Nuclear-Reactor Incidents

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Background and Nature of Nuclear-Reactor Incidents

Introduction

Initial interest in nuclear fission centered on its potential as a weapon. However, by 1953 the United States Government determined that nuclear power should be developed as an energy resource, and the Atomic Energy Commission (AEC) began to promote the construction of reactors by private industry. By 1963, success had been marginal, and 23 reactors were wholly or partially owned by the Government. Private industry had begun work on seven reactors, but all were regarded as experimental or demonstration facilities. The use of nuclear power has increased since that time. However, in 1979 in the United States only 8% of the electricity was generated from nuclear power, compared with 18% in Switzerland and 15% in Germany (1). In 1983, 76 nuclear reactors operating commercially in 27 states produced about 12% of the electrical energy in the United States

As the use of atomic power expanded, the risks associated with reactors became apparent. In the period 1950-1970, five U S. nuclear reactors were damaged substantially by incidents. An incident at Idaho Falls Sl-1 experimental reactor led to radiation exposure of the public, though at low levels. Exposure to the public from the incident at the Three Mile Island, Pennsylvania, reactor in 1979 was also minimal, but the damage to the reactor itself was severe. The incident at Chernobyl, in the Soviet Union, involved massive damage to the reactor core as well as substantial exposures to large numbers of people.

A radiologic incident can result in both acute, direct exposure of the public to the radioactive plume, as well as longer-term exposure to radionuclides deposited on food crops or in water. Similarly, the public health consequences of radiologic incidents can be acute or long-term. Acute health effects from radiation—such as vomiting and diarrhea—occur only in association with relatively high doses. In most cases, the long-term increase in the risk of cancer or genetic defects is of primary concern. Protection of the public from nuclear incidents begins with the design and siting of nuclear facilities and includes emergency-response planning and preparedness.

Characteristics of Nuclear Reactors

In any complex industrial process, incidents should be anticipated. A nuclear reactor has unique characteristics that pose special problems for emergency planners. To prevent or prepare for a radiologic incident, emergency planners must first understand how a nuclear reactor functions. In the reactor vessel or core, uranium (or, in some cases, thorium) nuclei are split by neutrons, and thermal energy is released. Two or more smaller atoms are created from the fission of each large uranium nucleus. Many of these new atoms are radioactive. These products of fission and the isotopes produced as they decay make up the core inventory. The fission process and the decaying of the products of fission generate heat that is removed by a coolant system (usually water) for conversion into steam and finally into electricity.

The uranium is packed inside fuel rods arranged in specific patterns within the core. During normal operation, fission products are trapped inside the fuel rods, but if heat builds up inside the core, the fuel cladding can melt and release fission products such as radioactive noble gases, iodines, cesium, and others. Fuel elements can also be damaged by chemical fires or explosions within the core. With commercial reactors, a containment building surrounds the core to provide physical containment of fission products and house mechanical safety features—including emergency cooling and filtration systems. These safety systems are designed to prevent a release of radioactive material into the environment. For example, filters can trap most large particulates and reactive compounds before they reach the environment. However, a release to the environment can occur if safety systems or the containment building are damaged by mechanical failure, human error, or a natural disaster such as an earthquake.

The Nuclear Fuel Cycle

Incidents can happen at any processing or transportation phase within the nuclear fuel cycle and during storage of spent fuel, so that environmental releases may involve a variety of chemicals, uranium compounds, or fission products. The operation of the nuclear reactor is only one step in the fuel cycle. Uranium must first be mined and milled to produce yellow cake, a combination of all uranium isotopes. Since only certain isotopes can be fissioned in a reactor, the yellow cake is chemically processed and changed into a gaseous compound for enrichment. The fissionable isotopes are then separated and concentrated into a solid uranium oxide. Uranium oxide is shaped into pellets at a fuel fabrication facility and loaded into fuel rods. A fuel rod may last 3-4 years in a reactor before being removed to a waste-storage facility (2). Because the issue of permanent disposal of this high-level waste has not been resolved, spent fuel rods are usually stored on site in special tanks with coolant systems to prevent the buildup of heat from the decay of fission products. Any operation that requires movement of the fuel rods within or out of the core (or within the storage facility) increases the risk of an incident that could cause a release of fission products similar to those that would be released during an incident within the reactor core.

The processing of uranium involves a variety of hazardous chemicals, which could be released during an incident. For example, the incident in December 1985 at a uranium processing plant in Gore, Oklahoma, produced a cloud of hydrogen fluoride. One worker was killed and others were hospitalized from the acute effects of this vapor (3). Chemicals such as hydrazine and chlorine are used and stored at nuclear power facilities and could be released into water supplies or into the atmosphere during a fire or other incident. A partial list of the chemicals used at nuclear reactors and their potential health effects is shown in Table 1 (4,5).

