CONF-8709104--3

THE CHERNOBYL ACCIDENT - CAUSES AND CONSEQUENCES*

CONF-8709104--3

DE87 014786

A. P. Malinauskas
Oak Ridge National Laboratory
Oak Ridge, Tennessee 37831

To be presented at the American Nuclear Society Topical Conference on Population Exposure from the Nuclear Fuel Cycle, September 15-18, 1987, Oak Ridge Associated Universities, Garden Plaza Hotel, Oak Ridge, TN.

---

*Research sponsored by the U.S. Nuclear Regulatory Commission under Interagency 0551-0551-A1 with the U.S. Department of Energy under contract DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

THE CHERNOBYL ACCIDENT - CAUSES AND CONSEQUENCES

A. P. Malinauskas
Oak Ridge National Laboratory
Oak Ridge, Tennessee 37831

ABSTRACT

Two explosions, one immediately following the other, in Unit 4 of the Chernobyl nuclear power station in the Soviet Union signalled the worst disaster ever to befall the commercial nuclear power production industry. This accident, which occurred at 1:24 am on April 26, 1986, resulted from an almost incredible series of operational errors associated, ironically, with an attempt to enhance the capability of the reactor to safely accommodate station blackout accidents (i.e., accidents arising from a loss of station electrical power).

Disruption of the core, due to a prompt criticality excursion, resulted in the destruction of the core vault and reactor building and the sudden dispersal of about 3% of the fuel from the core region into the environment. Lesser but significant releases of radioactivity continued through May 6, 1986, before attempts to contain the radioactivity and cool the remnants of the core were successful.

The amount and composition of material released in the course of the accident remain somewhat uncertain, and inconsistencies in the release estimates are evident. The Soviet estimates, in addition to the dispersal of about 3% of the fuel, include complete release of the noble gas core inventory, 20% of the fission product iodine inventory, 15% of the tellurium inventory, and 10-13% of the fission product cesium inventory. The iodine and cesium release estimates are not consistent with the noble gas values, and are as much as a factor of two less than some estimates made by experts outside the Soviet Union.

INTRODUCTION

There have been only four significant accidents involving nuclear reactors since the first such reactor was brought to criticality on December 2, 1942. Two of these, the Windscale accident in October, 1957, and the accident at Three Mile Island in March, 1979, were due to thermal transients; although considerable amounts of radioactivity escaped into the environment in both cases, no fatalities resulted. The remaining two accidents, the SL-1 accident at Idaho Falls in January, 1961, and the Chernobyl accident in April, 1986, involved reactivity transients; these accidents, in addition to releasing fission product radioactivity into the environment, resulted in fatalities to personnel onsite.

Hence, the Chernobyl accident was neither unique in cause nor in consequence, but the effects completely dwarfed the previous incidents in magnitude. For example, whereas the Windscale accident resulted in the escape of about 2×10^3 curies of ^{131}I into the biosphere,[1] approximately 7×10^6 curies of ^{131}I escaped from the Chernobyl reactor.[2] Similarly, 3 reactor technicians died as a result of the SL-1 accident,[3] but 31 fatalities to onsite and emergency response personnel were experienced in the course of the Chernobyl disaster.[4]

THE RBMK-1000 REACTOR[2]

The ill-fated reactor was one of four graphite-moderated, water-cooled reactors that were operating at the Chernobyl site in the Soviet Union. Each of the four reactors is of the RBMK-1000 design; essentially a boiling water reactor capable of producing 1000 MW of electrical energy and fueled using sintered uranium dioxide pellets 11.5 mm in diameter and 15 mm long. The pellets are stacked in zirconium/1% niobium alloy tubes; 18 of these tubes are arranged in two concentric rings to form a 3.5 m long subassembly, and two subassemblies are positioned end to end to form a fuel assembly.

The core of an RBMK-1000 reactor is a vertical cylinder that is 11.8 m in diameter and 7 m tall. It is formed from 2488 graphite blocks which serve as reactor moderator material. The graphite assembly contains cylindrical openings to accommodate 1661 fuel channels and 211 channels for reactor control rods. Like the fuel rods, the channels are fabricated from a zirconium/niobium alloy (but containing 2.5% niobium). Outside the core region, the zirconium alloy channels are connected to corrosion-resistant steel piping. The graphite itself is encased in a thin, cylindrical, steel vessel through which a helium-nitrogen gas mixture is made to flow continuously. This vessel thus contains over 1870 penetrations in its upper and lower parts, due primarily to the fuel and control rod channels.

