4. RADIATION ACCIDENTS

Radiation accidents may be viewed as unusual exposure events which provide possible high exposures to a few people and, in the case of nuclear plant events, low exposures to large populations. A number of radiation accidents have occurred over the past 50 years involving radiation producing machines, radioactive materials, and uncontrolled nuclear reactors. These accidents have resulted in a number of people being exposed to a range of internal and external radiation doses, and those involving radioactive materials have involved multiple routes of exposure. Some of the more important accidents involving significant radiation doses or releases of radioactive material, including any known health effects, are discussed below. It is important to carefully and critically assess each individual accident in order to identify the causes and then to implement indicated corrective measures that will prevent a recurrence. An analysis of the common characteristics of accidents is useful in resolving overarching issues, as has been done following nuclear power, industrial radiography, and medical accidents. Success in avoiding accidents and responding when they do occur requires planning in order to have adequately trained and prepared health physics organization; well-defined dose limits and action levels; a well-developed instrument program; close cooperation among radiation protection, experts, local and state authorities, and emergency responders; and solid communication among response groups, the medical community, the media, and the public (Morgan and Turner 1973). Focus is given to the successful avoidance of accidents and the response in the event they do occur. Examples of some accidents are discussed below.

4.1 PALOMARES, SPAIN

From the 1950s through the late 1960s, the Strategic Air Command (SAC) conducted Operation Chrome Dome which, in the interest of national defense, required the Air Force to fly aircraft carrying nuclear weapons around the world 24 hours a day. On January 16, 1966, two B-52 airplanes, each carrying four thermonuclear weapons containing ^{239}Pu, flew to the southern fringes of the former Soviet Union. On their return trip to the United States, one collided in mid-air with a KC-135 tanker aircraft during a refueling operation over Spain. After fire erupted on the planes, the B-52 broke apart and scattered all four nuclear weapons. The weapons were dispersed over Palomares, a town located in a remote area of Spain. Two weapons landed without incident, one in the water and the other on the beach near Palomares, and both were recovered. The third weapon landed in low mountains west of the town, and the fourth landed on agricultural land to the east. The high explosives in these last two weapons detonated and burned, causing some of the plutonium inside to also burn and spread plutonium contamination throughout the area. There were chemical but no nuclear explosions (Civil Defense Technology Workshop 1995).

Partial chemical burning of the fissile material from the two bombs that had been blown apart by their high explosive charges resulted in a cloud formation which was dispersed by a 35-mph wind. Approximately 2.25 km^2 of farmland was contaminated with plutonium at levels of 50–500 $\mu g/m^2$ (3–32 $\mu Ci/m^2$), and low levels of plutonium were detectable for a distance of 2 miles. Initially, 630 acres of land were reported to be contaminated; however, an additional 20 acres were subsequently classified as contaminated due to resuspension by the wind. The primary form of income for the citizens of Palomares was their tomato crop. The U.S. government purchased the tomato crop for a total of $250,000. These mildly contaminated tomatoes were washed free of contamination and were considered safe to eat. Crops in highly contaminated fields where levels exceeded 5 μg/m2 (0.3 $\mu Ci/m^2$) were dug up and burned in open-pit fires, which further spread the contamination.

An agreement between the United States and Spain called for removing the top 10 cm (4 inches) of soil in areas contaminated with more than 32 $\mu Ci/m^2$ (500 $\mu g/m^2$). This resulted in the removal of 1,100 m^3 of soil. The decontamination procedure required 747 people and 8 weeks of labor and resulted in the filling of 4,879 metal 55-gallon drums with contaminated soil. Soil with surface contamination levels between approximately 5 and 500 $\mu g/m^2$ was mixed with petroleum oil, plowed under to a depth of 8 inches, and then covered over with another layer of top soil. Following this decontamination, the concentration of activity in surface soil averaged 1 μg/g, with a maximum of 40 μg/g. The plutonium concentration in plants ranged from uncontaminated to 30 times the ambient level in Spain. The Air Force contracted 140 trucks to move 3,400 truck loads of replacement soil from a dry river bed. These actions essentially destroyed all of the indigenous population's crop lands. All soil levels greater than 462 $\mu g/m^2$, together with other contaminated materials, were transferred to the United States for burial. All but two of the barrels were shipped to the Savannah Naval Storage Facility in Aiken, South Carolina. The other two barrels were sent to Los Alamos National Laboratories in New Mexico, where they are still being monitored and tested (Civil Defense Technology Workshop 1995; Shapiro 1990; UNSCEAR 1993). No plutonium was found in the 100 residents of Palomares who were the most likely to have been exposed. The potential dose to the lungs, bone surface, and bone marrow of the local residents has been estimated to be much less than the ICRP recommended limits (Iranzo et al. 1987). Follow-up studies on this group of exposed individuals are not likely to provide useful information on the long-term effects of plutonium exposure in humans.

The Spanish government, concerned about public perception and panic, prohibited the U.S. Air Force cleanup crews from wearing anti-contamination suits or full face masks. Only uniforms, hats, and surgical gloves with tape over the openings between gloves and clothing were permitted. This resulted in internal contamination of some service members, who were monitored by urinalysis for plutonium content. Data indicate that a small number registered readily measurable levels, and some of those levels decreased to below detection limits in a few months. Long-term monitoring of the others was eventually discontinued. Counter to U.S. recommendations, civilians were not restricted in their movements in or around the area. In the hilly, rocky area surrounding the impact site of the fourth weapon, it proved impossible to reach the initial cleanup standards set by the Spanish Government, so the limits for this area were adjusted to meet the conditions, with the agreement that the area would not be used for agriculture. Where the soil could not be removed, the workers soaked it with water to force the contamination into the soil. This area has never been restricted by local authorities, and, although the local population was warned that the area was contaminated, Spanish citizens eventually began to farm some of this land (Civil Defense Technology Workshop 1995). Six years after the incident, follow-up studies found that there was little change in the community and in exposed persons (Shapiro 1990). Of the 714 people examined through 1988, 124 had urine concentrations of plutonium greater than the minimum detection limits (MDLs).

