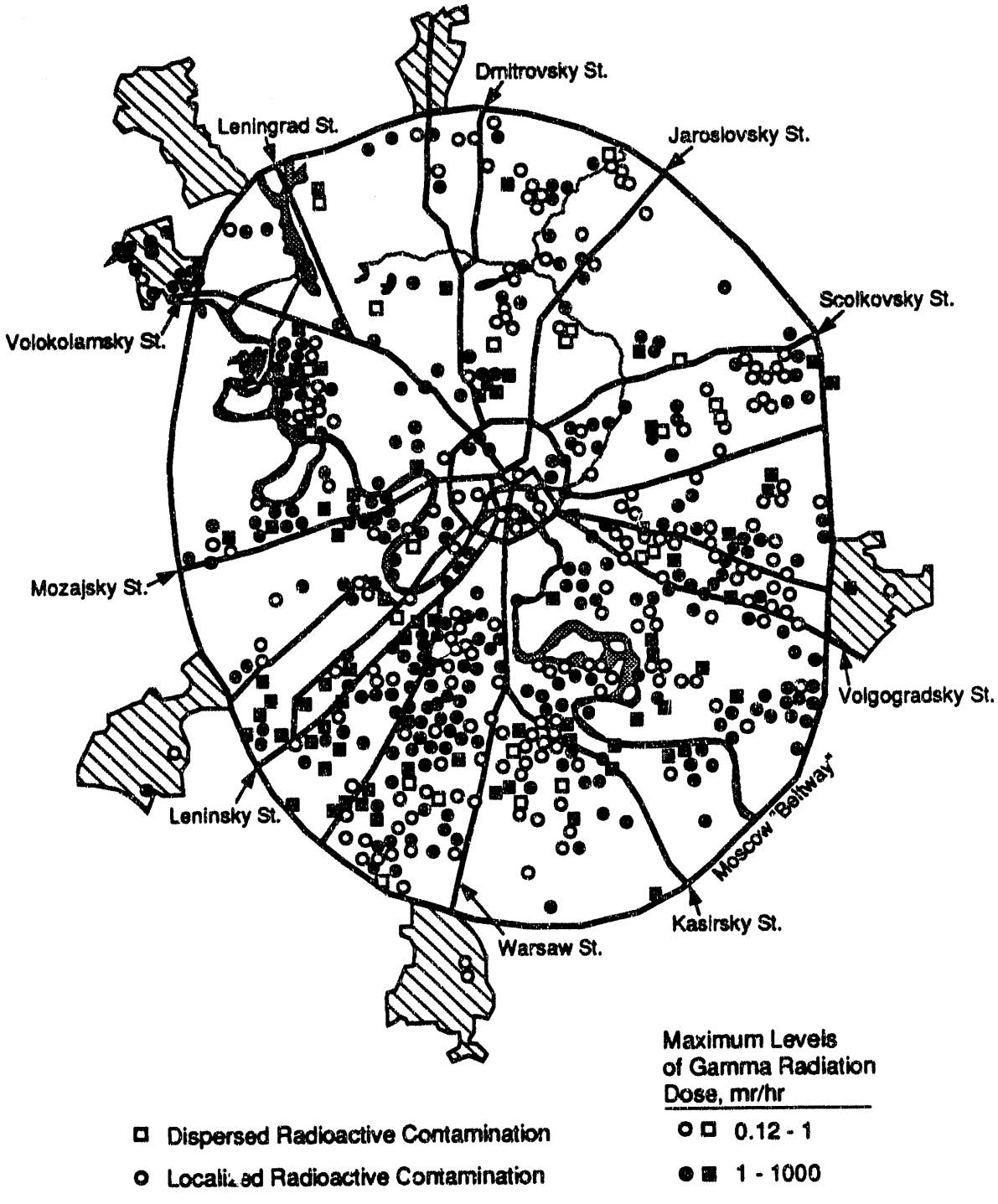


FIGURE 11.7. Radioactive Contamination Map of the City of Moscow, USSR (Rabochaya Tribuna January 30, 1991)

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APPENDIX A

APPENDIX A

An update of PNL-7182 is given in this appendix, which includes tables on Soviet and CMEA country nuclear power reactors, as well as recent background information.