A fuel assembly is suspended in each of the fuel channels. Fission heat is extracted using water as coolant, which is allowed to boil. The two-phase coolant mixture in each fuel channel is extracted from the top of the core and transported to one of four steam separators. In the steam separators, the liquid phase is separated from the steam phase and returned, with makeup coolant, to the core of the reactor, whereas the steam phase is used to drive one of two turbine-generators.

The rods used for reactivity control are cooled with water independently of the fuel assemblies. They consist of aluminum alloy casings which contain boron carbide as the neutron poison.[5] A graphite follower is attached to the individual control rods to displace the water which would otherwise fill the control rod channel as the rod is removed from the core to increase power. (In the RBMK-1000 reactors, water is, in a special sense, a neutron "poison.")

Unlike the other types of commercial light water reactors, which use water both as coolant and as neutron moderator, conversion of water into steam within the core of the RBMK-1000 reactor results in an increase in reactor power; the core is thus said to have a "positive void coefficient." This characteristic played an important role in the Chernobyl accident.

THE CHERNOBYL ACCIDENT[2]

The Unit-4 reactor at the Chernobyl site was to be shut down for routine maintenance. Prior to shutdown, however, an experiment was planned to determine the feasibility of utilizing the turbine-generators to supply electricity to selected safety systems while the turbines were coasting down. In this manner the operators hoped to demonstrate that electrical power could continue to be supplied to these components in the event of a loss of station electrical power (a station "blackout") during the brief period of time that is required for standby diesel generators to come to full power. The test was not unusual in that two such tests had been conducted previously,[4] but were unsuccessful because the decay of electrical output occurred much more rapidly than the power output of the turbine. The new experiment was to test modifications to the voltage regulation system which were made in an attempt to more closely match the turbine power and electrical generator output decays.

The experiment was to be conducted while the reactor power level was at 20-30% of its rated capacity. At 1:00 am on April 25, 1986, the operators initiated a pre-planned power reduction sequence. When the reactor was reduced to 50% power, one of the two turbine-generators was isolated and shut down, power to the reactors' coolant pumps was reconfigured, and the emergency core-cooling system was disconnected from the system. At this point, however, the shutdown operations were interrupted by a need to keep the reactor on the electrical grid. The reactor continued to operate at 50% power for about 9 hours; during this time, in violation of operating procedure, the emergency core-cooling system remained isolated from the reactor system.

The shutdown process was resumed at 11:10 pm. At this point, however, it was reported[6] that the operators deviated from the planned ramp rate in order to get on with the tests. If so, the operators violated a test procedure which was itself deficient,[2] and upset the delicate balance between fission product xenon-135 production and removal. The operators then compounded the problem by permitting the reactor power, through operational error, to decrease considerably below the level intended for the experiment. In so doing, the core power began to fluctuate, and the operators continued in their attempts to increase the power level even though the reactor was now at a power level that was considered unsafe for continuous operation. This circumstance was likewise ignored. In addition, in an attempt to steady the core and increase the power level, a number of safety systems were disengaged which would have automatically shut down the reactor, and the control rods were removed both in number and in extent that the reactor was now operating in a condition that was in gross violation of the very strictest operating procedures. The operators appeared to have been fully aware of the situation, but ignored it.

Even at this stage, the reactor was only at about the 6% power level, considerably less than that intended for the experiment. Nonetheless, the operators disengaged a final automatic shutdown safety system and, at 1:23 am on April 26, 1986, began the test. About 30 sec later, on observing a sudden increase in power level, the operators attempted to trip the reactor; shortly thereafter, two explosions, one immediately following the other, occurred, and fragments of burning material were thrown into the air above the reactor building.

There appears to be little doubt that the accident involved a reactivity excursion which occurred because of the positive void coefficient of the core and its peculiar significance at low reactor power operation. Also, it is likely that the situation was initially worsened by a positive insertion of reactivity when the control rods began to be inserted into the core, owing to the extreme positions to which they had been removed, and the use of graphite followers for water displacement.[5]

The nature of the explosions has not been identified as clearly. The first explosion may have been the result of a rapid overpressurization of the coolant system, followed by the ejection of hot fragmented fuel into coolant and a resultant steam explosion. Another hypothesis is that the initial explosion was the steam explosion, and the second explosion occurred in the reactor building as hydrogen, which had been formed from reaction between the coolant and the zirconium alloy in the core, was rapidly mixed with the air in the building in the course of the steam explosion. Still another hypothesis questions the existence of the second explosion.[6]

The energy with which the core and reactor building were destroyed caused the initial releases of radioactivity to occur at high elevations.