4.2. GOIANIA, BRAZIL

On September 13, 1987, two scavengers found an abandoned teletherapy device in an abandoned medical clinic in Goiania, Brazil. The machine contained a radioactive ^{137}Cs source with an activity of 1,375 Ci (50.9 TBq) in the form of powdered and soluble $^{137}CsCl$. After removing the source from its shield, they took it home and, in a crude attempt to break it apart, managed to rupture the source and spread pieces about the property. Both became ill within hours. Either 1 or 5 days later, according to various versions of the story, the device became the property of a junk dealer. This dealer noticed a luminescence emanating from the unit and used tools to cut the unit apart to gain access to the material inside. The rupture allowed the $^{137}CsCl$ powder to disperse easily and be further distributed by wind suspension and rainwater runoff. Several land areas and 129 people were significantly contaminated, resulting in four deaths and one forearm amputation (Amaral et al. 1991; Rosenthal et al. 1991).

Initial External Response. On September 29, 1987, the Secretary of Health for the State of Goiania allowed a local physicist to notify the Department of Nuclear Installations (DNI) which, in turn, notified the National Nuclear Energy Commission (CNEN) in Rio de Janeiro. The Director of DNI and technicians from the Institute of Nuclear Energy research (IPEN) left that day and arrived in Goiania the next morning (Moreira 1991). The abandoned hospital was searched first, but there was no source of contamination. Next, the houses of presumably contaminated patients were checked and contamination was found. A detailed search found 7 highly contaminated areas that included 2 houses, 4 lots, and the Public Hygiene Control Unit. Part of the original source was found at this unit. Testing showed maximum radiation readings of 1,000 rem/hr (10 Sv/hr) on contact and 40 rem/hr (0.4 Sv/hr) at 1 meter. The source was shielded with concrete for personnel protection. That night the Goiania task force developed its site action plan.

Initial Patient Management. The accident primarily exposed or contaminated about 80 people, who were all related, and an additional 170 were later contaminated to much lower levels. Initially, 11 individuals who had handled the source and who were the most highly contaminated were taken to the Hospital of Tropical Diseases or to the Santa Maria Hospital. The most highly contaminated of these were then transported to the Marcilio Dias Naval Hospital in Rio de Janeiro. People from the primary contamination zones were assessed and, based on clinical findings, sent to Goiania Hospital, FEBEM, or the House of the Good Shepherd. Twenty-two people who were evacuated from contaminated homes were taken to Olympic Stadium, and others who were in the vicinity were encouraged to go there. In a prioritized manner, the contaminated victims were provided with medical care, clean clothing, nourishment and orientation, and contamination monitoring; the public was informed. Because of exaggerated claims of water contamination by the press, an additional 112,000 unaffected individuals went to Olympic Stadium for monitoring. A total of 249 were found to be contaminated. About half had shoe and clothing contamination, that could have been picked up from walking in the stadium. Of the other 129, who were both internally and externally contaminated, 21 required intense medical treatment. Ten of these were seriously compromised, four died, and one required forearm amputation (Brandao-Mello et al. 1991; Oliveira et al. 1991a, 1991b).

Contamination Spread. The ^{137}Cs contamination was spread by social contacts, the sale of contaminated material, the movement of pieces of the source, and wind and rain dispersal (Amaral et al. 1991; Becker et al. 1991; da Silva et al. 1991; Godoy et al. 1991). Contamination was found on 7 major properties; in 42 residences, including 22 homes of family and friends who were evacuated and 20 others where radiation levels ranged from 0.1 to 1 rem/hr (1–10 mSv/hr); and on 68 of the more than 10 million currency bills tested. The population was internally exposed by inhalation and the ingestion of fruits and vegetables, and externally exposed to the penetrating ^{137}Cs gamma radiation, but the drinking water supply was found to be clean.

Contaminated materials in the environment were removed from the various sites and loaded into containers, with liquids being immobilized in concrete. Decontamination limits for solids were set by the national standard. Anything contaminated below 74 kBq/kg was considered to be clean and unaffected by the accident. Contamination level was characterized by the contact radiation level, with values of 0.2 and 2 rem/hr (2 and 20 mSv/hr) being the respective limits for low- and medium-level contamination. An estimated 1,200 Ci (44 TBq) of ^{137}Cs was recaptured during the decontamination effort, which left the area with no significant residual hazard (Rosenthal et al. 1991).

The type of media coverage of this accident caused a psychological impact on a community with recent memories of the Chernobyl reactor accident in the former Soviet Union. The situation improved when the news media refocused their efforts toward balanced reporting and public education.

