15

Nuclear Reactor Accidents

15.1 Historical Overview of Reactor Accidents

Despite the largely successful precautions taken to avoid nuclear reactor accidents, the record is not perfect. We list here the more important known reactor accidents, excluding accidents in submarine reactors and possible accidents in the former USSR and Soviet Bloc countries, other than the Chernobyl accident.[1]

The decision as to which accidents qualify as "major" accidents is somewhat arbitrary. In particular, ordinary industrial non-nuclear accidents are omitted. For example, in 1972 two workers at the Surry Power Station were fatally scalded by steam escaping from a faulty valve. This did not involve the nuclear components of the power station and therefore is not pertinent to the broader issue of nuclear reactor safety. The major past accidents are as follows:

- **Chalk River, Canada (1952).** There was a partial meltdown in a 30-MWt experimental reactor. The reactor was cooled by light water and moderated by heavy water. The accident was initiated by operator errors and a failure of the control rod system. This led to an elevated power

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[1] There are reports of reactor accidents in these countries prior to the much larger Chernobyl accident (see Refs. [1] and [2]), although accounts of their course and magnitude are in dispute. In addition, there was a major release of radioactive material in an accident in 1957 at the Kyshtym nuclear complex in the Urals. The accident was a non-nuclear explosion in tanks of reprocessed radioactive wastes, not a reactor accident. It led to the reported evacuation of 10,730 people and caused a collective effective dose of about 2500 person-Sv [3, p. 116].

output and some boiling and loss of cooling water. In a typical LWR, the accident would have been mitigated by a negative void coefficient (see Section 14.2.1), but in this case the feedback was positive. The reactor was eventually shut down by draining the heavy water moderator. There were no known injuries or deaths, but the reactor core was damaged and there was escape of an unspecified amount of radioactivity [4, p. 101].

- **National Reactor Testing Laboratory, Idaho (1955).** The 1.4-MWt experimental breeder reactor, EBR-I, suffered a 40% to 50% core meltdown during a test in which the power level of the reactor was intentionally raised but, due to operator error, was not reduced promptly. There was little contamination of the building, no injuries occurred, and the release of radioactive material was "trivial" [4, p. 103].
- **Windscale, England (1957).** Overheating and fire occurred in a graphite moderated reactor used for plutonium production. The accident began in the course of heating the fuel above normal operating temperatures to release energy stored in the graphite crystal lattice.[2] This energy is a consequence of radiation damage to the graphite, a problem that arises in graphite-moderated reactors if they operate below the temperature necessary for annealing radiation damage. In this case, the heating and the energy release, although intentional, were too rapid. The reactor was shut down with control rods, but the heating had been sufficient to cause a fire in the uranium fuel and, eventually, in the graphite. The fire smoldered for about 5 days, until extinguished by flooding with water [6]. The most serious consequence was the release of about 20,000 Ci of ^{131}I ($T = 8.02$ days), which was carried by winds over much of central and southern England. The estimated consequences for England and continental Europe are 260 thyroid cancers and 13 thyroid cancer fatalities over a period of 40 years, plus 7 additional fatalities or hereditary effects [7, p. 24].
- **National Reactor Testing Laboratory, Idaho (1961).** Three army technicians were killed when one of them apparently rapidly removed (manually) a control rod from a 3-MWt test reactor, known as SL-1, on which they were working. Reactors of this type were intended for heating and electricity production at remote sites, and they were so primitive that the control rods could be moved by an operator standing on top of the reactor. There was a rapid increase in reactor output, followed by a steam explosion, leading to lethal levels of radiation within the reactor building. Most, but not all, of the activity was contained within the building [4, p. 109].
- **Fermi Reactor, Detroit (1966).** There was a partial meltdown in a 200-MWt (61-MWe) commercial breeder reactor, which was a one-of-a-kind prototype. The cause was a blockage in the flow path of the sodium coolant. There were no injuries or significant release of radioactivity, and

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[2] The storage and release of energy in a graphite moderator is the so-called *Wigner effect* (see, e.g., Ref. [5]).

the reactor was briefly put back into operation before its final shutdown in 1973 [4, p. 32].[3]

- **Lucens, Switzerland (1969).** There was partial fuel melting in a 30-MWt experimental reactor due to loss of CO_2 cooling. There was severe damage to the reactor but no radiation release beyond permitted levels [4, p. 121].
- **Browns Ferry 1, Alabama (1975).** A fire in the electrical wiring did extensive damage to the control systems and threatened the reactor, but the reactor was turned off and cooling maintained with no radiation release and no injuries other than one individual suffering a minor burn from the fire. Despite the absence of damage to the reactor itself, this accident was of importance because it was the first major accident in a commercial LWR and demonstrated a serious vulnerability in the control systems of that period due to inadequate redundancy.
- **Three Mile Island, Pennsylvania (1979).** This accident is discussed in more detail in Section 15.2.
- **Chernobyl, USSR (1986).** This accident is discussed in more detail in Section 15.3.

Some aspects of these accidents are summarized in Table 15.1.

The only reactor accidents that caused a clearly identifiable loss of life were at Idaho Falls, where three workers died from the effects of the explosion and radiation, and at Chernobyl, where 31 operating and firefighting personnel died within about 2 months, primarily from high radiation doses. In addition, there possibly will be a small number of eventual, or "delayed," cancer fa-

Table 15.1. Major nuclear reactor accidents.

				Environmental Consequences		
Year	Reactor	Purpose	Capacity (MW)	Radioactivity Release	Prompt Deaths	Delayed Cancers[a]
1952	Chalk River	Experimental	30 (t)	Some	0	0
1957	Windscale	Pu production		Large	0	~ 13–20
1961	Idaho Falls	Test (army)	3 (t)	Small	3	0
1966	Fermi I	Demo breeder	61 (e)	Very little	0	0
1969	Lucens	Experimental	30 (t)	Very little	0	0
1975	Browns Ferry 1	Power	1065 (e)	None	0	0
1979	TMI-2	Power	906 (e)	Small	0	~ 0–2
1986	Chernobyl	Power	1000 (e)	Very large	31[b]	~ 30,000[b]

[a] Indicated cancers are possible cancer fatalities, calculated on the basis of the linear hypothesis (see Section 4.3).
[b] See Section 15.3.4 for further discussion of Chernobyl fatalities.

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[3] For two very different assessments of the significance of this accident and the level of hazard it created, see Refs. [8] and [9].

talities from the Windscale radiation release and a large number of delayed fatalities from Chernobyl.[4] It may be noted that none of these three reactors were commercial LWRs, and except for Chernobyl, the accidents took place more than 35 years ago. Their history therefore has only limited pertinence to the present safety of commercial LWRs or of other non-Soviet commercial reactors.