TABLE 1. Chemicals used at nuclear power plants

Chemical	Health effects
Sulfuric acid	Irritating to eyes, skin, mucous membranes, and respiratory tract
Chlorine	Irritating to skin, eyes, mucous membranes; may cause nausea, vomiting, and acute respiratory distress
Ammonia	Irritating to skin, eyes, mucous membranes, may cause headache, burning of the throat, nausea, and vomiting
Sodium hydroxide	Corrosive to body tissues; may cause blindness, cutaneous burns, pulmonary irritation
Hydrazine	Irritating to eyes, upper respiratory tract; may cause skin burns, severe dermatitis, dizziness, nausea, animal carcinogen

Sources References 4,5.

Public Health Consequences of Nuclear-Reactor Incidents

Routes of Exposure

A plume of airborne particulates and inert gases from the plant is the principal source of public exposure during most nuclear-reactor incidents. The first exposure pathways are external from being immersed in the plume or internal from inhaling gases or particulates. The plume is composed primarily of noble gases (e.g., krypton, xenon), organic, and inorganic iodides, and volatile inorganic material. The period of release may be short (a few hours) or last for over a month or more.

If the original release contains primarily inert radioactive gases, surface contamination and the resultant potential for long-term exposure will be minimal. However, if large quantities of particulates are released from the plant, surface contamination will be a substantial and long-term source of exposure. Occupants of a contaminated area could receive excessive whole-body or skin doses from radionuclides on the ground, cars, machinery, or on and within their own homes. Long after the initial release from the plant, public exposure from radionuclides deposited on the ground, food crops, or water can continue both by direct external radiation and through a number of ingestion pathways. Radionuclides can be ingested directly by drinking contaminated surface water or by eating fruits and vegetables coated by radioactive particulates. In addition, indirect pathways can develop through the food chain. For example, cows eating or drinking contaminated feed or water will produce milk containing radionuclides—most commonly iodine, strontium, or cesium. Food crops absorb radionuclides from the soil so that long-term contamination of locally grown fruits and vegetables or animal feed can be a serious health concern.

Potential Health Effects

ACUTE

A number of adverse health effects can be caused by a nuclear-reactor incident Health effects can result from direct injury (e g., burns associated with a break in a steam pipe), from the stress of the situation (e.g., myocardial infarction, psychological distress), or from exposure to radioactive material or chemicals released during the incident. Only radiation exposures that have adverse health effects are considered here because they are unique to radiologic incidents.

The biological effects of radiation exposure depend on the absorbed dose, the type of radiation, the rate of exposure and how much of the body and which organs are exposed (e g., thyroid gland) (6). The absorbed dose is the amount of energy (measured in **rads** or **grays**) deposited in the body during radiation exposure. Different types of radiation (e.g., gamma rays, beta particles, alpha particles) produce different tissue damage at the same absorbed doses. Gamma radiation is electromagnetic radiation like ordinary light but is able to penetrate the body, and beta and alpha radiation are accelerated particles released by the nucleus during radioactive decay. A single radioisotope may emit more than one type of radiation. Because these types of radiation can affect tissues differently at the same dose, the absorbed dose is often multiplied by a quality factor to give what is called the dose equivalent (measured in **rems** or **sieverts**) so that exposures can be compared.

Exposure of part of the body such as an arm or leg or a single organ is less damaging than exposure of the whole body to the same dose. Dose rate is also a significant factor in determining the type of biological response. Because of the body's repair mechanisms, the effects from a dose of 500 rem delivered instantaneously is quite different from those caused by the same dose given over a month or more. In general, adverse health effects increase with the combination of the total dose, the proportion of the body exposed, and the exposure rate.

Because genetic material is particularly sensitive to radiation, tissues that divide rapidly (e.g., blood-forming tissues, intestinal-lining cells) are more sensitive to damage than those that divide more slowly (e.g., muscles, nervous-system tissues). After an acute, whole-body dose of < 100 rems, an individual may have no outward symptoms, but may show increased chromosomal aberrations in blood lymphocytes and a decrease in blood count. A higher dose may produce acute radiation syndrome, an illness with dose-dependent symptoms. Acute, whole-body doses of > 100 rems may cause vomiting, hemorrhage, and an increased risk of infection due to reduced white-blood-cell counts. Treatment may include antibiotic therapy, blood transfusions, and possibly bone-marrow transplantation. Acute, whole-body doses of $> 1{,}000$ rems will damage the gastrointestional tract, provoking diarrhea and electrolyte imbalance, and may affect the central nervous system to cause seizures, gait disturbances, and coma. Ninety percent of persons exposed to such doses will die. Such acute, whole-body-radiation exposures in peacetime are very rare (7-9).

CHRONIC

More pertinent to most nuclear-reactor incidents are delayed effects from exposure to lower levels of radiation (10). Data on the biological effects of radiation have been collected from animal studies and studies of humans exposed to diagnostic (e g., children exposed prenatally to abdominal X-ray examination of their mothers during pregnancy), therapeutic (e.g., treatment for ankylosing spondylitis), inadvertent occupational (e.g., radium-dial painters, uranium miners), and wartime irradiation (e.g., survivors of the atomic bombing of Hiroshima and Nagasaki in World War II). These studies provide evidence for three types of delayed effects: somatic effects for the exposed person, teratogenic effects for the fetus exposed in utero, and genetic effects for the offspring of the exposed person.