RADIOACTIVITY RELEASES

Daily releases of radioactivity from the Chernobyl plant are presented in Table I; these values, which do not include the noble gas fission products, were taken from the Soviet report.[2] Curiously, the Soviets chose to correct for radioactive decay by referring the results to May 6, 1986, ten days into the accident. As a consequence, the actual quantities of radioactivity that entered the environment prior to May 6 are considerably higher than the tabulated values. For example, the actual amount of radioactivity that escaped from the reactor on the first day of the accident has been estimated[7] to be 20 MCi, rather than the 12 MCi value cited.

TABLE I
Daily Releases of Radioactivity from the Chernobyl Reactor[2]

Time after Accident (days)	Release (MCi)[a]
0	12
1	4.0
2	3.4
3	2.6
4	2.0
5	2.0
6	4.0
7	5.0
8	7.0
9	8.0
10	0.1
14	−0.01
28	20×10^{-6}

[a]These values are corrected to May 6, 1986 (day 10), and do not include noble gas releases.

Examination of the data in Table I indicates that the escape of fission products from the reactor occurred in four phases. The first, of course, involved the initial, highly energetic release. This was followed by a gradual decrease in the release rate, due partly to the relocation of the core and partly to the deposition of about 5000 tons of material on the exposed reactor vault. This material, which included boron compounds, lead, dolomite, sand, and clay provided a filtering action which retarded fission product release. It probably also retarded natural cooling of the core, since, on the sixth day, the daily rate of release began to increase, possibly because a fissure had formed in the blanket material. This constituted the third phase of the release pattern. The fourth phase was the sudden drop in release rate on the tenth day after the accident, which coincided with the injection of cold nitrogen into the space beneath the reactor.

Soviet estimates[2] of the fractions of core inventory of selected fission products that had escaped into the environment are presented in Table II; these data suggest that about 3% of the core itself had been dispersed into the biosphere. However, a number of inconsistencies in the results are apparent.

TABLE II
Estimates[2] of the Release of Selected Radionuclides

Nuclide	Fraction of Inventory Released
^{85}Kr	1.00
^{133}Xe	1.00
^{131}I	0.20
^{132}Te	0.15
^{134}Cs	0.10
^{137}Cs	0.13
^{99}Mo	0.02
^{95}Zr	0.03
^{106}Ru	0.03
^{140}Ba	0.06
^{144}Ce	0.03
^{90}Sr	0.04
^{240}Pu	0.03
^{242}Cm	0.03
^{239}Np	0.03

The Soviets apparently made few, if any, measurements of airborne noble gas concentrations, and merely assumed complete escape of this class of fission products. This implies that the entire core had attained temperatures in the vicinity of 1400°C or greater.[8] At these temperatures, experimental measurements of fission product releases from irradiated uranium dioxide fuel indicate identical fractional releases of the noble gas, iodine, and cesium nuclides under both chemically oxidizing9 and chemically reducing[10] conditions. The values presented in Table II for ^{85}Kr, ^{133}Xe, ^{131}I, ^{134}Cs, and ^{137}Cs thus suggest that either the estimates of the release of the noble gases has been badly overstated or, conversely, that the iodine and cesium releases have been underestimated significantly. Another possibility is that the releases of cesium and iodine species had been attenuated considerably by physical and chemical processes which occurred in the immediate vicinity of the core. This no doubt happened in the Windscale accident, in which 100% release of the noble gases was noted from the affected region of the core, but only 12% of the iodine inventory of the affected fuel entered the biosphere.[11] At Windscale, however, the escape pathway was comparatively long and was intercepted by a filtration system. A more marked difference between noble gas and iodine escape fractions, by several orders of magnitude, was noted for the Three Mile Island accident. In this case, whereas some 8 million curies of ^{133}Xe entered the biosphere, only 15 Ci of ^{131}I escaped. This has been shown to result from the chemical characteristics of the accident and the interception of the escape pathway by water.[11]

None of the mitigating features that were experienced at Windscale and at Three Mile Island were of course operable during the initial, explosively-driven releases at Chernobyl, but some may have come into play after the core had been covered by the materials which were deposited by helicopters. At present, the effects of possible attenuation mechanisms has not been explored in detail; nor is it clear that all of the data with which to arrive at unambiguous conclusions are available.

A complicating aspect of the data presented in Table II concerns a lack of detail in the Soviet report of how these estimates were made. Several investigators[7,12] have inferred that the values tabulated represent estimates of radionuclides released from the reactor and deposited only within the boundaries of the Soviet Union. If so, the results for cesium, tellurium, and iodine may be a factor of 2 or 3 too low.[12] The evidence, however, is somewhat tenuous.