4.3 THULE, GREENLAND

In January 1968, a U.S. Air Force plane experienced an on-board fire and subsequently crashed while attempting an emergency landing near Thule, Greenland. The plane was carrying four unarmed 1.1-megaton nuclear weapons; although the nuclear weapons did not detonate, the conventional explosives of the weapons exploded on impact, depositing an inventory of 1 TBq (27 Ci) combined ^{239}Pu and ^{240}Pu, 0.02 TBq (0.54 Ci) ^{238}Pu, and 0.1 TBq (0.27 Ci) ^{241}Am; igniting fuel; and creating an intense fire that burned for almost 4 hours. The force of the crash and explosions resulted in the spread of plutonium-laden debris over an area approximately 100 m by 700 m. The burning plutonium was converted mainly into insoluble oxides and dispersed as fine particles. Measurements of ^{239}Pu and ^{240}Pu

indicated that the radionuclides preferentially deposited in the fine-grained bottom sediments covering the basins in the vicinity of the crash site. Follow-up investigations found that plutonium levels in bivalves and crustacea to be increased by a factor of 10–1,000 over pre-accident levels (Aarkrog 1971, 1994; Handler 1992; Shapiro 1990; Smith et al. 1994).

The cleanup effort, called project Crested Ice, lasted 8 months and resulted in the shipping of almost 240,000 tons of contaminated ice and snow to the United States. About 99% of the plutonium was contained in the blackened ice at the crash site; this was recovered by road graders and mechanized loaders scraping away the affected ice. A total of sixty-seven 25,000-gallon fuel tanks were filled with debris and four additional containers were used for storing contaminated recovery equipment and gear. The materials were shipped to the United States for disposal. Although low-level contamination was detected on land close to the crash site, it is believed that minimal amounts of plutonium escaped from the crash site. No significant radionuclide exposure and no long-term effects to neighboring populations were expected (Handler 1992; Shapiro 1990).

4.4 ROCKY FLATS, COLORADO

The Rocky Flats Nuclear Weapons Plant, located approximately 15 miles from Denver, Colorado, occupies approximately 2 square miles of federally owned land. Approximately 2.2 million people from the 8-county Denver metropolitan area live within a 52-mile radius of the facility. As of December 1995, there were approximately 4,700 employees at the Rocky Flats facility. Since beginning operations in 1953, the plant has been a major processor of plutonium. During the Cold War, Rocky Flats was responsible for the fabrication of the hollow plutonium sphere, or "pit," that serves as nuclear fuel for nuclear warheads. Rocky Flats also was responsible for recycling plutonium retrieved from retired nuclear warheads. A high-tech machine shop produced other weapons parts from stainless steel, beryllium, depleted uranium, and other metals.

Due to its proximity to an urban area (Denver, Colorado) and because its property boundaries border two creeks feeding public waters, there is a potential for public exposure to radioactive material following an accident at this plant. Several significant incidents have occurred at this plant: two fires in 1957 and 1969 and leakage of plutonium-contaminated cutting oils from storage drums (Rocky Flats Citizens Advisory Board 1995; Shapiro 1990).

Probably no individual location at the Rocky Flats site has achieved more attention than the site known as the 903 Pad. In the late 1950s and early 1960s, Rocky Flats stored barrels at this location which were filled with plutonium-contaminated oil left over from the pit manufacturing operations. Over time, many of the oil barrels had corroded, allowing the contaminated oil to spill out onto the ground. The leakage was first detected in 1964, and efforts to prevent the spread of leakage were initiated the same year. Managers at the site attempted to solve the problem by removing all of the barrels and cleaning up the storage area. However, the cleanup effort resulted in the disturbance of the contaminated soil, and the radioactive dust was picked up and spread further by the high winds that are common at Rocky Flats. The Health Advisory Panel overseeing the Dose Reconstruction Project for the Colorado Department of Public Health and Environment lists the 903 Pad as one of the major contributors to off-site contamination from Rocky Flats (Rocky Flats Citizens Advisory Board 1995; Shapiro 1990).

The first of two major fires at the Rocky Flats facility occurred on the evening of September 11, 1957, when some of the plutonium on the glove box line spontaneously ignited. Although the area was designed to be fireproof, it was soon engulfed in flames. Firemen switched on ventilating fans, which ultimately spread the flames to contact more plutonium. Attempts to quench the fire with carbon dioxide also failed. Meanwhile, the filters designed to trap plutonium escaping up the stacks caught fire. The shift captain and other observers reported a billowing black cloud pouring some 80–160 feet into the air above the 150-foot-high stack. When the carbon dioxide gas failed to extinguish the fire, the firefighters began pouring water into the blaze. The fire was extinguished roughly 13 hours after it began. Some 14–20 kg of plutonium were estimated to have burned in the fire, not including plutonium liberated from the burning filters. In addition, the water used to extinguish the fire became contaminated with radioactive material, and approximately 30,000 gallons of it escaped unfiltered, spreading contamination into local streams and into the water table. Although some of the buildings were heavily contaminated, plutonium pit production was back under way within a few days (Wasserman et al. 1982).

The fire in 1969 also started with the spontaneous ignition of plutonium metal. Several kilograms of plutonium burned and the resulting smoke plume spread to surrounding areas. Soil samples collected from 15 locations ranged from background levels of 20 pCi/kg (0.7 Bq/kg) of material to 6,000 pCi/kg (220 Bq/kg) in the top centimeter; 7 water samples ranged from 0.001 to 0.2 pCi/L (10^{-5} to 10^{-2} Bq/L. Another study in 1970 of soil samples to a depth of 20 cm found levels up to 2 Ci/km^2 (70,000 MBq/km^2) at sites adjacent to the property boundaries (Shapiro 1990).