The main somatic effect of radiation exposures is cancer—especially leukemia and breast, thyroid, and lung cancer. According to current estimates of the risk from low-level radiation exposure, a whole-body dose of 1 rem increases an individual's lifetime risk of dying from any cancer by about 0.01% (10). The principal teratogenic effects described in studies of survivors of the atomic bombings of Nagasaki and Hiroshima have been mental retardation and reduced head size, especially persons who were exposed as fetuses 6-12 weeks post-conception. After 12 weeks of gestation, maternal exposure to significant quantities of radioactive iodine can destroy the fetal thyroid gland. Genetic effects among the offspring of the exposed population may include mutations. The estimated risk of mutations is about 1/1,000 live-born offspring/rem of parental exposure before conception, compared with a background rate of 107 gene mutations from other causes/1,000 live-born offspring.

None of these risk estimates are precise because they are extrapolated to low levels from relatively high radiation exposures. The exact risk at low levels of exposure is not known. Because the interaction of radiation with human tissue is believed to be harmful even at low levels, radiation exposures beyond natural background radiation and diagnostic or therapeutic exposures should be minimized.

Risk Factors for Exposure and Health Effects

The risk factors for exposure during a radiologic release are numerous. Obviously, both living adjacent to and downwind from a nuclear power plant increase an individual's chance of exposure if an incident occurs. Persons such as farmers or construction workers who work outdoors are also at additional risk because they probably take longer to return home for sheltering or evacuation. To alert these people in case of an incident, sirens should be used to supplement radio or television warnings. In addition, systems should be developed for alerting the hard of hearing. People who have difficulty evacuating are also at risk. For example, the handicapped, nursing-home and hospital patients, and prisoners require special aid and additional time to evacuate. In areas surrounding nuclear facilities, individuals who will need assistance should be identified as part of the local emergency-response planning. Plans should also be developed to alert local schools, hospitals, and prisons of any unintentional release. Some populations more sensitive to radiation exposure, such as children and fetuses, require extra consideration when protective actions are implemented. For example, children and pregnant women may be evacuated before the rest of the population or when lower exposure levels are expected. By developing county and state emergency response plans, additional risk to these special groups can be reduced.

Many of the risk factors for long-term environmental exposure after the plume has passed are identical to factors that can increase exposure during a radioactive release. Children and fetuses are more sensitive to radiation effects from external or internal exposure. Children are more vulnerable to exposure from radioisotopes in milk because they generally drink more milk than adults. People who live in rural areas and people of low economic status may eat more locally grown fruits and vegetables and are at greater risk of ingesting contamination. A population that uses surface water such as that from reservoirs or rivers may receive additional exposure from drinking water contaminated by surface runoff or by direct deposition from the plume.

Preventive and Control Measures

Design and Placement Factors

The prevention of a nuclear-reactor incident should be part of the planning stages of a plant. The choice of plant location involves geographic and meteorologic considerations. A site should not be selected in an area with high seismic activity (5), although it may not be possible to choose a site with no history of seismic vibrations. The probability of earthquakes can be estimated for a general area based on past seismic activity and the location of faults. The site should not be located in areas such as a flood plains or in tornado- or hurricane-prone areas. The potential health effects from a release can also be limited by locating the plant in an area with a low population density and establishing an uninhabited area around the plant to act as a barrier between the reactor and the population.

After the site is selected, the plant should be designed in accord with the conditions at that particular site. Special construction features can increase the safety of the plant. In areas in which tornadoes or earthquakes may occur, the plant should be built to withstand high winds and impact from blowing debris in tornados or vibrations from minor earthquakes.

Factors Relating to Plant Operation

Despite the fact that many of a nuclear reactor's safety systems are computer-controlled, operators are essential to the safe operation of the plant. To lower the probability of human error, plant personnel are trained to respond to unusual conditions within the plant and are assigned specific responsibilities during an incident. However, fatigue from rotating shifts, boredom, and inadequate training or supervision can lead to serious human error. In fact, all radiologic incidents can be partially attributed to human error. To deter deliberate sabotage of the reactor, security systems can be used to prevent unauthorized personnel from being on site and to limit access to sensitive areas of the plant.

Offsite, elected officials and emergency workers such as fire fighters and policemen should also learn to assist in activities such as evacuation and to protect themselves and others from radiation hazards. State and Federal emergency-response plans provide a blueprint for agencies to respond to emergencies and minimize—to the extent possible—errors in human judgment during an incident.