Beyond reactors, the most serious nuclear accident since Chernobyl occurred at Tokaimura, Japan on September 30, 1999, at a facility for preparing reactor fuel.[5] Although this was not a reactor accident, we mention it here because a significant accident at any nuclear facility reflects unfavorably on the nuclear industry in general. The accident occurred in the course of preparing fuel for an experimental fast reactor which used uranium enriched to 18.8% in ^{235}U. In one stage of the process, in violation of authorized procedures, workers poured buckets of enriched uranium solution into a tank, apparently unaware that given the size and shape of the tank (45 cm in diameter and 61 cm high) they could create a critical mass. When they filled the tank with about 40 L of the solution, criticality was reached and there was an intense burst of gamma rays and neutrons, setting off radiation alarms. The three workers involved left the building, but all were heavily exposed and two eventually died. The only "significant" health consequences cited in an IAEA report on the accident were to these workers, although other workers were exposed to some extent, including some involved in measures taken to terminate the chain reaction [10, p. 30].[6]

15.2 The Three Mile Island Accident

15.2.1 The Early History of the TMI Accident

The Three Mile Island (TMI) accident occurred in one of two similar reactors at the Three Mile Island site in Pennsylvania.[7] The accident was in the second

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[4] The number of fatalities is in question, given the uncertainties surrounding the effects of radiation at low doses and dose rates, but in the discussion of these accidents, we quote numbers based on the adoption of the linearity hypothesis (see Section 4.3).

[5] This summary is based largely on an IAEA report prepared shortly after the accident [10].

[6] There was no explosion, but criticality continued with a low power output for about 20 h, stabilized by thermal expansion of the fluid and the formation of bubbles. The chain reaction was terminated by draining water from a cooling jacket surrounding the tank, which reduced reflection of neutrons back into the tank, and as a precaution by injecting a boric acid solution into the tank.

[7] Extensive studies were carried out after the accident. One, referred to later as the "Kemeny report," was by a commission appointed by President Carter and

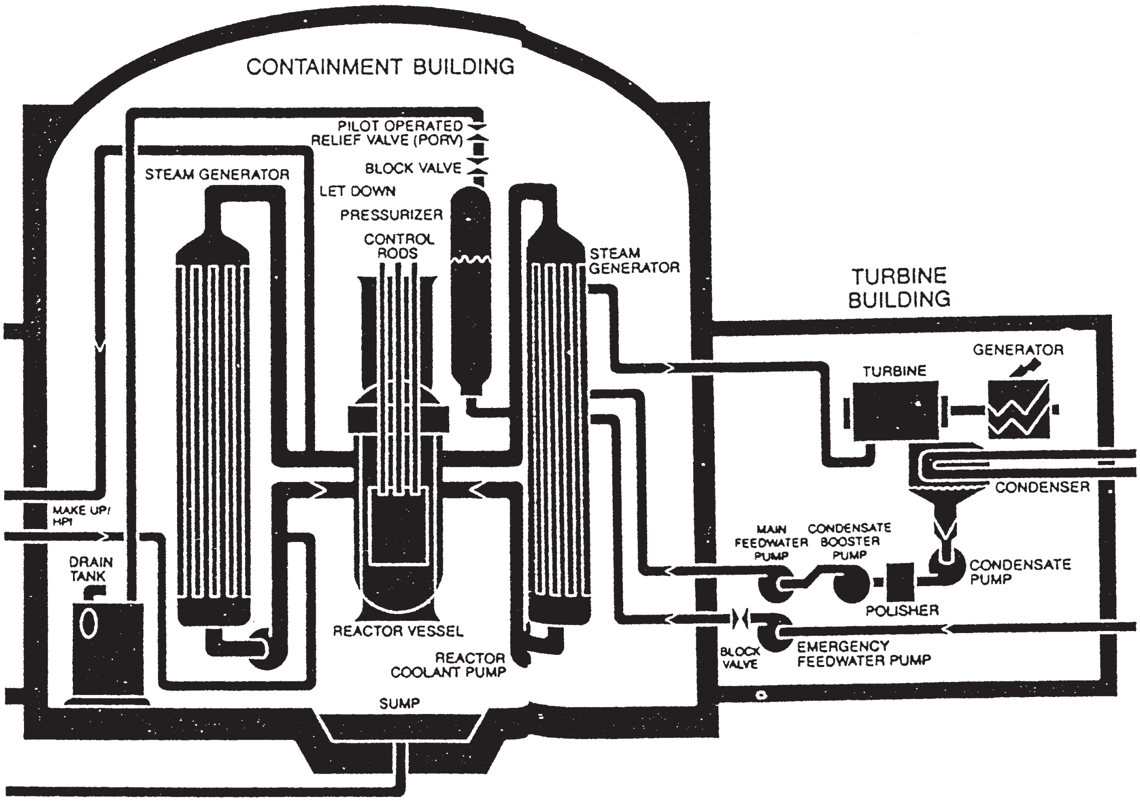

Fig. 15.1. Schematic of the TMI-2 facility, including reactor building and turbine building. Piping goes, from right to left in the diagram, through the containment building wall to the auxiliary building (not shown); piping also goes, from left to right, through the turbine building wall to the condensate storage tank and cooling tower (not shown). (From Ref. [11, pp. 86–87].)

unit, known as TMI-2. It was a 906-MWe pressurized water reactor built by Babcock and Wilcox, the smallest (in terms of number of units completed) of three U.S. manufacturers of PWRs. It had first received a license to operate at low power in February 1978 and was in routine operation at full power by the end of 1978. A schematic of the TMI-2 facility is shown in Figure 15.1 [11, pp. 86–87].

The accident started with a failure of the cooling system of TMI-2 in the early morning of March 28, 1979. The initial problem was an interruption in the flow of water to the secondary side of the steam generator. This water is the so-called feedwater. In the secondary loop, feedwater enters the steam

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chaired by John Kemeny, the president of Dartmouth College [11]. The second, the Rogovin Report, was by a special inquiry group instituted by the Nuclear Regulatory Commission and chaired by Mitchell Rogovin, a partner in an independent Washington law firm. The description here is drawn largely from the Kemeny Report [11] and Part 2 of Volume II of the Rogovin Report [12], as well as a further review article [13].

generator, and steam emerges to drive the turbine. The steam is condensed in a second heat exchanger (the condenser), and water is returned to the steam generator after passing through a "polisher," in which dissolved impurities are removed. The flow of water between the condenser and steam generator is maintained by the condensate pump and the main feedwater pump (see Figure 15.1).

The chain of events that led to the accident appears to have been initiated by work done to clean the polishers. In a sequence that has not been conclusively established, this operation may have caused one or more of the valves in the condensate polisher system to close, automatically shutting off (tripping) one of the condensate pumps. The tripping of the condensate pump, whatever the cause, in turn, tripped the main feedwater pumps.[8] This failure caused the emergency feedwater pumps to start automatically, in order to maintain the flow of water to the steam generator. Maintenance of feedwater flow is essential to cool the water from the reactor that flows through the primary side of the steam generator.

Up to this point, everything was "normal," in the sense that reactors are designed to handle occasional equipment failures; protection then comes from backup systems. However, the block valves in the emergency feedwater lines (there were two) were closed; according to proper operating procedures, they were supposed to be open. Indicator lights in the control room showed the closed status, but the operators at first did not notice this. Thus, no water was being fed to the secondary side of the steam generator because the pumps for the main supply were off and valves in the emergency line were closed. With no flow of water, the pressure in the steam generator rose and in response, the pilot-operated relief valve (PORV) on the "hot" side of the steam generator heat exchanger opened. The pressure excursion also caused the reactor to trip, with automatic insertion of the control rods. With the reactor turned off and the PORV open, the pressure dropped. The PORV should then have automatically closed.

At this point, there were additional equipment and design failures. The PORV did not close properly, but the control panel indicator light displayed the status of the control power to the valve (namely that it was supposedly closed), not the actual status of the valve (namely that it was open). Thus, the operators had to cope with unusual conditions in the cooling system without knowing the actual status of the valves in it. In particular, the PORV remained open for almost 2.5 h, causing a very large loss of needed cooling water.