Johnson (1981) examined the relation between cancer rates and plutonium exposures using cancer diagnosis data for 1969–1971 and plutonium exposures estimated from an analysis of soil samples collected near Rocky Flats in 1970. Johnson claimed to have found increases in many cancer types for persons in exposed areas, as compared with those for unexposed areas. However, a feasibility study for an epidemiologic study of persons who lived near the plant concluded that exposures were not high enough to be evaluated statistically (Dreyer et al. 1982). Cobb et al. (1982) compared plutonium concentrations in autopsy samples from persons who lived near Rocky Flats with those who lived far from the plant. A weak relation between plutonium concentrations in autopsy samples and distance from Rocky Flats was detected; however, these authors did not believe that the elevated concentrations could be conclusively linked to emissions from Rocky Flats. Crump et al. (1987) re-evaluated cancer diagnosis data for 1969–1971 and for 1979–1981 using the study designed by Johnson (1981). For both study periods, the authors found no increase in cancer rates for combined cancers, for radiation-sensitive cancers, or for cancers of the respiratory system in those living within 10 miles of Rocky Flats. A National Cancer Institute (NCI) study of cancer incidence and mortality around nuclear facilities in the United States found slight elevations for some cancers in some age groups among those living near the Rocky Flats facility; however, the study should be interpreted with caution because county-by-county cancer mortality data were used and because of limited information on potential confounding factors (Jablon et al. 1990), and because it appears that plutonium exposures were not detectable.

4.5 THREE MILE ISLAND, PENNSYLVANIA

On March 28, 1979, an accident occurred at the unit 2 civilian nuclear power reactor at Three Mile Island (TMI). Figure 4-1 is a simplified diagram of the TMI pressurized water nuclear reactor design. Under normal operating conditions, the control rods are withdrawn from the reactor core to produce power, and water from the principal source (#1) circulates through the core and a primary heat exchange loop. A secondary water source (#2) is in standby. To prevent a major accident, it is imperative that the reactor core be submerged in water at all times. Although the water should never be allowed to boil inside

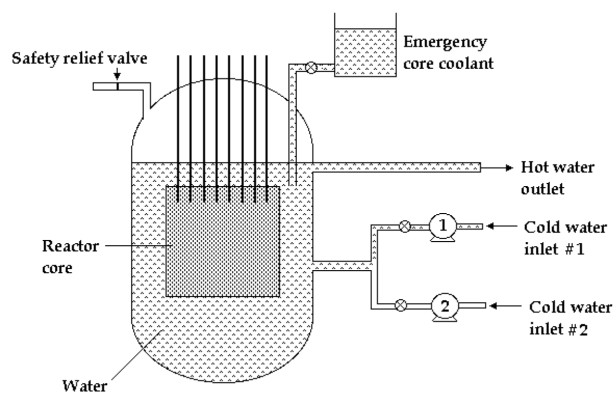

Figure 4-1. Schematic of Three Mile Island Unit 2 Nuclear Reactor (adapted from PSU 1999)

the pressure vessel, a pressure safety relief valve exists to release steam to an alternate collection location in the event of inadvertent boiling; during normal operation, this valve is closed. During shutdown, there is no chain reaction, but the cooling water continues to circulate through the core to remove the heat generated by the decay of the radioactive fission products in the fuel rods.

In the TMI incident, water from supply #1, which returns condensed steam from the steam generators, was interrupted because the feed water pumps that pumped water from the reactor to the reactor's steam generators stopped. The loss of water flow resulted in a loss of cooling of the reactor core. The operators immediately switched on the emergency feedwater pumps. However, the water did not enter into the cooling loop because the valve was accidentally left closed the previous day following a scheduled maintenance activity (the reactor operators didn't realize this). Emergency water injection pumps started automatically, but an operator misinterpreted the gauge readings and reduced the flow. The water overheated and steam bubbles began forming. The operators responded improperly, draining water out of the system, exacerbating the coolant problems. The fuel heated up and partially melted, releasing radioactive material into the remaining coolant, which continued flowing out of the reactor through the relief valve and onto the containment room floor (Eisenbud 1987; PSU 1999; Shapiro 1990).

The cleanup is still in progress at a cost that has already exceeded 1 billion dollars. The high cost is not only due to the cleanup itself, but to the research into the materials and their behavior during the accident. This has made the cleanup a huge research project. However, very little radioactivity was released to the environment. The main contaminants reaching the environment were ^{133}Xe and ^{131}I, with total releases of approximately 370 PBq (10 MCi) and 550 GBq (14.85 Ci), respectively. The actual quantity of ^{131}I released was much smaller than the overconservative models of the time projected. Subsequent research confirmed previous scientific studies which showed that hot iodine is very reactive; during the accident, much of the iodine plated out on the concrete and structural metal components inside the containment dome, greatly limiting the quantity released. The average dose to the general public within 80 km was estimated to be 0.0015 rem (0.000015 Sv), and the highest dose was estimated to be 0.085 rem (0.00085 Sv), mainly in the form of external gamma radiation. In contrast, the average annual radiation dose from natural radiation is approximately 0.3 rem (0.003 Sv), of which 0.036 rem (0.00036 Sv) is from radioactive material naturally inside the human body (PSU 1999; UNSCEAR 1993). No radiation effects have been reported among the surrounding population because population exposures were small relative to normal background radiation. Psychological effects have been documented at TMI. One cause was the very large ^{131}I release estimates that were projected using models known to be overconservative, and another was the emotional political response and media coverage which projected fetal health outcomes based on those projected releases and uninformed reporting. Public panic ensued despite the small radiation doses. Research in the aftermath led regulators to accept more realistic radionuclide release models on which to base emergency response recommendations. Lessons learned from this event include the need to accurately project releases of radioactive material and to keep the news media accurately informed of the situation and response actions. The media must then make the decision to provide fair and balanced coverage in the public interest.