A.1 POWER REACTOR OPERATIONS

Soviet nuclear power plant construction has been slowed down considerably, and many plants have been canceled since the accident at Chernobyl in 1986. A recent article indicates that even plants that were nearly completed are being suspended, such as at Rostov, Zaporozhye, and Gorky (TANJUG 1990). The following section gives further information on Soviet reactor shutdowns, safety concerns, and the potential construction of the South Urals power station near Chelyabinsk.

The Ukrainian Supreme Soviet officially declared in March 1990 that it plans to phase out operation of nuclear reactors at the Chernobyl site one at a time over the next 5 years, and then close the site completely (Washington Post March 4, 1990). The Soviets stated they would shut down the three Chernobyl reactors one by one "by the end of next year" [1991] with Unit #3 probably being the first to be decommissioned. In addition, a recent visitor reports being told that radioactive "magma" has migrated into the piping under Unit #3, causing high radioactivity levels in that units control room (Nucleonics Week May 3, 1990).

Soviet engineers and scientists continue to develop improved versions of the RBMK reactor, as was reported at a seminar in Vienna on May 15, 1990. The Soviets appear to be keeping the RBMK reactor as part of their nuclear power mix by developing the MKR-800 a "modular channel reactor." Another version, however, the UKR-1500, a 1500-MWe "enhanced safety" version of the RBMK-1000, appears to have less of a chance of being built. Details of the modifications to the RBMK reactors since the Chernobyl reactor accident were also described by Vislav Vasilevsky, chief of research laboratories of the Institute of Power Engineering in Moscow (Nucleonics Week May 31, 1990a).

The Soviet Union has dropped a project to build a 1,000-MW nuclear plant in Soviet Karelia, and instead has confirmed plans to build two VVER-1000s to replace the four VVER-440s at the Kola site. The VVER-1000s are to be built next to Lake Imandra, about 30 kilometers from the old VVER-440 plant. The two sites are near the city of Kovdor about 100 miles south of Murmansk. Construction is expected to take six years. The Finnish company, IVO, through its subsidiary, IVO International, is jointly developing new VVER-1000 models with the USSR's export supplier, Atomenergoexport (Nucleonics Week June 7, 1990b).

The East German government recently ordered the first four Soviet-designed VVER-440 PWRs at Greifswald shut down pending a decision, expected December 16, whether to backfit the reactors extensively to meet new regulatory requirements and keep them operating until the mid-1990s. The plants were ordered to be closed on June 1 following completion of a report on their safety by West German safety experts Gesellschaft fuer Reaktorsicherheit mbH (GRS).

GRS cited insufficient monitoring of reactor component performance following repair and maintenance, inadequate requalification of safety-related equipment following a repair, and insufficient functioning of instruments for monitoring safety systems during outages and startup. As of June 1990, Greifswald-4 was operating at 65% power in anticipation of a delayed outage at the end of the year. Greifswald-2 and -3 were shut down in February and March, 1990, respectively, for long outages accommodating pressure vessel annealing. Greifswald-1, recently returned to service after being shut down for repairs in May, was expected to operate for several weeks to produce process heat required by some plant safety systems (Nucleonics Week June 7, 1990c).

The MAPI, under "orders" from the State Committee for the Supervision of Safety in Industry and the Nuclear Power Industry, reduced power at 6 RBMK-1000 reactors in June 1990. This action, due to safety concerns, reduced power to 700 MWe at Leningrad 1 and 2, Kursk 1 and 2 and Chernobyl 1 and 2. MAPI officials hoped to bring the reactors to fuel power within a "month or two" (Nucleonics Week July 12, 1990b). It was then reported that VVER-1000

reactors are operating at "significantly reduced power levels" for up to 200 days after refueling to partially compensate for a positive thermal reactivity coefficient. (Nucleonics Week July 26, 1990b). Within the next two years, all VVER-1000 reactors will use one-third core annual refueling, instead of the originally designed one-half core annual refueling, to "avoid positive reactivity coefficients with fresh fuel" (Nucleonics Week October 4, 1990).