Within 2 min after the start of the accident, the steam generators boiled dry because they had no feedwater source and there was a substantial heat output from the reactor core due to radioactive decay. Overall, the conditions of the cooling system were both unusual and confused, with the operators

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[8] Figure 15.1 does not show the redundancy in the system. There were two main feedwater pumps and three emergency feedwater pumps.

not having correct information or sufficient training to recognize the nature of the evolving anomalies and cope with them. They did recognize that there were serious problems, and by 4:45 AM supervisory personnel began to arrive at TMI, only three-quarters of an hour after the start of the accident. By 6:22 AM, the PORV was closed, but the problems were not over. At 7:00 AM a "site emergency" was declared because there had been some release of radioactivity.

15.2.2 Evolution of the TMI Accident

Over the next few days, the accident continued to unfold, with continued difficulty in establishing proper cooling conditions. There were some small releases of radioactivity outside the plant, as well as one misinterpreted report of radiation levels that led to the incorrect belief that there had been a large release. There was a great sense of emergency both at the site and in the surrounding area, as no one was willing to give unequivocal assurances that matters were under control. This led to a recommended evacuation of pregnant women and preschool children from the immediate vicinity and a large self-initiated evacuation by individuals.

Concern reached a peak on Saturday, March 31, over the possibility of a hydrogen explosion inside the pressure vessel. As described in the subsequent Kemeny Report:

> The great concern about a potential hydrogen explosion inside the TMI-2 reactor came with the weekend. That it was a groundless fear, an unfortunate error, never penetrated the public consciousness afterward, partly because the NRC made no effort to inform the public it had erred. [11, p. 126]

Hydrogen is produced by the reaction of steam with the zircaloy cladding at high temperatures. Oxygen is formed by the breakup of water under radiation, so-called radiolysis. Together, hydrogen and oxygen can form an explosive mixture. There was fear that such an explosion could occur within the pressure vessel. Within a day or so, some NRC experts came to the conclusion that a hydrogen explosion was impossible, but this conclusion was not immediately accepted by all of the authorities. In the meantime, the hydrogen bubble had become a matter of great public concern, a concern not unambiguously dismissed by the NRC. However, by 6:00 PM on April 1, the hydrogen was removed from the bubble by "letdown, leakage, and venting" [12, p. 535]. It never had been the threat that had been believed.

The reason that the problem was not a real one was an insufficient accumulation of oxygen. In a PWR, it is normal to have some hydrogen dissolved in the water and to have continued recombination of oxygen and hydrogen. This recombination prevented the amount of oxygen from rising sufficiently to create a danger of explosion. This point is brought out in the Rogovin Report:

> Little or no oxygen was present in the bubble and a very low probability of explosion existed. The incorrect perception of an explosion hazard stemmed from contradiction among supposed experts. This perception was known or should have been known to be false by the afternoon of April 1. [12, p. 535]

It may be noted that a Babcock and Wilcox scientist had given assurances from the first that there was no problem from oxygen production [12, p. 534], but apparently this assurance did not receive much attention.

President Carter visited the site on Sunday, April 1; the hydrogen bubble itself dissipated (although not the perception of a near miss with hydrogen) and the worst of the crisis was over. However, it took more than another week for the advisory evacuation of pregnant women and preschool children to be withdrawn by the governor of Pennsylvania.

15.2.3 Effects of the TMI Accident

Core Damage and Radionuclide Releases

In retrospect, several major aspects of the Three Mile Island accident were not fully appreciated at the time and might seem to be in conflict:

- There was very little release of radioactivity and very little exposure of the general population. According to the Kemeny Commission, “the maximum estimated radiation dose received by any one individual in the off-site general population (excluding the plant workers) during the accident was 70 millirems. . . . three TMI workers received radiation doses of about 3 to 4 rems; these levels exceeded the NRC maximum permissible quarterly dose of 3 rems” [11, p. 34]. In essential agreement, the Rogovin Report found that “the maximum off-site individual dose was less than 100 mrem” [12, p. 400].
- The total collective dose to the 2 million people living within 50 miles of TMI was approximately 2000 person-rem (20 person-Sv).[9] From this, the Kemeny Commission estimated a 50% chance of no fatal cancers from the accident, a 35% chance of one fatal cancer, and a 15% chance of more than one [11, p. 12]. These results correspond to an average expectation of 0.7 cancer fatalities. If the 1993 NCRP risk estimate of 0.05 per sievert is adopted, then one fatal cancer is calculated for the collective dose of 20

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[9] See Ref. [11, p. 34] and Ref. [12, p. 399].

person-Sv (see Section 4.3.4). Among these 2 million people, it is expected that 325,000 will die of cancers unrelated to TMI, so the TMI impact, if any, will be far below any detectable level.

- The core damage was very great. As cleanup and dismantling of the TMI-2 reactor proceeded, it was found that the core damage was greater than originally thought, and some observers have expressed surprise that the reactor vessel itself withstood the molten fuel at its bottom.

Thus, those who thought that the accident was causing, or was about to cause, large releases of radioactive material were proven to be wrong. Those who thought that matters were being exaggerated and that there was relatively little actual damage to the reactor were also wrong. The biggest surprise, however, was having these two outcomes together—great core damage and almost negligible external radionuclide releases. Only about 15 Ci of ^{131}I were released to the environment outside the containment [12, p. 358], despite an initial core inventory more than 1 million times greater. It had been commonly assumed that with core damage of this magnitude, a large fraction of the iodine would escape. Thus, the containment system, including the system to spray water into the containment to remove radionuclides, performed unexpectedly well. In the aftermath of TMI, understanding this performance—now part of what is known as the source term question—became a major issue in reactor safety studies (see Section 14.1.4).

Studies of Health Effects of TMI

The release of radioactivity from the Three Mile Island plant and the resulting radiation exposures were too small to have produced any observable effects, if one accepts official accounts of the magnitude of the releases and standard dose–response relationships. One or even 10 cancer deaths would be lost among a total of over 300,000 "natural" cancer deaths. Nonetheless, there have been persistent claims of health problems from TMI. In response to some of the early concerns, the Pennsylvania Health Secretary stated in a news release: "After careful study of all available information, we continue to find no evidence to date that radiation from the nuclear power plant resulted in an increased number of fetal, neonatal, and infant deaths. That simply isn't the case" [14]. This was based on an examination of death rates near TMI and in Pennsylvania as a whole, before and after the accident.

The Pennsylvania Department of Health carried out a later study of spontaneous abortions, in the face of a rather widespread belief among residents of the TMI area that there had been an increase in stillbirths and miscarriages [15]. The study identified 479 women living within 5 miles of the plant who were pregnant at the time of the accident. For this group, there were 436 live births, 28 spontaneous abortions or stillbirths, and 15 other abortions. The rate of spontaneous abortions and stillbirths was compared to the rate expected from earlier studies of nonexposed populations and it was found that there was no excess. In the author's words, the TMI incidence rates "compared favorably with the four baseline studies."