Reducing Off-Site Exposures During a Radiologic Release

The U.S. Environmental Protection Agency (EPA) has set "protective action guides," which are levels at which action should be taken to lower the potential radiation exposure of the public. These doses are not actual exposures but are projected or estimated doses if no action is taken. For the general population, EPA recommends that protective action be taken if the projected thyroid dose is 5-25 rem or if the whole-body dose is 1-5 rem (11). However, more stringent limits may be applied by state health authorities, particularly for pregnant women and children. Protective actions may include evacuation, sheltering, or respiratory protection in addition to, or in place of, administering potassium iodide (KI)

In the event of a nuclear-power-plant incident, actions to minimize or eliminate exposure of the public begin in the period between the realization that a potentially serious problem is developing and the actual release of radioactive material. If a safety system or other component of a reactor is damaged or malfunctions, Federal emergency-response plans require that local, state, and Federal officials be notified. The degree of response by state and Federal agencies depends on the severity of the incident and the size of the potentially exposed population. Federal and state activity increases dramatically if a release is imminent. Decisions to initiate a particular protective action are based on factors such as local weather conditions as well as the conditions at the plant, which determine the probability of a release and which isotopes will be released. To be effective, all protective actions should meet the following criteria (9).

- The action must be effective in reducing or preventing exposure to the public and must not carry health risks greater than those of the incident itself.
- The implementation must be feasible both logistically and financially.
- The agency or agencies responsible for implementing the protective action must be clearly identified, and the authority to implement the action must exist.
- The action must not have a large economic impact on the public, business, industry, or government compared with the health and economic impacts of the incident.

IMMEDIATE PROTECTIVE ACTION

In the early stages of an incident, a number of actions can be implemented to protect the public. One of the first decisions to be made is whether to advise evacuation or whether to advise residents to remain in their homes with windows and doors shut and ventilation turned off while the radioactive plume passes. Together, sheltering and respiratory protection in the form of wet handkerchiefs or towels can lower the inhalation of particulates but not of noble gases (12). Sheltering can also reduce gamma exposure from the plume by a factor of 2-10 (12), but it is a viable alternative only for short periods due to the infiltration of gases and vapors into the dwelling by normal air exchange with outside air. The use of sheltering is questionable if the release period is unpredictable or likely to be longer than several hours. Evacuation is a more costly but generally more effective method for reducing public exposure before a release has occurred. The decision to evacuate must include considerations such as weather conditions (e.g., the presence of a blizzard may make evacuation an unsuitable alternative), the likelihood of a release, the availability of shelters for the evacuees, and the quality of the evacuation routes. If a release has already begun, the benefits of evacuation must be weighed against the increased dose accrued while evacuating.

If radioiodine is released from the plant, the administration of stable iodide in the form of potassium iodide (KI) can lower or block the uptake of radioiodine by the thyroid. However, iodide will not protect against external radiation exposure or exposure to other inhaled radionuclides. To be effective, the iodine must be administered before or shortly after (within 1 day) exposure to radioiodine (11,12). Although some persons may also suffer side effects after taking KI, a risk assessment by the Food and Drug Administration (FDA) indicates that the risk from a projected thyroid dose of $\geq$ 25 rem outweighs the risk from short-term use of KI. During an actual release, the potential dose of radioiodine to the thyroid is estimated using dispersion modeling and the actual conditions at the plant. The decision to use or not use KI and how it should be distributed is left to the individual states (13). However, the rapid distribution of KI tablets required during an emergency is difficult, stockpiling for an unlikely release is costly, and the KI tablets have a limited shelf-life.

LONG-TERM PROTECTIVE ACTIONS

If the external exposure rate from surface contamination is high, residents can be evacuated or, if already evacuated, permanently relocated outside the contaminated area. Additionally, access to highly contaminated areas can be physically restricted to prevent the public from entering. In less severe situations, dilution and removal of contamination can be attempted by washing cars, houses, and streets and by trimming grass and disposing of the clippings (12). Weathering from rain or snow also decreases the concentration of radioisotopes on structures and on the ground surface, although surface runoff may recontaminate local lakes and streams after each heavy rain.

Direct ingestion of contamination can be prevented by supplying fresh drinking water to residents if necessary. Normal food preparation such as peeling or washing can remove the contamination on some fruits and vegetables (13). Food that cannot be appropriately decontaminated may need to be destroyed. Significant contamination of milk can be avoided by providing uncontaminated feed and water to cattle. The success of this action depends on the availability of stored feed and fresh water and the ability of farmers to remove cows from pastures in a short time.

FDA has developed action levels based on the projected doses from food or milk at which protective or emergency actions would be appropriate. According to these guidelines, if the projected dose to the public from food consumption is 0.5 rem whole-body or 1.5 rem to the thyroid, cattle should be given stored feed instead of being allowed to graze. At a projected dose of 5 rem whole body or 15 rem to the thyroid, responsible agencies are expected to prevent the food or milk from entering into commerce either by storage for decay or by condemnation (14). For example, milk contaminated with short-lived isotopes can be diverted into milk products such as cheese. However, storage is not practical if the food or milk is contaminated with long-lived radioisotopes. For local food crops, long-term recommendations must be based on soil concentrations of each radioisotope and on the effectiveness of soil management and decontamination efforts (15).