4.6 CHERNOBYL, UKRAINE

In April 1986, an accident at the civilian nuclear reactor facility at Chernobyl in the former USSR, resulted in the largest accidental release of radioactive material to date. The RBMK-1000 reactors utilized at Chernobyl have a design flaw that makes their operation at low power unstable. In this mode of operation, any increase in the production of steam can boost the rate of energy production in the reactor. If that extra energy generates still more steam, the result can be a runaway power surge. While performing an unauthorized engineering test on a generator, instabilities developed in the reactor system which could not be controlled; the operators had deliberately disabled safety systems that could have averted the reactor's loss of control because the safety systems might have interfered with the performance of the test. At 1:23 a.m, an operator pressed a button to activate the automatic protection system, but by this time it was too late.

Within 3 seconds, the fission rate in the reactor dramatically increased to hundreds of times the normal operating level. The fuel temperature consequently rose within seconds to beyond the melting point of uranium dioxide (2,760 EC; 5,000 EF). The resulting steam explosion lifted the 90-ton covering of the reactor, destroyed the roof, and ejected fuel debris from the facility (Figure 4-2). Molten nuclear fuel and graphite from the reactor core caused fires in and around the reactor that burned for 10 days.

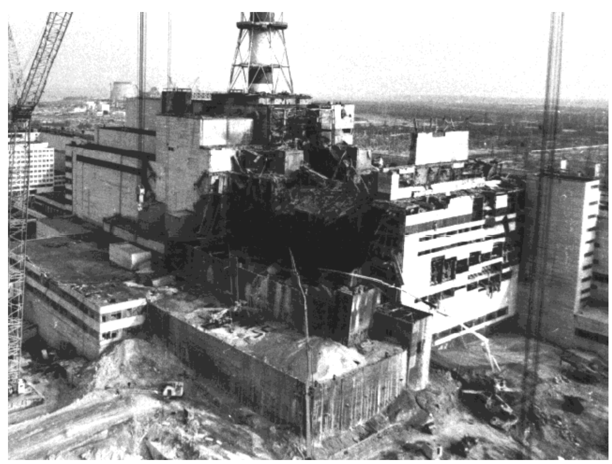

Figure 4-2. Aerial View of the Damaged Chernobyl Reactor Facility
(adapted from http://193.125.172.36/www-klae/POLYN/history.html)

Efforts to quench the flames included dumping 5,000 tons of various materials (boron carbide, dolomite, sand-clay mixture, and lead) by helicopter. By the time the fires were extinguished, 250 tons of graphite had been consumed by the fires (Shapiro 1990; Shcherbak 1996). The total release of radioactive material from Chernobyl was estimated to be 1–2 EBq (27–54 MCi). The major radionuclides released were ^{131}I (630 PBq; 17.0 MCi), ^{134}Cs (35 PBq; 0.95 MCi), and ^{137}Cs (70 PBq; 1.9 MCi). A plume containing these radionuclides moved with the prevailing winds to the north and west, and then east around the world, transporting the radioactive material thousands of miles (Figure 4-3).

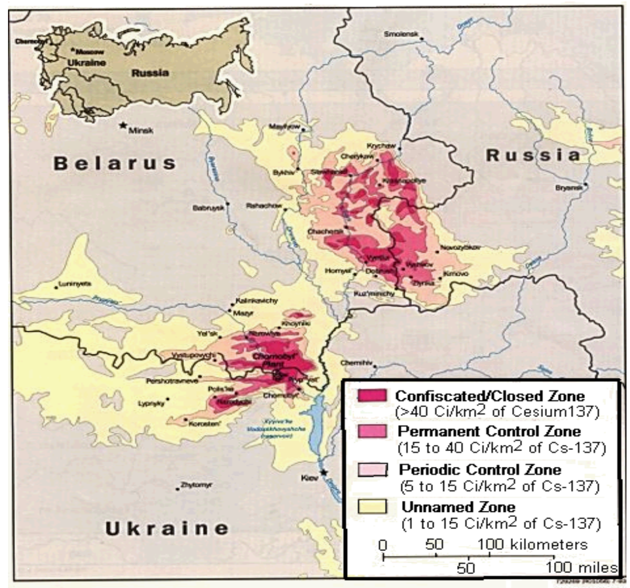

Figure 4-3. Hot Spots of Radioactivity in Regions Surrounding the Chernobyl Facility (BRAMA 1996)

The deposition on the ground varied considerably during the accident due to variations in temperature and other atmospheric conditions during the release. ^{137}Cs was the main contributor to the radiation doses received by the population once the short-lived ^{131}I had decayed. The three main areas of ^{137}Cs contamination resulting from the Chernobyl accident were identified as the Central, Bryansk-Belarus, and Kaluga-Tula-Orel spots. The central spot, formed during the initial, active stage of the release, had ground depositions of ^{137}Cs of more than 40 kBq/m^2 (1.1 µCi/m^2) over large areas of Northern Ukraine and Southern Belarus. The most highly contaminated area was the 30-km zone surrounding the reactor, where ^{137}Cs ground depositions exceeded 1,500 kBq/m^2 (40.5 µCi/m^2). The Bryansk-Belarus spot, centered 200 km to the north-northeast of the reactor, was formed as a result of rainfall on the region. The ground depositions of ^{137}Cs in the most highly contaminated areas reached 5,000 kBq/m^2 (135.1 µCi/m^2) in some villages. The Kaluga-Tula-Orel spot, approximately 500 km northeast of the reactor in Russia, was also formed as a result of rainfall; the levels of ^{137}Cs deposition in this area were usually less than 600 kBq/m^2 (16.2 µCi/m^2). Outside the three main hot spots there were many areas in the European territory of the former Soviet Union contaminated with ^{137}Cs at levels ranging from 40 to