In a broader study of cancer rates near Three Mile Island, investigators found a statistically significant increase in cancer incidence, compared to rates at greater distances, during 1982 and 1983 [16].[10] However, this excess did not persist, and in 1985, the cancer incidence rate was slightly lower for the near-TMI group than for the more distant group. Further, the increase was seen only in cancer *incidence*, not in cancer fatalities. This lack of increase was commented on particularly for lung cancer, which progresses rapidly from incidence to fatality, as pointing to possible "screening bias." The authors concluded:

> We observed a modest postaccident increase in cancer near TMI that is unlikely to be explained by radiation emissions. The increase resulted from a small wave of excess cancers in 1982, three years after the 1979 accident. Such a pattern might reflect the impact of accident stress on cancer progression. Our study lacked a direct, individual measure of stress, however. The most plausible alternative explanation is that improved surveillance of cancer near the TMI plant led to the observed increase.

These results are consistent with the belief that there is virtually no possibility that there have been or will be observable health effects from radioactivity released in the TMI accident, given the low exposure levels. However, the post-TMI history illustrates the extent of skepticism about official reassurances in situations of possible radiation hazard. This skepticism is fed by anomalies in the data (such as the increase in observed cancer incidence in 1982). Anomalies often cannot be explained in any conclusive fashion, and the ruling out of radiation exposure as the cause may hinge on somewhat indirect arguments, such as comparisons to standard models of the time intervals between radiation exposures, cancer incidence, and cancer fatalities. The families and friends of the "victims" of the anomalies may have little incentive to accept these arguments.

These difficulties may be of only marginal interest in the case of TMI, where the weight of evidence and scientific opinion is strong, but they could assume much greater importance in evaluating the Chernobyl accident, where the exposures were very much greater and the conditions for systematic epidemiological studies are poorer. It is probable that there will be large health consequences from Chernobyl, and it is possible that some will be observable, but it may prove difficult to assess the validity of individual reports and to resolve the disagreements that will arise.

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[10] The authors were from the School of Public Health at Columbia University, with the exception of one from the Audubon Society.

15.3 The Chernobyl Accident

15.3.1 The Chernobyl Reactors

Among reactor accidents, the Chernobyl accident in 1986 stands alone in terms of magnitude.[11] The design features of “Chernobyl-type” reactors are unique, and it is the standard assumption of nuclear analysts that a similar accident could not occur in any of the other types of reactors operating today. However, Chernobyl demonstrated the seriousness of a near “worst-case” accident. It intensified preexisting public concern about reactors of all sorts and strengthened the position of those who oppose nuclear power on safety grounds.

The Chernobyl reactor was one of the Soviet RBMK-1000 reactor series, designed to operate at a (gross) capacity of 1000 MWe. These are graphite moderated and water cooled, of a type originally used in the USSR (and with important differences in the United States) for the production of plutonium. Such reactors were also used for the generation of electricity in the USSR, dating back to a 5-MWe water-cooled, graphite-moderated reactor at Obninsk, put into operation in 1954 [18, p. 9].

At the beginning of 1986, there were four RBMK-1000 reactors at the Chernobyl site in the Ukraine, located about 130 km north of the major city of Kiev. The most recently installed reactors, completed in 1983, were Units 3 and 4, housed in a single building. At the time of the accident, all four reactors were operating and two more were under construction. The accident itself occurred in Unit 4 on April 26, 1986 at 1:24 AM. Unit 3 was turned off by the operators after almost 5 h and the nearby Units 1 and 2 were turned off after about 24 h. Units 1 and 2 were returned to operation in late 1986 and Unit 3 in December 1987. Construction was suspended and then canceled on the two reactors being built at Chernobyl [19].

Unit 2 was permanently closed, following a fire on October 1, 1991. The fire was in a non-nuclear part of the plant, and there was no release of radioactivity, but there was damage to the engine room [20]. Units 1 and 3 continued in operation beyond 1991, with the Ukrainian authorities balancing the need for their electrical output against concerns about their safety, but both were eventually shut down permanently—in 1996 and 2000, respectively. Outside Ukraine, there are 11 RBMK-1000 reactors operating in Russia (4 at Kursk, 4 near St. Petersburg, and 3 at Smolensk) and two larger RBMK reactors (1380 MWe) at Ignalina in what is now Lithuania [21].[12] In an effort to reduce the chance of another accident, steps have been taken since 1986 to improve operator training, and significant modifications have been made in the RBMK reactors themselves.

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[11] The account of the accident progression given here is based largely on parts of Refs. [17], [18], and [24]–[27].

[12] Lithuania has agreed to shut down these plants, one in 2005 and the other in 2009, as a condition for joining the European Union [22].

Although the USSR in the past exported reactors to its neighbors, these were all PWRs, not RBMKs. Outside the USSR, the only reactor bearing some similarity to the Chernobyl reactor was the not so very similar N reactor at Hanford, which stopped operations in 1988. Future Russian plans are based primarily on LWRs, although the Chernobyl accident did not stop the completion of all RBMK reactors: One of the RBMK-1000 units now operating at Smolensk was put on-line in 1990 and a fifth unit at Kursk, for which construction began in 1985, remains under construction [23].

15.3.2 History of the Chernobyl Accident

Deficiencies in Attention to Safety

There was no crisp single cause of the Chernobyl accident. Even 6 years later, a review by a major international technical body, the International Nuclear Safety Advisory Group (INSAG), reported: "It is not known for certain what started the power excursion that destroyed the Chernobyl reactor" [24, p. 23]. The quotation may suggest more ignorance than is the case. A great deal is known about the conditions before and during the accident, even if the development of a definitive, detailed scenario has been made difficult by the complexity of the reactor conditions, the speed of unfolding of the accident, and the damage itself.

Overall, the accident was the result of a combination of design deficiencies, operator errors, and an unusual set of prior circumstances, all of which put the reactor and the operators to a test that they failed. In the INSAG view, "the accident can be said to have flowed from deficient safety culture, not only at the Chernobyl plant, but throughout the Soviet design, operating and regulatory organizations." The INSAG report listed a whole gamut of weaknesses in institutions and attitudes [24, p. 24]. In this view, with greater vigilance in both design and operations, there would have been no accident.

Design Weaknesses

Two aspects of the design have been particular targets of criticism: a positive void coefficient of reactivity and an improperly configured control rod system. Both contributed positive feedbacks, which turned an initial excursion in reactor performance into the Chernobyl disaster.

The void coefficient in a water-cooled reactor would be negative if the water acted only as a coolant and moderator. However, the water also acts as a poison, due to capture of neutrons in hydrogen. In an LWR, when water is lost or steam bubbles develop, the dominant effect is a decrease in reactivity, corresponding to the negative void feedback discussed in Section 14.2.1. However, in a Chernobyl-type reactor, most of the moderation is provided by the graphite, and the water acts mainly as a poison. When some of the cooling water is replaced by steam, there is a different balance than in an LWR between the competing feedbacks: increased resonance absorption in ^{238}U (negative void coefficient), increased neutron leakage from the reactor (negative void coefficient), and decreased absorption of thermal neutrons in H_2O (positive void coefficient). The net outcome depends on the relative amounts and arrangement of the uranium, carbon, and water in the reactor. For the Chernobyl reactor, the overall void coefficient was positive, whereas a graphite-moderated, water-cooled reactor in the United States, the Hanford-N reactor, had a negative void coefficient.