Reducing the Adverse Health Impact After Exposure

Acute

If, despite precautions to prevent exposure, some persons are exposed through a nuclear-plant incident to external irradiation or internal sources of radiation, morbidity and mortality from these exposures can still be prevented (8,9). In the case of acute exposures, emergency lifesaving assistance to prevent shock from trauma or to maintain respiration has highest priority. Persons exposed to external X-ray, gamma, or other radiation may require symptomatic treatment at a specialized hospital if their whole body dose is > 50 rem. People whose skin or clothing has been contaminated by radioactive material may pose a hazard not only to themselves but also to the hospital environment, staff, and other patients. These people must go through decontamination procedures to avoid adverse health effects and to protect other people from being exposed (16).

Treatment for radiation injuries depends on the degree of exposure and on whether the exposure is internal or external (9,17). It is extremely unlikely that a live patient will be so contaminated as to pose an acute radiation risk to rescue or medical personnel. Therefore, for any acutely exposed radiation victims, the usual priorities of emergency care—the saving of life and the prevention of further injury—take precedence over decontaminating the patient or minimizing exposure of attending personnel.

Assessment of the level of exposure of a hospitalized individual (e.g., a heavily exposed worker) is generally more accurate than assessment of exposure of the general population. Personal dosimeters; direct measurement of radioactivity in and on the body; and clinical assessment of symptoms, signs, and white blood cell counts may provide evidence of the severity of exposure. For the general population, exposures can be estimated from levels of radiation measured by detectors around the plant and factors such as distance and direction from the plant and time spent at different exposed locations (18). Analysis of biological samples as well as whole-body radiation counters can be used to detect internal levels of radioisotopes. Even though studies of chromosomal aberrations in blood lymphocytes may detect exposures as low as 10 rem within a few hours after an incident (9), medical examinations and treatment should be confined to individuals who are highly exposed, or contaminated, or have ingested or inhaled significant quantities of radioactive material.

Chronic

For low-level chronic exposures, both internal and external, it is unclear whether long-term follow-up and monitoring can reduce subsequent morbidity and mortality. Epidemiologic studies based on registries of exposed persons, such as the Three Mile Island Population Registry (18), may provide further information on the effects of low-level radiation, although their low statistical power may make interpretation difficult (19).

History of Nuclear-Reactor Incidents

Many of the major nuclear reactor incidents in the United States have involved test reactors or experimental breeder reactors that create plutonium-238 during the fission process. Four of these incidents did not cause a release of radiologic material to the environment despite damage to the core. These incidents involved the Chalk River Reactor; the Idaho Experimental Breeder, Unit 1; the Westinghouse Test Reactor; and Detroit Edison's Fermi Reactor (breeder). Significant quantities of radioiodine were released during two reactor incidents at facilities in the United States and one in England. Of these, the Windscale reactor in England and the SL-1 reactor in the United States did not have containment buildings and were not for commercial use or power production. However, the incident at Three Mile Island—a commercial reactor—resulted in substantial damage to the core and the release of radioactive noble gases and radioiodine (9). The more recent incident at Chernobyl in the Soviet Union is the most serious incident recorded at any nuclear-power facility, causing massive damage to the core and allowing millions of curies of fission products to escape into the environment. A summary of these incidents is given in Table 2. Descriptions of some of the incidents are presented below.

TABLE 2. Incidents with core damage in nuclear reactors

Description of incident	Site	Date	Adult thyroid dose
			(rem)
Minor core damage (no release of radiologic material)	Chalk River	1952	NA*
	Breeder Reactor, Idaho	1955	NA
	Westinghouse Test Reactor	1960	NA
	Detroit Edison Fermi	1966	NA
Major core damage (radioiodine released)			
Noncommercial	Windscale, England	1957	16
	Idaho Falls SL-1	1961	0.035
Commercial	Three Mile Island	1979	0.005
	Chernobyl, Soviet Union	1986	100†

* Not applicable.

† Estimated median dose

Chernobyl, Soviet Union

Elevated levels of environmental radiation were detected during routine monitoring at a nuclear-power facility in Eastern Sweden on April 28, 1986. The radioactive cloud directed attention eastward into the Soviet Union (20). Shortly afterward, the Russian government reported that an incident had occurred at reactor number four in Chernobyl located in the Ukraine. In fact, on April 26 at 1:23 a.m., an explosion tore open the reactor core, dispersing an estimated 12 million curies of radioisotopes into the environment during the first 24 hours after the incident. Over the next 10 days, another 38 million curies escaped from the burning graphite core (21).

The reactor was one of the many graphite-moderated reactors that produce approximately 4% of the electrical power in the Soviet Union (22) Though construction features of this reactor are unique to Russian graphite-moderated reactors, the basic cause of the incident—human error—is not. The incident started during a test procedure, when critical safety systems were shut down, allowing the reactor to surge out of control in a matter of minutes. Reports on May 2 indicated that all graphite reactors (16-20) had been shut down temporarily because of the incident.

The first reports from the Soviet Union indicated that two workers were killed immediately and that 197 were injured—18 seriously. Immediately after the incident, 1,000-2,000 people were screened for signs of acute radiation exposure, and 400-500 were admitted to hospitals—although only 200 had indications of radiation exposure. Of the persons hospitalized, 80 developed acute radiation syndrome. By June 7, 1987, 27 deaths had been attributed to the incident (23).