The Soviet BN, or fast reactors, are also facing safety concerns. Older BN reactors will have to be backfit with a sodium-to-air residual heat removal system now being designed. It is expected to be installed between 1993-1995 at a cost of 100 million rubles. Additional concerns are being expressed over the fact that BN-600 reactors will begin to burn plutonium in the future. Breeder reactors in the Soviet Union do not now use plutonium fuel. BN-600 reactors use uranium in three enrichment zones of 21%, 26%, and 27%, as does the BN-350 fast reactor. Only the small BOR-60 fast reactor in Dimitrovgrad [formerly called Melekess] has been burning mixed-oxide fuel since 1983. The fuel is produced onsite in a pilot facility using vibration compaction technology. The current BN-600 fuel and blanket are reprocessed "normally" at Mayak by diluting them with lower-enriched fuel. The Soviets were concerned with the void coefficients in the BN-600 and also BN-800 reactors when these reactors use mixed-oxide fuel (Nucleonics Week July 26, 1990c).

At the BN-800 site in Beloyarsk, construction has been halted at a very early stage due to safety concerns by the public. It will not be resumed until the public, apparently centered in Sverdlovsk, agrees to it, a U.S. visitor was recently told. Additionally, construction of the BN-800s being planned at the "South Urals" site near Chelyabinsk-40 had also been halted by public concerns [centered in the city of Chelyabinsk] of safety. The Soviets stated that the BN-800s were sited at the "South Urals" location to help maintain the water level in the man-made reservoirs containing contaminated water from Chelyabinsk-40 operations [using reactor heat for water evaporation], as well as to provide jobs for the staff of the shutdown plutonium production reactors at Chelyabinsk-40 (McNeece 1990). In November of 1990, however, the People's Deputies of the Soviet Oblast in Chelyabinsk voted in favor of

restarting construction of the "South Urals" power plant. The facility was cited as needed to improve the ecological condition of the nearby Chelyabinsk-40 site and its reservoirs as well as "burning the plutonium that has already accumulated" at the site (TASS November 22, 1990). Following this decision, the Councillors of the city of Chelyabinsk decided in early December to hold a referendum on the construction of the South Urals plants (TASS December 6, 1990).

Soviet reactor engineer, Grigori Medvedev, recently published a book on Chernobyl in which the occurrences of reactor and waste-related accidents in the Soviet Union since 1957 were discussed. These accidents [with the addition of the accident at Chernobyl Unit 4 in April 1986] as translated from the French edition of his book, are described in Table A.1.1 (Nucleonics Week May 31, 1990b).

The Deputy Chairman of the USSR State Committee for the Supervision of Safety in Industry and the Nuclear Power Industry, recently refuted Medvedev's claims as being overstated. Among other assertions, Nikolai Steinberg claimed that the accident at Leningrad Unit 1 on November 30, 1975 released only 200 curies, instead of 1.5 million curies (Nucleonics Week, July 12, 1990c).

A.2 DEFENSE REACTOR OPERATIONS

In 1989, as a result of a visit to the Chelyabinsk-40 site, the NRDC reported the shutdown of three plutonium production reactors at the site, two in 1987 and another in 1989. (Bradley et al. 1990) On July 14, 1990 a fourth plutonium production reactor, AV-2, was shutdown by Yevgeniya Zotova, senior reactor engineer after nearly 40 years of operation. Factory Director Vitaliy Sadovnikov noted that the reactor was originally planned to operate "until at least 1995." (TASS July 1990). The fifth and last production reactor was shut down at Chelyabinsk-40 in a ceremony on November 1, 1990 at the site. The facility had been in operation since 1952 (Nuclear News December 1990).

A reactor at the Siberian Chemical Combine and Atomic Power Station, located at Tomsk-7, has been shut down after operating for over thirty years. It was also reported that the Atomic Power Station "is working its last few