The second major defect, involving the control rods, is also related to the role of water. At the onset of the accident, most of the control rods had been fully withdrawn from the reactor to compensate for an excursion in xenon poisoning to above the normal level (see next subsection). Remarkably, the first effect of the insertion of the control rods from the full-out position was to *increase* the reactivity. This was due to a peculiarity of the RBMK-1000 control rod system, which has since been corrected. The control rods move vertically through the reactor core and are withdrawn by being lifted upward. To prevent the control rod from being replaced by water, which acts as a poison and lessens the effect of withdrawing the rod, a long graphite "displacer" was attached to the bottom of the rod. When the rod was fully withdrawn, most of the channel in the core was occupied by this graphite, and the control material was above the core. However, the graphite displacer did not completely fill the channel; instead, there was still a 125-cm column of water below the graphite displacer [24, p. 5]. The first effect of inserting the control rod, before the absorbing part of the control rod reached the core, was for the graphite to drive out the water column, increasing the reactivity by reducing the poison. The full motion of the control rods was slow, and by the time the control rod proper entered the core region, it was too late.

Since Chernobyl, there have been a number of changes to correct these defects in the RBMK reactors. These include increasing the enrichment of ^{235}U in the fuel, changing the control rod geometry so that the displacer will not displace water when inserted, and speeding up the control rod insertion [25].

Reactor Operations Prior to Accident

The accident evolved from a test that disturbed normal operating conditions. Ironically, the test was undertaken to demonstrate a safety feature of the reactor. Power for the pumps and other plant facilities normally comes from the plant's own turbogenerator units or from the off-site power grid. Should there be an off-site power outage and a shutdown of the reactor, standby diesel generators at the plant come on-line to supply power. There could be an interval of several seconds between the loss of normal power and the start-up of the diesel generators. The test was to demonstrate that the inertial coasting of the turbogenerator would provide sufficient power to operate pumps during this interval.

The first step taken to perform this test was a reduction of reactor power to one-half of its normal 3200 MWt, beginning at about 1:00 AM on April 25. One of the turbogenerators was switched off at 1:06 AM, and the power reached 1600 MWt at 3:47 AM [24, p. 53]. The remainder of the test, involving a further reduction of power, was to start at about 2:00 PM. As part of the test, the emergency core-cooling system was disconnected at 2:00 PM.

However, the reactor's power was required for the electricity grid fed by Chernobyl and instructions were given to postpone the further power reduction. The test did not resume until 11:10 PM on April 25. It was then intended to reduce the power to about 700–1000 MWt, but there was an overshoot in the shutdown and the power level dropped to 30 MWt. By about 1:00 AM on April 26, it had been brought back to 200 MWt, but the period of operation at low power caused a buildup of xenon poisoning (see Section 7.5.3), which was compensated for by removal of a large number of the control rods, more than proper under operating guidelines.[13]

At this point, there were at least two unusual circumstances: The power level for the test was lower than planned and the margin of safety, in terms of the ability to shut down the reactor with the control rods, was less than the normal operating limit. In addition, a number of safety systems had been turned off to facilitate the planned test. In hindsight, it is clear that the test should have been terminated at this point, but it was continued.

Initiation and Progress of the Accident

As the test proceeded at low power, water flow conditions were not normal, there was some decrease in steam, and the reduced reactivity caused automatic control rods to withdraw to restore the reactivity. This was a manifestation of the fact that the Chernobyl reactor operated with a positive void coefficient.[14]

This action was in itself harmless, but it raised the control rods to unusually high positions out of the core. At 1:23:04 AM, despite warning indications of the dangerous control rod configuration, the operators initiated the turbine test by shutting a valve and reducing steam flow to the turbine. The resulting changes in steam pressure and in water flow from the cooling water pumps led to a decreased water flow through the core and some boiling in the core. The displacement of water by steam caused the reactivity to rise.

In response, at 1:23:40 AM, an emergency shutdown (scram) was attempted. However, the control rods had been withdrawn too far to take im-

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[13] After power is reduced, the decay of ^{135}I ($T = 6.57$ h) to ^{135}Xe ($T = 9.14$ h) continues, but the destruction of ^{135}Xe by neutron capture is decreased. Therefore, the amount of ^{135}Xe increases for several hours.

[14] According to Richard Wilson [26], Russian experts explained to him that this design was adopted for cost savings in establishing the graphite configuration. For power levels of 20% of normal or higher, the negative fuel temperature coefficient (the Doppler coefficient) was supposed to provide an adequate margin of safety, and at lower power levels, there were to be stringent operating regulations.

mediate effect and, due to the graphite displacers at their ends, their first effect was to increase rather than decrease the reactivity. Within 3 s there was a sharp increase in the neutron flux and power output, as the reactor went superprompt critical. Within not more than 20 s, there were two large explosions—one apparently a steam explosion that exposed the reactor fuel to the air and the other an explosion due to exothermic reactions, including the interaction of liberated hydrogen and carbon monoxide with the air.

These explosions breached the reactor building (there was no true containment) and sent burning fragments into the air, which started fires on the roof of the reactor. Firefighters from the nearby towns of Chernobyl and Pripyat arrived shortly after the accident and put out the building fires by 5:00 AM There had been a threat that the fires would spread to the other units at Chernobyl (Units 1, 2, and 3), but this was prevented by firemen working under extreme conditions of heat and radiation exposure. Remarkably, Unit 3 was not turned off until about 6:00 AM.

Although the exterior fires had been extinguished, the problem of heat generation in the reactor continued, due to (chemical) burning of the fuel and graphite in the reactor and to radioactive decay heat. These interior fires were not extinguished until May 6, following a series of attempts to quench them by dropping massive amounts of boron carbide (intended to prevent recriticality), limestone, lead, sand, and clay. In total, Unit 4 was entombed under about 5000 tons of material, and the acute phase of the accident was then over.

15.3.3 Release of Radioactivity from Chernobyl

The initial explosions and subsequent reactor fires caused large amounts of radioactive materials to be released from the reactor. The release was not all immediate, with about 24% the first day, 28% over the next 5 days, and 48% over the following 4 days [27, p. 3.9]. The release was mainly of the volatile nuclides, including the noble gases, iodine, and cesium. Much less of the nonvolatile nuclides, such as strontium, escaped. Estimated release fractions and total releases are given in Table 15.2 for some of the important radionuclides.

The cloud of radioactivity from the accident during the first 2 days spread generally to the north and west and, thus, did not severely impact Kiev. In later days, when releases were lower, the winds shifted to form plumes in other directions, including to the south [28, p. 459]. The accident was not immediately made public, and the first awareness outside the USSR came from radiation measurements in Sweden and Finland. The cloud reached Sweden at about 2 PM on April 27 and was first detected about 18 h later by monitors at the Forsmark nuclear power station [18, p. 13]. This was approximately 2 days after the start of the accident itself.

Eventually, the radioactive cloud spread over most of the northern hemisphere, depositing radionuclides widely. The amounts deposited decreased with increasing distance, although the correlation with distance was not pre-

Table 15.2. Radionuclide releases from the Chernobyl accident, for selected radionuclides.

Isotope	$T_{1/2}$	Core (MCi)	Release[a] (MCi)	Fraction Released
^{85}Kr	10.8 years	0.89	0.89	1.0
^{133}Xe	5.24 days	176	176	1.0
^{131}I	8.02 days	86	48	0.6
^{134}Cs	2.07 years	4.1	1.5	0.36
^{137}Cs	30.1 years	7.0	2.3	0.33
^{90}Sr	28.8 years	5.9	0.27	0.05

[a] The actual release was less for short-lived isotopes because of decay before release; these numbers are "corrected" back to the activity at the time of the accident.