200 kBq/m^2 (1.1–5.4 $\mu Ci/m^2$). Overall, the territory of the former Soviet Union initially contained approximately 3,100 km^2 contaminated by ^{137}Cs at levels exceeding 1,500 kBq/m^2 (40.5 $\mu Ci/m^2$); 7,200 km^2 with levels of 600–1,500 kBq/m^2 (16.2–40.5 $\mu Ci/m^2$); and 103,000 km^2 with levels of 40–200 kBq/m^2 (1.1–5.4 $\mu Ci/m^2$) (NEA 1995). The regions affected included not only the Ukraine, Belarus, and Russia, but also Georgia, Finland, Poland, Sweden, Germany, Turkey, and other countries. Even such distant lands as the United States and Japan received measurable amounts of radioactive material. In Poland, Germany, Austria, and Hungary as well as in the Ukraine, some crops and milk were contaminated and had to be destroyed, while others were destroyed out of panic. In Finland, Sweden, and Norway, carcasses of reindeer that had grazed on contaminated vegetation were destroyed (Shcherbak 1996; UNSCEAR 1993).

A total of 237 plant workers and firefighters suffered from ARS (Shapiro 1990). Within 3 months, the death toll from the incident was 30 persons; all of the deceased were either plant operators or firefighters (UNSCEAR 1993). Approximately 15,000 persons from the plant or surrounding communities were reported to have lost their ability to work as a result of diseases which they claimed could be attributed to radiation exposure including: gastrointestinal (inflammatory immediately after the accident and ulcerative in later years); immunological; metabolic (5–6 year latency period); respiratory (chronic obstructive bronchitis); hemopoietic (increase or decrease in white blood cell numbers); and neuropathologies (reduced mental capacity, inability to estimate one's own abilities). In addition, 12,000 children received large doses to the thyroid, and 9,000 persons were exposed *in utero*. An increase in thyroid cancer among those who had been exposed as children is the only major public health effect documented and authenticated to date. An investigation of brain damage *in utero*, performed by the International Programme on the Health Effects of the Chernobyl Accident (IPHECA), found some evidence of retarded mental development and deviations in behavioral and emotional reactions in exposed children; however, the extent to which radiation contributed to these problems could not be determined due to the lack of individual dosimetry data (Bebeshko 1995; WHO 1995). By 1992, the frequency of occurrence of thyroid cancer had increased dramatically in the children of Belarus, but these data may be difficult to interpret because of endemic goiter in the population. The pattern of the increases was not uniform but was correlated with those areas in the direct path of the radioactive fallout (Kazakov et al. 1992). Other health-related side effects of the accident included: radiophobia, an increase in stress-related illnesses due to both fear of radiation and to the dislocation of people; poor diets due to stringent safeguards against potentially contaminated food, that may have led to vitamin deficiencies; the aborting of as many as 200,000 healthy fetuses because of concern that they might have been damaged in the womb by minor radiation exposures; and an increase in alcoholism following the accident (Atomic Energy Insights 1996).

About 200,000 people involved in the initial cleanup received an average whole-body dose on the order of 10 rem (0.1 Sv). An exclusion zone (within 30 km [18.6 mi] of the reactor) was established that required the evacuation of 116,000 of the surrounding residents. Fewer than 10% of these people received doses greater than 5 rem (0.05 Sv), and the dose to more than 95% of these was less than 10 rem (0.10 Sv), but exceeded 30–40 rem (0.3–0.4 Sv) in some cases. In contrast, the average annual radiation dose from background radiation is approximately 0.36 rem (0.0036 Sv). A total of 786 settlements in Belarus, the Russian Federation, and the Ukraine were declared strict control zones. In the settlements, food consumption was restricted as a protective measure. The average dose during the first year to persons in these settlements was 3.7 rem (0.037 Sv); in 2 subsequent years, average annual doses were approximately 2.3 rem (0.023 Sv) (UNSCEAR 1993).

Figure 4-4. A View of the Sarcophagus Covering the Chernobyl Reactor Facility
(adapted from http://193.125.172.36/www-kiae/POLYN/history.html)

The collective dose (the sum of all individual doses) from the Chernobyl accident has been estimated to be 600,000 man•Sv. The majority of this dose is expected to be received by the population in the former USSR (40%) and Europe (57%). The remainder (3%) is expected to be dispersed over other countries of the northern hemisphere (UNSCEAR 1993). Direct costs of the accident, due to loss of the facility, firefighting, and relocating citizens, approached $7 billion (Shapiro 1990). This figure does not include current or predicted future medical expenses. The explosion left approximately 180 metric tons of fuel exposed to the atmosphere. In an attempt to prevent the further escape of radiation, the Ukrainian government built a concrete covering over the entire facility, referred to as the sarcophagus (Figure 4-4), beginning in May 1986 and completed in November of that year. However, the sarcophagus is not leak-tight. There is concern that rainwater and wind might enter the structure and disperse some of the residual contamination to the environment (NEI 1995).

4.7 KYSHTYM

In September 1957, a major accident occurred at the Chelyabinsk-40 military plutonium production facility near Kyshtym in the southern Ural mountains of the former Soviet Union. The facility, built in 1953, had a number of underground steel storage tanks equipped with cooling systems to store high-level waste so that it would not be dumped in the River Techna. These high-level wastes overheated when the cooling system failed. The heat buildup resulted in evaporation of the coolant water, which allowed the sediment to heat further and dry. The chemicals in the tank exploded on September 29, 1957, with an explosive power of 70–100 tons of TNT, which hurled the 2.5-m-thick concrete lid 25–30 m away. The radioactive cloud from the explosion reached about 1 km. Due to calm wind conditions, about 90% of the materials deposited locally, while 100 PBq (2.7 MCi) was dispersed away from the plant in an oblong fallout pattern about 300 km in length, including parts of Chelyabinsk, Sverdlovsk, and Tyumen counties. Almost all of the radioactive fallout occurred within the first 11 hours (UNSCEAR 1993; Wasserman et al. 1982).