TABLE A.1.1. Nuclear Reactor and Radioactive Waste Accidents in the USSR

September 1957	- Explosion of a high-level liquid waste tank at Chelyabinsk-40. Large areas of land remain off-limits for decades.
May 7, 1966.	- Power excursion in the 62-MW prototype BWR at Melekess. A health physicist and a shift supervisor are irradiated. The chain reaction stopped when two sacks of boric acid were thrown on the reactor.
1964-1979	- Frequent destruction of fuel assemblies at Beloyarsk-1 [RBMK prototype]. Operating staff were irradiated during repairs to the core.
January 7, 1974	- Explosion of a reinforced concrete tank containing radioactive gases at Leningrad-1 [RBMK-1000].
February 6, 1974	- Explosion of the tertiary circuit at Leningrad-1 [RBMK-1000] from hydraulic shocks induced by violent boiling. Three people died, and "highly radioactive" water containing filter wastes was released into the environment.
October 1975	- Meltdown of 25 fuel assemblies at Leningrad-1 [RBMK-1000]. A day later, over 1.5 million curies were released through the stack.
1977	- Half of the fuel assemblies melted at Beloyarsk-2 [RBMK-prototype]. Staff received radiation doses from repairs, which lasted a year.
December 31, 1978	- Fire at Beloyarsk-2 [RBMK-prototype] caused by the collapse of the turbine building roof. The control cable was completely burned and the reactor could not be controlled. Eight people were irradiated while trying to inject coolant into the reactor.
September 1982	- Partial core melt at Chernobyl-1 [RBMK-1000] following an incorrect action by the operating staff. Radioactive material was released into the industrial zone and the city of Pripyat, and staff received radiation doses from repairing the core.
October 1982	- Explosion of the generator of Armenia-1 [VVER-440], setting fire to the turbine building. The operating staff managed to keep the coolant flowing, and a team from the Kola reactor station arrived to help the Armenia operators save the reactor core.

TABLE A.1.1. (contd)

June 27, 1985 - Accident at Balakovo-1 [VVER-1000] during initial startup. Fourteen people died when the pressurizer relief valve opened suddenly and steam at 300 degrees C was sprayed into staff working areas.

April 26, 1986 - Destruction of the Chernobyl Unit #4 reactor [RBMK-1000]. Very widespread contamination involving 50 MCi causes the evacuation of 135,000 people with at least 300 deaths. Further evacuations are being planned.

months and soon another reactor will be shut down" (TASS August 21, 1990). It has also been reported that other defense reactors are located near the city of Krasnoyarsk (New Scientist July 22, 1989).

A.3 RADIOACTIVE WASTE CLASSIFICATIONS IN THE USSR

Categories of radioactive waste are given as follows (National Academy of Sciences 1990):

Type	Activity Level
Liquid	
• Low Level	$<1 \times 10^{-5}$ Ci/L
• Intermediate-level	$\geq 1 \times 10^{-5} \leq 1$ Ci/L
• High Level	≥ 1 Ci/L
Solid	
• Low Level	≤ 30 mr/h
• Medium-level	$30 \leq 300$ mr/h
• Intermediate-level	$0.3 \leq 1$ r/h
• High Level	≥ 1 r/h

Notes: Solid wastes below 30 μr/h are not considered radioactive and do not require any special treatment or handling.

In the United States, LLW is that remaining waste that is not classified as HLW or TRU (i.e., alpha activity >100 nCi/g and $T_{1/2}$ > 20 years); HLW is defined as spent fuel and wastes from fuel reprocessing.

Solid wastes in the Soviet Union are judged to be radioactive if they meet the following criteria (Drozhko 1990):

- specific activity for beta-active wastes > 2×10^{-6} Ci/kg
- specific activity for alpha-active wastes > 2×10^{-7} Ci/kg
- specific activity for transuranic wastes > 1×10^{-8} Ci/kg
- exposure dose rate for gamma-active wastes > 1×10^{-7} g-equi•Ra/kg or the solid waste has a surface activity of:
- For beta-activity > 50 particles/cm^2•min over a surface of 100 cm^2
- For alpha-activity > 5 particles/cm^2•min over a surface of 100 cm^2

Gamma-active wastes are categorized by disposal method as follows (Drozhko June 1990):

1 group	less than 0,3 μR/h	trenches
2 group	from 0,3 μR/h to 10 μR/h	trenches
3 group	more than 10 μR/h at the depth of 0.1 m from the surface	waste storage