Source: Ref. [28, pp. 518–519].

cise due to wind patterns and rainfall. In general, it could be said that the fallout was substantial near Chernobyl, moderate in some other parts of Europe, and negligible in North America.

15.3.4 Observations of Health Effects of Chernobyl Accident

Overall Summary up to 2000

Subsequent to the Chernobyl accident, there have been many studies of its health impacts, and studies are likely to continue for many decades. A succinct summary of current knowledge was presented in the 2000 Report of the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) in an Overview section on "The Radiological Consequences of the Chernobyl Accident":

> The accident at the Chernobyl nuclear power plant was the most serious accident involving radiation exposure. It caused the deaths, within a few days or weeks, of 30 workers and radiation injuries to over a hundred others. It also brought about the immediate evacuation, in 1986, of about 116,000 people from the areas surrounding the reactor and the permanent relocation, after 1986, of about 220,000 people from Belarus, the Russian Federation and Ukraine. It caused serious social and psychological disruption in the lives of those affected and vast economic losses over the entire region. Large areas of the three countries were contaminated, and deposition of released radionuclides was measurable in all countries of the northern hemisphere.
>
> There have been about 1,800 cases of thyroid cancer in children who were exposed at the time of the accident, and if the current trend

> continues, there may be more cases during the next decades. Apart from this increase, there is no evidence of a major public health impact attributable to radiation exposure 14 years after the accident. There is no scientific evidence of increases in overall cancer incidence or mortality or in non-malignant disorders that could be related to radiation exposure. The risk of leukemia, one of the main concerns owing to its short latency time, does not appear to be elevated, not even among the the recovery operation workers. Although those most highly exposed individuals are at an increased risk of radiation-associated effects, the great majority of the population are not likely to experience serious health consequences as a result of radiation from the Chernobyl accident. [29, p. 4]

Thus, two groups have been unambiguously harmed by radiation from Chernobyl: emergency workers at the site of the accident and children in a wide surrounding region who have developed thyroid cancers. No other radiation damage had been observed by the time of the UNSCEAR report in 2000. Further details on the affected groups are presented in the next two subsections.

Effects on Plant Workers and Firemen

Severe medical effects of the accident were suffered by workers at the plant and the firemen who responded to the accident. By 8:00 AM of the morning of the accident, these totaled about 600, including 69 firemen [28, p. 522]. In all, 31 died within several months of the accident: 28 from acute radiation syndrome (ARS), 2 from nonradiation injuries, and 1 apparently from coronary thrombosis [30, p. 6].[15] Most of those who died from radiation sickness also received severe skin burns from beta-particle radiation. These early deaths were exclusively among plant personnel and firemen. The latter appear to have performed in an exceedingly dedicated and self-sacrificing manner.

A total of 237 people were suspected of having ARS and this diagnosis was confirmed for 134, including the 28 who died. The deaths among the ARS group were strongly correlated with the magnitude of the radiation exposures. The fractional death rates at different exposure levels were: 0 out of 41 up to 2.1 Sv, 1 out of 50 from 2.2 to 4.1 Sv, 7 out of 22 from 4.2 to 6.4 Sv, and 20 out of 21 above 6.4 Sv [28, p. 523]. In the decade following the accident, from 1987 to 1996, an additional 14 of the original 237 patients died, but these deaths do not appear to be primarily attributable to radiation exposure [31, p. 187].

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[15] ARS was defined by "at least minimal bone-marrow suppression as indicated by depletion of blood lymphocytes" [28, p. 488]. In many accounts of Chernobyl, the number of prompt fatalities is given as 30, apparently omitting the coronary thrombosis victim.

Childhood Thyroid Cancer

The accident led to high thyroid exposures, primarily due to ^{131}I in the cloud of radionuclides from the reactor. The relatively short half-life of ^{131}I (8.02 days) means that the dose was received within several weeks of the accident. The main pathways for this dose were through inhalation and consumption of milk or locally grown produce.[16] High thyroid cancer rates began to be seen among children in the early 1990s. Sixty-two cases were observed in 1990 and the number of cases grew steadily until about 1994, when the rate leveled off at roughly 250 per year [28, p. 545]. At first, it was suspected that the high rate of observed thyroid cancers was due to the careful search for them. However, the rate of cancer incidence is seen to be much higher for young children (based on age at the time of the accident) than for older ones, and there is no increased rate for children born after the accident [28, p. 501]. Further, the cancer rate correlates with inferred dose. Thus, the excess is well established.

Through 1998, a total of 1791 thyroid cancer cases were reported in children up to the age of 17 [28, p. 545]. A 2002 UN report states that "some two thousand cases of thyroid cancer have been diagnosed" and anticipates that "the figure is likely to rise to 8–10,000 in coming years" [32, p. 7]. Thyroid cancer is rarely fatal, but requires continued medical treatment.

15.3.5 Radiation Exposures at Chernobyl and Vicinity

Effects on Cleanup Personnel

A prolonged cleanup was carried out in the aftermath of the accident by military servicemen and civilians who were brought in to work for short periods. These were the so-called liquidators. About 600,000 people have been so designated for the years 1986 to 1989, including about 200,000 for 1986 and 1987 when the radiation levels were highest [28, p. 469]. Individual doses often reached several hundred millisieverts [28, p. 525], which is well above the U.S. occupational limit of 50 mSv in 1 year.

There have been reports of increased fatalities and sickness among the liquidators, but in the absence of comparisons to similar populations of nonexposed individuals, it is not clear that the results are meaningful [28, p. 516]. The 2000 UNSCEAR document reported no findings of increased rates of leukemia or other forms of cancer among the liquidators [28]. However, this remains an important group for continued study over the next several decades, because most radiation-associated cancers appear more than 10 years after the exposure. As summarized in the UNSCEAR report:

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[16] Consumption of milk from cows that grazed in contaminated soil provides a quick path for transfer of ^{131}I from the ground to the human body. Use of potassium iodide tablets reduces uptake of other iodine to the thyroid, and many of the children in the Chernobyl vicinity received these tablets.

> Apart from the radiation-associated thyroid cancers among those exposed in childhood, the only group that received doses high enough to possibly incur statistically detectable increased risks is the recovery operation workers. Studies of these populations have the potential to contribute to the scientific knowledge of the late effects of ionizing radiation. Many of these individuals receive annual medical examinations, providing a sound basis for future studies of the cohort. It is, however, notable that no increased risk of leukemia, an entity known to appear within 2–3 years after exposure, has been identified more than 10 years after the accident. [28, p. 517]

In short, by the year 2000, no statistically significant radiation-caused harm was seen among the liquidators, but that does not establish that there has been no harm or that no statistically significant effects will ever be identified.

Exposure of Population in the "Affected Region"

The largest exposures of people near Chernobyl initially came from ^{131}I and other short-lived radionuclides, in part through inhalation. After several weeks, the iodine had decayed sufficiently to be a lesser contributor, and over the longer term most of the dose came from ^{134}Cs and ^{137}Cs and, later, just ^{137}Cs.

After passage of the radioactive cloud, the most important pathways for exposures were from ingested radionuclides and from gamma rays and beta particles emitted by radionuclides deposited on the ground. Ingestion is the more important in the first year, but as deposition from the atmosphere ends and the radionuclides are washed off vegetation by rain, the ground exposure becomes the more important. Overall, in terms of the long-term dose commitment (including the dose from ingested radionuclides that remain in the body), the external surface dose and the ingestion dose are roughly equal, with the former somewhat predominating.