The major contaminants released were ^{144}Ce, ^{95}Zr, ^{95}Nb, and ^{90}Sr. Most fission products deposited on the ground, allowing the strontium isotopes to enter the food chain. A ban on food containing ^{90}Sr at concentrations greater than 2.4 Bq/g (64.8 pCi/g) resulted in the destruction of 10,000 tons of agricultural produce in the first 2 years. All stores in Kamensk-Uralskiy which sold milk, meat, and other foodstuffs were closed as a precaution against consuming radioactive material, and new supplies were brought in 2 days later by train and truck. Approximately 10,000 people were evacuated from the high-contamination area, while approximately 260,000 people remained in less contaminated areas. The highest individual doses were experienced by those evacuated within a few days of the accident. These individuals received an average external dose of 17 rem (0.17 Sv) and an average internal (gastrointestinal) dose of 150 rem (1.5 Sv); the average effective dose equivalent was approximately 52 rem (0.52 Sv). The average 30-year committed dose for persons living in areas with a ^{90}Sr surface contamination level of 40–70 kBq/m^2 (1.1–1.9 μCi/km^2) was estimated to be 2 rem (0.02 Sv) (CIA 1959; UNSCEAR 1993).

4.8 WINDSCALE, U.K.

In October 1957, the first substantially publicized release of radioactive material from a nuclear reactor accident occurred at the Windscale nuclear weapons plant at Sellafield in the United Kingdom. During a routine release of stored energy from the graphite core of a carbon dioxide-cooled, graphite-moderated reactor, operator error allowed the fuel to overheat. This led to uranium oxidation and a subsequent graphite fire. Attempts to extinguish the fire with carbon dioxide were ineffective. In the end, water was applied directly to the fuel channels but not before the fire had burned for 3 days, resulting in the release of ^{131}I (740 TBq; 20 kCi), ^{137}Cs (22 TBq; 0.6 kCi), ^{210}Po (8.8 TBq; 0.2 kCi), ^{106}Ru (3 TBq; 0.08 kCi), and ^{133}Xe (1.2 PBq; 32.4 kCi). The fire consumed much of the uranium fuel, and some of the resulting fallout was in the form of flake-like uranium oxide varying in size from 1 to 25 cm (Schultz 1996; UNSCEAR 1993).

The contamination of pastureland was widespread; for those in close proximity to the accident, the greatest threat of exposure was considered to be from ^{131}I via contaminated cow's milk. Those living farther from the accident were exposed to significant amounts of ^{131}I via milk consumption and air inhalation. The consumption of cow's milk was quickly banned; this lessened the exposure to ^{131}I. The highest individual doses (approximately 100 mGy) were to the thyroids of children living near the accident site. The collective dose equivalent received in the United Kingdom and the rest of Europe was estimated to be 2,000 man•Sv, of which 900 man•Sv was from inhalation, 800 man•Sv was from ingestion, and 300 man•Sv was from external exposure. The main radionuclides contributing to the exposures were ^{131}I (37%), ^{210}Po (37%), and ^{137}Cs (15%) (UNSCEAR 1993). There has been no detected impact on the health of the public from this accident.

4.9 TOMSK

An incident occurred at a plant near Tomsk in the Russian federation in 1993 in which individual exposures were low and few in number. The Tomsk site featured one of Russia's three operating plutonium production reactors. The Tomsk reactors were built to produce plutonium and to supply steam for the city's district heating plant. Reprocessing, which involves the use of chemical processes to separate uranium and plutonium from spent nuclear fuel, occurs at the plant. Under certain conditions, the chemical solutions can cause an explosion. In April 1993, a tank containing a blend of paraffin and tributyl phosphate chemically exploded, resulting in the involuntary release of uranium, plutonium, niobium, zirconium and ruthenium. The tank had a volume of 34.1 m^3, and held 25 m^3 of solution. The solution contained 8,773 kg of uranium, and about 310 kg of plutonium. The total amount of radioactivity in the solution was approximately 20.7 TBq (559.3 Ci). The explosion caused substantial damage to the facility and contaminated a largely unpopulated area of about 123 km^2. The release from the tank was estimated to be 4.3 TBq (115 Ci) of long-lived isotopes. Radioactive material spread to the north-east and fallout was detected over an area of 120 km^3. Gamma radiation 20 times higher than the norm was measured in the area that received the most fallout. The personnel who assisted in putting out the flames received the maximum radiation dose of 2 mSv (200 mrem). The accident could have had more serious local consequences if the wind had carried the contamination to two large nearby cities. In June 1993, DOE officials visited Tomsk to investigate the accident. Although they were not permitted to view the chemical tank that had exploded, they did see other parts of the facility. Several operational errors, such as improper mixing of chemicals in the reprocessing tank, and possible design flaws, such as inadequate tank ventilation, were identified as contributors to the accident (GAO 1995; Nilsen 1997; OTA 1994; UNSCEAR 1993).

4.10 LOST INDUSTRIAL OR MEDICAL SOURCES

Four incidents in which sealed sources of radiation intended for industrial or medical use were lost or damaged have occurred since 1982.