A.4 SUMMARY TABLES ON SOVIET AND CMEA COUNTRY NUCLEAR POWER REACTORS

TABLE A.4.1. Operational USSR Power Reactors

Location	Name	Type	Capacity, MWe	Year in Operation	Reference
Obninsk	AM-1	Pressurized water (PWR), graphite moderated	5	1954	A
"	--	Mobile; PWR	1.5	1961	A
Siberian	Unit 3	LWGR	100	1960	B
"	Unit 4	LWGR	100	1961	B
"	Unit 5	LWGR	100	1962	B
"	Unit 6	LWGR	100	1963	B
Dimitrovgrad	ARBUS	Organic-cooled and -moderated	(0.75)[a]	(1963)[a]	A
(New Melekess)	BOR-60	Boiling water	12	1968	C
"	VK-50	Boiling water; superheat	50	1965	C
Novovoronezh	Unit 3	VVER	440	1972	B
"	Unit 4	VVER	440	1973	B
"	Unit 5	VVER	1000	1981	B
Shevchenko (Caspian Sea)	BN-350	LMFBR	350[b]	1973	B
Bilibino	Unit 1	LWGR	12	1973	D
"	Unit 2	LWGR	12	1974	D
"	Unit 3	LWGR	12	1975	D
"	Unit 4	LWGR	12	1976	D
Kola or Kolsk	Unit 1	VVER	440	1973	B
(Polyarnyye	Unit 2	VVER	440	1975	B
Zori, Murmansk)	Unit 3	VVER	440	1982	B
"	Unit 4	VVER	440	1984	B
Sosnoviy Bor, Leningrad	Unit 1	RBMK	1000	1974	B
	Unit 2	RBMK	1000	1976	B
"	Unit 3	RBMK	1000	1980	B
"	Unit 4	RBMK	1000	1981	B
Kursk	Unit 1	RBMK	1000	1977	B
(Kurchatov, Kursk)	Unit 2	RBMK	1000	1979	B
	Unit 3	RBMK	1000	1984	B
"	Unit 4	RBMK	1000	1986	B
Chernobyl	Unit 1	RBMK	1000	1978	B
(Pripyat, Ukraine)	Unit 2	RBMK	1000	1979	B
"	Unit 3	RBMK	1000	1982	B
Beloyarsk (Zarechnyy, Sverdlovsk)	BN-600	LMFBR	600	1981	B

TABLE A.4.1. (contd)

Location	Name	Type	Capacity, MWe	Year in Operation	Reference
Rovno					
(Kuznetsovsk,	Unit 1	VVER	402	1981	B
West Ukraine)	Unit 2	VVER	416	1982	B
	Unit 3	VVER	1000	1987	B
Smolensk	Unit 1	RBMK	1000	1983	B
(Desnogorsk, Smolemsk)	Unit 2	RBMK	1000	1985	B
"	Unit 3	RBMK	1000	1990	B
South Ukraine or					
Konstantinovka or	Unit 1	VVER	1000	1983	B
Nikolaivev	Unit 2	VVER	1000	1985	B
	Unit 3	VVER	1000	1989	B
Ignalina	Unit 1	RBMK	1500	1985	B
(Snieckus, Lithuania)	Unit 2	RBMK	1500	1987	B
Kalinin	Unit 1	VVER	1000	1985	B
(Udomlya, Kalinin)	Unit 2	VVER	1000	1987	B
Zaporozhye	Unit 1	VVER	1000	1985	B
(Energodar, Ukraine)	Unit 2	VVER	1000	1985	B
	Unit 3	VVER	1000	1987	B
	Unit 4	VVER	1000	1988	B
	Unit 5	VVER	1000	1989	B
Balakovo	Unit 1	VVER	1000	1986	B
(Balakovo, Saratov)	Unit 2	VVER	1000	1988	B
	Unit 3	VVER	1000	1989	B
Khmel'nitskiy					
(Neteshin,	Unit 1	VVER	1000	1988	B
West Ukraine)					

References:

A = Seaborg, et al., May 1963. Atomic Energy in the Soviet Union, Trip Report of the U.S. Atomic Energy Delegation, U.S. Atomic Energy Commission, Washington D.C., May 1963.

B = Nuclear News, August 1990, pp. 79-81

C = Katsman, David. 1986. Soviet Nuclear Power Plants: Reactor Types, Water and Chemical Control Systems, Turbines. Delphic Associates, Inc.

D = Atomnaya Energiya, November 1977.

Notes:

(a) Data in parentheses represent estimates.

(b) Plant also desalinates 120,000 cubic meters of seawater per day, or about 200 MWe equivalent.