On the day after the accident, almost 50,000 people were evacuated from Pripyat, 3 km from the reactor site [28, p. 527]. Later, the evacuation was extended to cover an "exclusion zone" around Chernobyl, which included the region within 30 km of Chernobyl plus a few outlying areas [28, pp. 472–473]. In all, about 116,000 people were evacuated in 1986 and another 220,000 people were relocated after 1986 [28, p. 453].

A series of zones have been defined around Chernobyl, in part in terms of the deposition of ^{137}Cs:

- *Exclusion zone.* This is the 30-km zone (cited above) from which 116,000 people were evacuated in 1986.[17]

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[17] There has been some ambiguity about this total. Earlier estimates put it at 135,000, as reflected in Table 15.3 [28, p. 473].

- *Strict control zone (SCZ).* Region where the ^{137}Cs density on the ground exceeds 15 Ci/km^2 is the region of strict control [28, p. 475]. The initial population of this region was about 270,000 [28, p. 475]. At this level, resettlement is obligatory in Ukraine, but not necessarily mandatory in Belarus and Russia [32, p. 36]. In all three countries, people have a right to resettle from regions where the density exceeds 5 Ci/km^2.
- *Other contaminated areas.* These are regions where the ^{137}Cs ground density is between 1 and 15 Ci/km^2. Most of the people in these regions were in areas at the low end of the range (i.e., 1–5 Ci/km^2).

The future health impacts of Chernobyl on these groups can be estimated from a study of the radiation doses. A summary of average and collective doses for the groups considered above is given in a review by Elizabeth Cardis and colleagues, prepared as a background paper for the *One Decade After Chernobyl* conference that was held in 1996 with the joint sponsorship of the IAEA and the World Health Organization (WHO) [30]. It also included data for the subgroup of liquidators who worked in 1986–1987, when the radiation levels were highest. In this paper, cancer mortality was estimated separately for solid cancers and leukemia [33]. The results are presented in Table 15.3.

The doses for the populations other than the liquidators are doses received from 1986 to 1995.[18] This represents about 60% of the total estimated long-term dose (1986–2056) [28, Table 33], suggesting that the doses in Table 15.3 underestimate the total impact of the accident. On the other hand, as the authors pointed out, no dose and dose rate effectiveness factor (DDREF) was applied in estimating the cancer fatalities (see Section 4.3.4). Thus, the calculated number of fatalities is not an underestimate if a DDREF of 2 is the "correct" factor to apply. Overall, however, it is to be remembered that there are large uncertainties in both the doses and the dose–response relation. In particular, the number of fatal cancers may be greatly overestimated, because the calculation is based on the linearity hypothesis. Thus, the 9,000 excess fatalities of Table 15.3 are the predictions of a specific model, not an assured outcome, and even in the context of the model, the results are approximate.

It is seen from Table 15.3 that the calculated number of excess fatalities is, in most cases, small compared to the normal natural rates. Even when in principle the excess is statistically significant, uncertainties in the "normal" rate may make it difficult to confirm the result by observations. The best opportunity for doing this may be for leukemia incidence among the liquidators, where a 25% excess is predicted.

The average doses for most of the people in these groups are well below the 10-year background level of 20–30 mSv (roughly 2.4 mSv/year), but the

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[18] In such calculations, the calculated dose includes the contributions from all radionuclides, with the ^{137}Cs density taken as an indicator of the concentrations of other radionuclides. After the first year, most of the dose is due to ^{134}Cs and ^{137}Cs; after the first decade, most of the ^{134}Cs has decayed, leaving ^{137}Cs as the dominant contributor.

Table 15.3. Cumulative radiation doses (1986–1995) and calculated deaths over a 95-year period among populations in the vicinity of Chernobyl and among liquidators working in the 1986–1987 period (see text).

			Solid Cancer Deaths		Leukemia Deaths	
Group	Population size	Average dose (mSv)	Normal Rate	Calc. Excess[a]	Normal Rate	Calc. Excess[a]
Liquidators (1986–1987)	200,000	100	41,500	2,000	800	200
Evacuees (30-km zone)	135,000	10	21,500	150	500	10
Residents, SCZ	270,000	50	43,500	1,500	1,000	100
Residents, other areas	6,800,000	7	800,000[b]	4,600	24,000	370

[a] This calculated number of excess fatalities is based on the linearity hypothesis, without a DDREF.

[b] This number, given in Ref. [33] for the normal rate, appears inconsistent with the 16% normal cancer incidence rate indicated for all groups other than the liquidators.

Source: Ref. [33, p. 255].

liquidators and the SCZ residents received higher doses. By 2003, with most of the long-term dose already received, the annual dose from Chernobyl radionuclides is below natural background radiation levels, even in the SCZ.

Controversies over Health Effects from Chernobyl

It is too soon for the health effects of the Chernobyl accident to have been fully manifested, for either the workers who participated in the Chernobyl cleanup efforts or the surrounding population. Most cancers, other than leukemia, have a latent period of 10 years or longer. Further, it is impossible to attribute a given observed cancer to a particular cause. The ambiguities of statistical evidence, the dramatic nature of anecdotal evidence, and the strong incentives to reach one conclusion or another almost guarantee that there will be very different assessments of the consequences of Chernobyl.

Even at Three Mile Island, there has been some controversy over the consequences (see Section 15.2.3), and the situation is likely to be far more difficult in the Chernobyl case, especially in view of the political and economic problems in the area. These may make it difficult to obtain satisfactorily comprehensive and reliable records. It is important that vigorous efforts be made to carry out detailed health surveys and data analyses, in order to improve our understanding of the effects of prolonged exposures to radiation at low and intermediate levels.

The disagreements about Chernobyl could be reduced if there are careful epidemiological studies by a group whose legitimacy is widely accepted. There is a precedent for this in the Radiation Effects Research Foundation,[19] which has carried out continuing studies of the aftermath of Hiroshima and Nagasaki. In this vein, the 2002 United Nations report proposed the establishment of an International Chernobyl Foundation to “channel resources into health and ecological research relating to the effects of the Chernobyl accident” [32, p. 17].

15.3.6 Worldwide Radiation Exposures from Chernobyl

One of the important set of results reported at the *One Decade After Chernobyl* conference was an UNSCEAR assessment of total global population doses. These results, as presented in a paper by R.G. Bennett, are summarized in Table 15.4.

The total collective dose commitment in the northern hemisphere is estimated to be 600,000 person-Sv, where the dose commitment is calculated until 2056 (70 years after the accident). For populations that were not near Chernobyl, the accident added relatively little to the natural background. In

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[19] This was formerly known as the Atomic Bomb Casualty Commission. It is a joint research activity of the United States and Japan.

Table 15.4. Distribution of radiation doses from Chernobyl accident (total lifetime collective dose commitment = 600,000 person-Sv).