In 1983, an obsolete teletherapy machine from a hospital in Ciudad Juarez, Mexico, containing 16.7 TBq of ^{60}Co was sold as scrap metal. As a result, thousands of tons of steel products sold in Mexico and the United States, as well as several foundries and streets and hundreds of houses, were contaminated and approximately 1,000 people were exposed to an approximate dose of 0.025 rem (0.25 mSv). About 80 people received doses of 0.25–3 Sv (25–300 rem), and 700 people received doses of 0.005–0.25 Sv (0.5–25 rem) (UNSCEAR 1993). No deaths resulted from this exposure.

In 1984, a family in Morocco found and kept within their house a sealed radiography source containing ^{192}Ir. The source was used to radiograph (make x-ray-like pictures) to noninvasively check the integrity of metal welds at construction sites. The capsule holding the source became disconnected from the restraint system inside the source shield and fell out of the shield. A passer-by found the source and took it home, consequently exposing himself and his family. The resultant effective doses were estimated to be 800–2,500 rem (8–25 Sv); 8 members of the family died (UNSCEAR 1993). A poorly designed source- capsule-locking device along with personnel error on the part of the contractor led to these deaths and injuries. Radiography source-locking mechanisms have been redesigned to help prevent such accidents from occurring.

In Goiania, Brazil, in 1987, 54 people were hospitalized and 4 died after removing a teletherapy source containing ^{137}Cs from its enclosure. Individual doses were estimated to range up to 500 rad (5 Gy) (UNSCEAR 1993). This accident is described in more detail in Section 4.2.

In 1992, in the Shanxi province of China, three people in one family died after a member found a ^{60}Co source. The U.S. Nuclear Regulatory Commission has published a safety document that describes the acute health effects of these types of radiation accidents (USNRC 1982).

4.11 IDENTIFICATION OF DATA NEEDS

The following has been identified as a potential data need regarding health effects associated with exposure to ionizing radiation.

A number of people have been exposed to a range of radiation doses as a result of the accidents discussed in this chapter. Some human data do exist on the health effects associated with acute exposure to ionizing radiation (see Chapters 3 and 5); however, most of the radiological effects have been derived from laboratory animal data. It would be helpful to estimate the dose of radiation each of these individuals was exposed to and monitor these people over the long term to determine what health effects (if any) these doses of ionizing radiation had on lifespan, cancer rates, and reproductive effects. There is ongoing research in these areas, mainly the observation of the survivors of the nuclear bombings in Japan and their children and grandchildren by the Radiation Effects Research Foundation (RERF). The RERF is a binational agency that is supported by the United States and Japan.

4.12 CONCLUSIONS

Although most radiation to which the public is exposed is of natural origin, that portion arising from human activities, particularly accidental releases, is perceived by the public to be a very serious threat to health. For the majority of the world's population, less than 1% of radiation exposure arises from nuclear weapons testing fallout and the generation of electricity in nuclear, coal (many coal-fired electric generating stations emit more radioactivity than do nuclear stations), and geothermal power plants. Selected military and civilian accidents have resulted in the exposure of certain populations to substantial amounts of radiation. Few exposures of general populations have been of sufficient size to produce quantifiable deleterious effects. The thyroid cancer rates (the only type of excess cancer seen to date) associated with the Chernobyl accident have begun to rise. After the Hiroshima and Nagasaki bombings, there was a surge of childhood leukemia cases into the 1950s (Pierce et al. 1996). There are also elevated incidence rates for some cancers in the population exposed by the Hiroshima and Nagasaki bombings. To date, there have been about 500 excess deaths from cancer among the survivors of the bombings. The circumstances and results of nuclear power plant accidents indicate that rapid mobilization of clean-up efforts, imposed dietary restrictions, and evacuation of residents (especially pregnant women) minimizes the public risk. Three-Mile Island and Chernobyl are cases in which the evacuations caused a health detriment and a health benefit, respectively.

4.13 OTHER SOURCES OF INFORMATION

This chapter provided a brief synopsis of population exposures to ionizing radiation. Readers are encouraged to read Chapters 2 through 6 of this toxicological profile for more in-depth information on the basic principles of ionizing radiation, the health effects of ionizing radiation, and the sources of population exposure to ionizing radiation. Further scientific information can be obtained from the United Nations specialized agencies, such as the World Health Organization (WHO), Geneva, Switzerland, and the International Atomic Energy Agency (IAEA), Vienna, Austria. Readers are also referred to the Internet sites listed in Table 4-1 for further information on the general principles and health effect issues involving the different types and doses of ionizing radiation. These sites are sponsored by scientific, government, and academic organizations.

Table 4-1. Internet Sites Pertaining to Population Exposures to Ionizing Radiation

HyperText Transfer Protocol (HTTP) Address	Web Page Contents
http://www.hps.org	The Health Physics Society, a scientific organization dealing with radiation safety
http://www.rerf.or.jp	Atomic bomb survivor studies provide by Radiation Effects Research Foundation, a joint Japanese-U.S. sponsored research organization
http://www.sandia.gov/LabNews/LN01-19-96/palo.html	A newspaper for the employees of Sandia National Laboratories and recounts the Palomares incident
http://fema.gov/home/fema/radiolo.htm	Federal Emergency Management Agency information on how to prepare for an emergency and what to do if an accident occurs
http://www.radres.org/intro.htm	The Radiation Research Society
http://www.afrri.usuhs.mil/www/index.html	The Armed Forces Radiobiology Research Institute
http://cedr.lbl.gov	Comprehensive epidemiologic data resource related to radiological releases from sites
http://radefx.bcm.tmc.edu/	Radiation Health Effects Research Resource page. A comprehensive page on radiation and health effects, including extensive literature searches on Chernobyl health effects