Evacuation of the general populace was not begun until April 27, 1986, when at least 49,000 people were relocated. The delay is attributed to administrative issues and a lack of understanding about the seriousness of the incident. A total of 135,000 people were eventually evacuated from the area. By June 1987 two towns within an 18-km area had been reinhabited, and 16 other areas were being prepared for habitation. However, 27 towns have been permanently abandoned because of high levels of contamination (24). Soviet reports indicate that people within 15 km of the plant received doses of 35-50 rem.

Fallout from the incident spread over large parts of Europe during the release. Large variations in the deposition of radionuclides due to rain created localized hot spots. Long-term exposures will continue through the food chain and direct irradiation from deposited radionuclides. The number of future deaths from cancer attributable to radiation exposure can only be speculated about at this time because of the assumptions needed to estimate the total population dose. Although estimates have ranged from 5,000 to 40,000 cancer deaths over the next 70 years, 9.5 million individuals are expected to die of cancer from other causes in the same time period (21). A 2% and 0.001% increase was predicted for teratogenic effects and genetic abnormalities, respectively, affecting babies born within 9 months after the incident (25). However, a study of nervous-system and eye defects in Western Europe indicated an increase in numbers of neural-tube defects only in Odense, Denmark, and no general increase in congenital nervous-system or eye defects (26).

A number of European countries took protective action after the incident. Poland banned the sale of milk from pastured cows and issued potassium iodide to 11 million children. In Romania, children were kept indoors, and the government recommended that fruits and vegetables be washed before being consumed. Without additional information it is difficult to say whether actions taken in these and other European countries were useful in lowering exposures. Some actions, such as distribution of potassium iodide, may have been taken too late to be effective or may have been unnecessary (27). Exposure rates as high as 100 milliroentgen/hour were reported in Belgrade, Yugoslavia. However, without knowledge of how widespread these levels were or how long they existed, the adverse health impact on the population cannot be predicted.

Some Americans who were in Russia during the incident were monitored for radiation when they returned to the United States. Thyroid burdens for these people ranged from undetectable quantities to 270 nanocuries of $iodine^{131}$, which would result in a dose of about 2 rem to the thyroid (28). Exposures in the United States from the fallout were negligible.

Three Mile Island, Pennsylvania

On March 28, 1978, at the Three Mile Island power plant near Middletown, Pennsylvania, a series of mechanical failures and human errors led to a loss of coolant in the Unit 2 reactor, which allowed the fuel to overheat. During the incident, contaminated coolant water was routed out of the containment building into an auxiliary building. Volatile radionuclides escaped through the ventilation system, after passing through a filtration system that removed the chemically active compounds—including most of the radioiodine (2). The principal radionuclides released were xenon and small quantities of iodine (29). During the incident, Pennsylvania Governor Richard Thornburgh advised all people within 10 miles of the plant to remain indoors and recommended that all pregnant women and preschool-age children within 5 miles of the plant evacuate. However, reports after the incident by an interagency dose-assessment group indicated that the largest external dose was < 100 mrem, and the average dose was 1.5 mrem. Health surveys indicate that the most significant health impact from the incident was psychological due to the stress of the incident— not an impact of exposure to radiation (30,31). On the basis of dose calculations, one to two individuals in the exposed population would be expected to develop either cancer or genetic effects from the radiation exposure (4).

Soon after the Three Mile Island incident, the Pennsylvania Department of Health (PDH), with assistance from CDC and the U.S. Bureau of Census, set up a population registry of the nearly 36,000 persons who lived within 5 miles of the plant (32). Each registrant provided information about total time spent in the 5-mile area during the 10 days after the incident so that individual radiation doses could be estimated. Demographic and health-related information was also gathered to use in future epidemiologic studies of adverse health effects. Among women registrants who said they were pregnant at the time of the incident, the estimated incidence of miscarriage before completion of 16 weeks of gestation or of delivery of a dead fetus after 16 weeks of gestation resembled those reported elsewhere in non-exposed populations (33).

The PDH has also collected information on some 8,000 women who lived within 10 miles of the plant and who gave birth within 2 years of the incident, and is conducting studies of cancer incidence and mortality among nearby residents. Persons within 20 miles of the plant reported feeling distressed after the incident, but this dissipated within a month; distrust toward authority, however, persisted much longer (34). Planning responses for emergencies (e.g., centralizing public information, controlling rumors) may reduce this distrust during future incidents (35).

Windscale, England

When the United Kingdom began production of nuclear weapons, plutonium-producing reactors were constructed at a site on the Northwest coast of England called Windscale. In 1957 a fire started in one reactor due to overheating, and a substantial amount of fission products was released. Estimates of the whole-body gamma dose to residents nearby range from 30 to 75 mrem (34). Radioiodine was released during the incident, and protective actions for milk were implemented. The highest thyroid dose was 16 rad for children and 4 rad for adults (35,36). Other food products such as vegetables, meats, and water did not require protective action. Ingestion of radioiodine in milk was considered the most important pathway of exposure.