TABLE A.4.2. Decommissioned USSR Power Reactors

Location	Name	Type	Capacity, MWe	Year in Operation	Date Decommissioned	Reference
Chernobyl	Unit 4	RBMK[a]	1000	1983	1986	A
Beloyarsk (Zarechnyy, Sverdlovsk)	AMB-1	Boiling water; superheat; graphite moderated[b]	100	1963	1987	B, C, D
	AMB-2	Boiling water; superheat; graphite moderated[c]	200	1967	1989	B, C, E
Novovoronezh	Unit 1	VVER[d]	210	1964	1988	A, B
	Unit 2	VVER[e]	365	1969	1990	C, F
Oktemberyan, Armenia	Unit 1	VVER[f]	408	1976	1989	C, G
"	Unit 2	VVER[f]	408	1979	1989	C, G
Siberian	Unit 1	LWGR	100	1958	1990	H
	Unit 2	LWGR	100	1959	1989	H

References:

A = Nuclear News, February 1989.
B = Seaborg, G. S., et al. 1963. Atomic Energy in the Soviet Union, Trip Report of the U.S. Atomic Energy Delegation, U.S. Atomic Energy Commission, Washington D.C., May 1963.
C = Atomnaya Energiya, November 1977.
D = Nuclear News, August 1987.
E = Nucleonics Week, March 22, 1990, pp. 6-7.
F = Nucleonics Week, March 14, 1991, pp. 5-6.
G = Nucleonics Week, March 9, 1989, p. 3.
H = Nuclear News, August 1990, p. 81.

Notes:

(a) Unit 4 was destroyed in an accident on April 26, 1986.
(b) Plant was taken off line for decommissioning in 1987, Reference D.
(c) Plant was taken off line for decommissioning in October 1989, Reference E.
(d) Plant was taken off line for decommissioning in 1988, Reference A. (It was noted that the plant was shut down in 1984, according to information given during a U.S. National Academy of Sciences tour February 12-23, 1990 to the USSR).
(e) Plant was taken off line in 1990 for decommissioning, Reference F.
(f) Units 1 and 2 were shut down in February and March of 1989, respectively, for conversion to a fossil-fired plant (Reference G).

TABLE A.4.3. Countries with VVER Reactors Operating or Under Construction (Nuclear News 8/90)

Location	Name	Capacity, MWe	Year in Operation
Bulgaria	Kozloduy -1	440	1974
"	" -2	"	1975
"	" -3	"	1981
"	" -4	"	1982
"	" -5	1000	1988
"	" -6	"	1990
"	Belene -1	"	1992
"	" -2	"	1994
Cuba	Juragua -1	"	1995
"	" -2	"	1997
Czechoslovakia	Bohunice -1	440	1979
"	" -2	"	1981
"	" -3	"	1985
"	" -4	"	1986
"	Dukovany -1	"	1985
"	" -2	"	1986
"	" -3	"	1987
"	" -4	"	1987
"	Mochovce -1	"	1991
"	" -2	"	1992
"	" -3	"	1992
"	" -4	"	1993
"	Temelin -1	1000	1992
"	" -2	"	1994
"	" -3	"	1995[a]
"	" -4	"	1997[a]
Finland	Loviisa -1	"	1977
"	" -2	"	1981
Germany (Dem. Rep.)	Rheinsberg-1	70	1966[b]
"	Nord -1	440	1974[c]
"	" -2	"	1975[c]
"	" -3	"	1978[c]
"	" -4	"	1979[c]
"	" -5	"	1990
"	" -6	"	1992
"	" -7	"	1994
"	" -8	"	1995
"	Stendal -1	1000	--
"	" -2	"	--

TABLE A.4.3. (contd)

Location	Name	Capacity, MWe	Year in Operation
Hungary	Paks -1	440	1983
"	" -2	"	1984
"	" -3	"	1986
"	" -4	"	1987
"	" -5	1000	--(d)
"	" -6	"	--(d)
Poland	Zarnowiec -1	"	1992(e)
"	" -2	"	1992(e)
"	" -3	"	1994(e)
"	" -4	"	1995(e)

References

Nuclear News 8/89 unless otherwise noted.

(a) Cancelled, as reported in the Washington Post 5/15/90, p. A-12.

(b) Shutdown in 1990, as reported in Sovetskaya Rossiya 10/23/90.

(c) Shut down in 1990, as reported in Nuclear News July 1990, p. 55.

(d) Cancelled, as reported in Nuclear News 2/1990, and Nucleonics Week 9/13/90.

(e) Indefinitely postponed, as reported in the Washington Post 5/15/90, pp. A-12 and suspended until the year 2000, as reported in Nucleonics Week 9/13/90, p. 1.

INDEX

END

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