Category	Percent
Geographical distribution	
Former Soviet Union (FSU)	36
Other Europe	53
Other, northern hemisphere	11
Time distribution	
First year	~ 33
Later years	~ 67
Contributing radionuclides	
^{137}Cs	70
^{134}Cs	20
^{131}I	6
Other[a]	4
Mode of exposure	
External radiation	60
Internal radiation	40

[a] Ascribed to "short-lived radionuclides deposited immediately after the accident."
Source: Ref. [34, p. 125].

the first year after Chernobyl, when the impact of the accident was greatest, the collective dose in Europe (outside the FSU) was about 100,000 person-Sv, corresponding to an average individual dose of 0.2 mSv for a population of about 500 million.[20] Thus, on average, Chernobyl in the first year added about 8% to the average natural radiation dose of 2.4 mSv/yr. The total per capita doses in Europe (outside the FSU) summed over the 70 years following the accident are expected to average about 0.7 mSv from Chernobyl and 170 mSv from natural radiation sources [35, p. 369]. For North America, the average dose is estimated to be 0.001 mSv in the first year and 0.004 mSv summed over all years.

If one uses a risk factor of 0.05 deaths per person-Sv, the worldwide collective dose of 600,000 person-Sv would imply a total toll from Chernobyl of 30,000 deaths spread over more than 70 years (mostly in Europe, including the FSU).[21] For the most part, these 30,000 deaths would be impossible to identify or verify. For example, about 16,000 of these deaths would be in Europe (outside the FSU). In the same time period, the European population is

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[20] The country outside the FSU with the highest first-year dose was Bulgaria, with an average first-year dose of slightly under 0.8 mSv [34, p. 122].

[21] It should again be noted that considerable controversy surrounds the linearity hypothesis, especially when applied to the low individual doses considered here.

expected to suffer over 100,000,000 "natural" cancers.[22] The calculated 0.02% increase—if it occurs—would be undetectable.

Different perspectives on Chernobyl may be stated as follows: (a) The accident may lead to about 30,000 cancer deaths; (b) the number of cancer deaths attributable to Chernobyl is a very small fraction of those occurring "naturally"; or (c) it is inappropriate to calculate expected deaths from the collective dose, when most of the collective dose is made of individual doses that are well under 10% of the natural background. Depending on which of these formulations is taken to be the more appropriate, Chernobyl may be considered to have been either a major global disaster or no more than a serious accident, with tragic local consequences.

15.3.7 General Effects of the Chernobyl Accident

Human Consequences for People in the Affected Region

One of the major consequences of the Chernobyl accident was the fear engendered in nearby populations. An IAEA study of the consequences of the Chernobyl accident was requested in 1989 by the USSR government, apparently prompted by concerns among people living in the vicinity of Chernobyl but not close enough to have been among those originally evacuated from the exclusion zone. The regions considered were places where the ground surface concentrations of ^{137}Cs exceeded 5 Ci/km^2. It embraced an area of about 25,000 km^2, with a population of about 825,000 [37, p. 3].

This study, known as the International Chernobyl Project (ICP), was undertaken by an international committee under the sponsorship of the IAEA, with the assistance of the WHO, UNSCEAR, and other international organizations. An overview of these results was published in Spring 1991 [37]. In the populations studied, the International Chernobyl Project found no indications of adverse medical consequences from the radiation. In its conclusions it stated

> ....[there were] no health disorders that could be attributed directly to radiation exposure. The accident had substantial negative psychological consequences in terms of anxiety and stress...[37, p. 32]

This referred to health effects as of 1991.

A similar stress on psychological factors appears in a report on the *Human Consequences of the Chernobyl Nuclear Accident* that was published in 2002. This report was commissioned by several United Nations agencies and the WHO, with the goal of studying the "current conditions in which people affected by the Chernobyl accident are living" and to make recommendations for addressing their needs [32, p. ii]. It lays particular stress on the disruption

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[22] The "over 100,000,000" figure is a crude extrapolation from Ref. [36], where an estimate of 88,000,000 deaths in Europe is given for the next 50 years.

of the lives of the people who were evacuated and the fears experienced by them and people still living in contaminated areas. Economic conditions have been poor in the countries of the former Soviet Union, and the Chernobyl accident has made matters worse due to the costs of remedial measures and the inhibitions on growing crops in contaminated areas.

While disclaiming an intent to "minimize the seriousness of the situation for health and well-being or the role played by the exposure to ionizing radiation," the report suggests giving priority to improving "basic primary health care, diet, and living conditions" [32, p. 8]. Among the adverse consequences of the Chernobyl accident, the report describes the social demoralization which has accompanied the dislocation of populations and their living with a poorly understood hazard. It suggests that "determined efforts need to be made at national and local level to promote a balanced understanding of the health effects of radiation among the public, many of whom at present suffer distress as a result of ill-founded fears" [32, p. 10].

One of the difficulties in assessing the health impacts of the radiation exposures is the generous compensation afforded to people who can establish injury and who, therefore, have an incentive to find health damage. Children in areas with a ^{137}Cs concentration of over 5 Ci/km^2 are entitled to 2 months of health holidays. With accompanying adults, in the year 2000 almost 300,000 people took holidays in Belarus and about 372,000 in Ukraine. Overall, as described in the UN report:

> [s]carce resources are allocated not primarily on the basis of medical need but rather on an individual's ability to register as a victim. The system has promoted an exaggerated awareness of ill-health and a sense of dependency, which has prevented those concerned from taking part in normal economic and social life. The pattern of behavior was described by the Kiev Conference on the Health Effects of the Chernobyl Accident...as the "Chernobyl accident victim syndrome."[32, p. 32]

Extended Effects of the Chernobyl Accident

The above-cited report suggests that Chernobyl produced a demoralization among the neighboring population, beyond that which could be directly attributed to the health effects of radiation. Chernobyl may also have had profound effects on the Soviet Union as a whole. The technological failure at Chernobyl and the attempted coverup of the accident is cited as one of the reasons for the collapse of confidence in the Soviet system. This possibility is reflected, for example, in an op-ed piece entitled "Will SARS be China's Chernobyl?" Before drawing the parallel with SARS, the author writes:[23]

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[23] This article, by James Goldgeier, Director of the Institute for European, Russian, and Eurasian Studies at George Washington University appeared in a number of newspapers in April 2003, e.g., the *Los Angeles Times* on April 23, 2003, [38].

> ...a major event in the Soviet Union's downward spiral was the accident at the Chernobyl nuclear power station in April 1986. The Soviet Union initially tried to keep a tight lid on what had occurred, but radioactive fallout was not confined to Soviet territory, and European governments were quick to announce that initial reports from Moscow underplayed the danger....
>
> Chernobyl alone would not have brought down the Soviet Union. However, the government's clumsy reaction and the growing demands for the truth on this and other issues helped stir the caldron of resentment that culminated in Soviet collapse.

The effects of Chernobyl on the stability of the Soviet Union may have been magnified by the fact that, by chance, the radiation exposures and negative impacts of the accident were greatest in two Soviet Republics that already had separatist tendencies. As described by Martin Malia, "Chernobyl, in particular, accelerated the development of Ukrainian and Belorussian separatist sentiments; and the local apparatus easily found it in their interests to espouse this sentiment against Moscow" [39, p. 440].

The accident also had a great effect on nuclear power. Like the Soviet Union, nuclear power was facing problems of its own, prior to Chernobyl. The shock of the Three Mile Island accident, 7 years earlier, had not fully dissipated and the post-TMI improvements in nuclear power plants had not yet paid off (e.g., in the higher capacity factors that began in the United States in the 1990s). Chernobyl came at a time when nuclear power was already facing economic and political difficulties, and it reinforced the existing public fears that contributed to these difficulties. There is little justification for extending the analogy and assuming that nuclear power will go the way of the Soviet Union. However, even if not a fatal setback, the Chernobyl accident was a major blow to its progress.

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