There is considerable uncertainty about the health impact of radiation released during the Windscale incident and afterward through normal effluents (36-39). More study is needed before conclusions can be drawn about cancer or other health effects from the Windscale incident.

Cheliabinsk, Soviet Union

In 1957, a major incident occurred at a reprocessing facility in the Soviet Union. Although this incident did not occur at a nuclear power plant, the results are typical of what might be expected from a catastrophic incident at a nuclear plant. Details have not been directly reported from the Soviet Union; however, theories about the nature of the incident have been proposed on the basis of reviews of radioecology literature. The release involved a military facility near Kasli in the Cheliabinsk Province. Evidence suggests that improper storage and chemical processing may have caused a single release or a series of radioactive releases. Contamination was extensive and may have resulted in the permanent relocating of residents from an area of 100-1,000 square kilometers. Contamination of a principal river and several lakes and reservoirs was severe enough to warrant relocating the entire populations of several towns (40). Because of the secrecy in the Soviet Union surrounding this incident, little is known in the United States about associated acute or chronic health effects.

Planning for the Future

Probability of Future Incidents

In 1957, the Atomic Energy Commission completed an evaluation of the possible health consequences of an unintentional release of radioisotopes from a nuclear power plant. However, this evaluation did not assess the probability of a particular incident or the effectiveness of engineering safety features built into plants (2). A more thorough study completed in 1975 (41) provided a quantitative and realistic evaluation of the risks to the public from nuclear-reactor incidents, developed methodologies for assessing these risks, evaluated the status of reactor safety, and identified areas requiring additional research. The study addressed only the 100 light-water reactors expected to be in operation in the early 1980s (light-water reactors are the most common commercial reactors, although other types are in operation). This report excludes boiling-water reactors, as well as other commercial reactors, weapons-producing facilities, and reactors in other countries.

For purposes of risk assessment, possible health effects from a release were divided into five categories: all fatalities within 1 year, all fatalities from cancer, injuries requiring treatment, thyroid injuries requiring treatment, and genetic effects (8). This report predicted that the probability of an incident that could cause approximately one of each of these health effects was 1 in 200/year/100 operating reactors. The most serious incident evaluated in the report would cause 1,500 cases of cancer/year in the 10-40 years after an incident. The probability of this type of incident was calculated to be 1 in 10 million/year (2,18). The potential error in this type of prediction can be several orders of magnitude since the sequences of incidents and the success of engineering safeguards must be predicted by mathematical models whose accuracy cannot be tested

Surveillance for Incidents

The Nuclear Regulatory Commission (NRC) and the Federal Emergency Management Agency (FEMA) have established a system to identify unusual occurrences at nuclear facilities. The operator of a nuclear power facility must notify the NRC of changes in the plant's normal status so that officials can prepare to respond immediately to any release that occurs (9). A tiered classification system based on four emergency action levels defines the severity of the status of a reactor and the potential for a release. Investigation of reports of unusual occurrences can clarify the types of incidents that occur at a nuclear facility. Other nuclear-power-plant operators are notified of the results from these investigations so that they can evaluate the safety of their own procedures and avoid similar incidents. The emergency action levels defined by NRC are described in Table 3.

Emergency-Response Planning

Since the Three Mile Island incident in 1979, FEMA has developed a national contingency plan, the Federal Radiological Emergency Response Plan (FRERP), to coordinate Federal response to peacetime radiologic emergencies (42). The FRERP describes the Federal government's concept of operations for responding to radiologic emergencies, outlines Federal policies and planning assumptions that underlie this concept of operations and on which Federal agency response plans (in addition to their agency-specific policies) are based, and specifies authorities and responsibilities of each Federal agency that may play a substantial role in dealing with such emergencies (43).

Individual Federal agencies (e.g , Department of Health and Human Services, Centers for Disease Control) have developed their own more specific plans applicable to their unique capabilities and responsibilities (43). All operating nuclear-power-plant sites have state and local offsite emergency-preparedness plans, but they have not all been approved by FEMA. The General Accounting Office has reported to the U.S. Congress on "...further actions needed to improve emergency preparedness around nuclear power plants," especially the need for better centralized Federal agency control and coordination (44).

"Tabletop" and field exercises are regularly conducted by FEMA to test Federal plans for radiologic emergency response. All agencies with primary responsibility participate in these exercises to test their own readiness and to refine the Federal response plan. State and local officials also participate in these FEMA-sponsored exercises so that methods for local, state, and Federal interactions can be developed. However, no exercise can fully test an emergency-response plan or can fully anticipate political, economic, or social issues that may drive public health recommendations during an emergency.

TABLE 3. Emergency action levels defined by the Nuclear Regulatory Commission

Emergency action level	Plant status
Notification of unusual event	Potential degradation of the normal level of plant safety with no release of radioactivity requiring offsite response
Alert	Actual or potential degradation of plant safety at a substantial level; any potential release expected to be well below established emergency action levels
Site-area emergency	Actual or probable failure of safety systems that normally provide protection for the public; potential releases not expected to exceed established action levels except at plant boundary
General emergency	Actual or imminent core degradation or melt down with a potential for loss of containment protection; potential releases expected to exceed established action levels

Recommendations

1. Education about the potential risks from nuclear reactors, the effects of any radiologic release, and protective actions that can be taken in the event of a release may alleviate the mental stress from a future incident and minimize inappropriate or unnecessary action by the public.

2. More research is needed on ways to control human error associated with radiologic incidents. Appropriate questions include: Should safety systems be designed so that plant operators cannot turn them off? Should rotating shifts be eliminated? Do current training programs need improvement? How can quality work be maintained during off-shifts such as weekends or nights?

3. Since incidents can occur throughout the nuclear fuel cycle, Federal emergency-response planning should place more emphasis on planning for incidents at all parts of the cycle rather than concentrating efforts solely on preparation for a catastrophic event at a nuclear power reactor.

4. Additional research is needed to determine which isotopes will most likely pose the greatest source of exposure during a variety of release scenarios. Until the TMI incident, emergency plans for reactors centered around a large release of radioiodine. However, during the TMI incident, significantly less radioiodine was released than expected; and at Chernobyl, long-lived isotopes pose a more significant hazard than would have been estimated previously.

5. There is a continuing need within state and Federal agencies for expertise in emergency response and radiologic safety. Methods for building current resources need to be investigated.

6. More concrete guidance to states on the efficiency of stockpiling potassium iodide or distributing it during an incident is needed.

7. Traditional methods for treating victims of a major radiologic incident need to be re-evaluated in view of the experience gained during the treatment for trauma or severe radiation exposure at Chernobyl

Summary and Conclusions

The reactor core is the central component of a nuclear power plant. However, complex mechanical systems cool and protect the reactor, convert the thermal energy to electricity, and filter effluents. Natural disasters, mechanical failures, and human errors can all contribute toward an incident by damaging the safety systems or the core itself. A release of radioactive material such as noble gases and radioiodine is most likely to be caused by a series of malfunctions or errors rather than by a single event. To prevent exposures, nuclear power plants can be designed to minimize the possibility of an incident caused by a natural disaster or mechanical failure. Plant personnel can also be trained to maintain safety systems within the plant and to response appropriately if an incident does occur.

Health effects from a radiologic release can be acute or long-term. Relatively high doses of radiation can damage the bone marrow, intestinal lining, and the nervous system depending on the magnitude of the exposure. Cancer or genetic defects induced by radiation exposure may not appear until many years after exposure and may be induced by low levels of exposure. Chemicals stored on-site at nuclear facilities can also pose a health hazard during an incident. To prevent adverse health effects from an incident at a nuclear facility, exposure to the public can be avoided or reduced when an incident occurs. The public around a nuclear plant can be evacuated or sheltered before or during an unintentional release to prevent external exposure and inhalation of radioisotopes. After the release has ended, food and water pathways as well as surface contamination can be important sources of exposure Supplying fresh food and water can minimize direct ingestion of radioisotopes. However, radionuclides can also build up in food chains (e.g , the cow to milk to human pathway) and may require different strategies to prevent exposure. If exposure occurs despite protective actions, morbidity and mortality can be reduced through medical care for acute effects and possibly through long-term screening for cancer.

Populations and individuals that are more sensitive to radiation may be at higher risk from an incident. Children and fetuses are more sensitive to radiation effects than adults and are more likely to be exposed through the cow-milk pathway than adults. Individuals living closest to a reactor are at higher risk of exposure during an incident, as are persons who work outdoors. Individuals who eat vegetables and fruit from local gardens are more likely to ingest radionuclides through food pathways. The elderly, handicapped, or hospitalized require special assistance during an emergency. Protective actions to reduce the risk for sensitive populations and other individuals from a radiologic release should be addressed in radiologic emergency-response plans.

Although major incidents at commercial nuclear plants are rare, several have occurred. In 1957, a fire at the Windscale, England, facility caused a release that led to protective actions taken for milk but not agricultural products. An extremely severe incident reportedly occurred at a reprocessing facility in the Soviet Union in 1957, although very little is known about its cause or about the adverse health effects on the surrounding population. The Three Mile Island incident in 1978 has been the most significant nuclear reactor incident in the United States in terms of potential public exposure. However, actual doses to the public were calculated to be <100 mrem, and the most significant adverse health effect was stress on the population around the plant.

Federal and state planning for nuclear-power incidents was expanded after the incident at TMI. State emergency plans and exercises to test those plans are required around the nuclear facilities. A Federal plan has also been developed and tested through exercises. However, in both state and Federal plans, exercises are not likely to fully explore political, economic, social, and technical problems that will develop during an actual emergency. In light of this fact, flexibility must be allowed within emergency-response plans, and the technical and managerial expertise to cope with emergency-response issues must be maintained within state and Federal agencies

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