It is clear that a discrepancy exists in the Soviet report[2] between the amount of radioactivity released and the fraction of inventory released for the cesium nuclides. For example, it is possible to back-calculate the total inventory of radioactivity in the core of the reactor prior to the accident independently from data provided in the report for individual nuclides. When this is done, the calculations[7] indicate an inventory of about 35 x 10^8 Ci. Although the results for ^{131}I and ^{132}Te are consistent with this value, the values back-calculated from the data for both ^{134}Cs and ^{137}Cs are too low, by about a factor of two. Evidently some of the data presented for the cesium nuclides are in error.

The large tellurium release suggests its escape under chemically oxidizing conditions, i.e., extensive oxidation of the zirconium alloy, which is an effective gettering agent for elemental tellurium, had occurred. Under such conditions, one can expect an enhanced release of ^{99}Mo and ^{106}Ru, owing to formation of volatile oxides, and little or no enhancement of ^{140}Ba and ^{90}Sr, whose oxides are considerably less volatile than their elemental forms. An examination of the data in Table II suggests just the reverse behavior. Hence, if the results listed in Table II are fairly accurate and are indeed representative of the total quantities of fission products that had escaped into the environment (and not just an undetermined fraction, as has been implied earlier), then the chemical environment characteristic of the accident is more complex than first thought. Attempts to include effects due to the possible carburization of the fuel have not been entirely successful in accounting for the anomalous behavior observed.[7]

CONCLUDING REMARKS

Unlike the Three Mile Island reactor accident, which at first appeared to be relatively benign, it was recognized at the outset that there was no possibility for eventually returning the stricken reactor at the Chernobyl site to power production. As a consequence, a detailed post-accident examination of the reactor was neither practical nor possible, and many questions concerning the course of the accident will remain unanswered. Moreover, because the RBMK design differs in many important respects from commercial light water reactors elsewhere, there is little incentive to develop a detailed understanding of the Chernobyl accident. But the subsequent transport and distribution of the fission products that were introduced into the biosphere and, more importantly, the consequences of this introduction into the environment, are pertinent. Similarly, since the accident resulted in the relocation of large segments of the population, much could be learned from details regarding emergency response actions. Resolving the many issues that have been raised in these areas, however, will require the continued cooperation and dialogue that the Soviets displayed in its August, 1986 presentation to the International Atomic Energy Agency.[2]

(Research sponsored by the Office of Nuclear Regulatory Research, U.S. Nuclear Regulatory Commission under Interagency Agreement 0551-0551-A1 with the U.S. Department of Energy under contract DE-AC05-84OR21400 with the Martin Marietta Energy Systems, Inc.)

REFERENCES

1. G. B. SCHOFIELD, "Environmental Health and Windscale," paper presented to a meeting of the Oak Ridge National Laboratory Health and Life Sciences Division, Oak Ridge, Tennessee (Oct. 1979).

2. USSR State Committee for Atomic Energy Utilization, "The Accident at the Chernobyl AES and Its Consequences" (Aug. 1986).

3. T. J. THOMPSON, "Accidents and Destructive Tests," Chapter II in *The Technology of Nuclear Reactor Safety*, Volume 1, T. J. Thompson and J. G. Beckerley, eds., The M.I.T. Press, Cambridge, Massachusetts (1964).

4. A. P. MALINAUSKAS, J. R. BUCHANAN, R. A. LORENZ, and T. YAMASHITA, "Calamity at Chernobyl," *Mech. Eng.*, p. 50 (Feb. 1987).

5. U.S. Department of Energy, "Report of the U.S. Department of Energy's Team Analyses of the Chernobyl-4 Atomic Energy Station Accident Sequence," Report DOE/NE-0076 (Nov. 1986).

6. T. S. KRESS, M. W. JANKOWSKI, J. K. JOOSTEN, and D. A. POWERS, "The Chernobyl Accident Sequence," *Nucl. Safety* **28**, 1 (1987).

7. D. A. POWERS, T. S. KRESS, and M. J. JANKOWSKI, "The Chernobyl Source Term," *Nucl. Safety* 28, 10 (1987).

8. U.S. Nuclear Regulatory Commission, "Technical Bases for Estimating Fission Product Behavior During LWR Accidents," Report NUREG-0772 (June 1981).

9. F. C. IGLESIAS, C. E. L. HUNT, D. S. COX, N. A. KELLER, R. D. BARRAND, J. R. MITCHELL, and R. F. O'CONNOR, "Fission Product Release and UO_2 Oxidation," *Proc. of the Workshop on Chemical Reactivity of Oxide Fuel and Fission Product Release*, April 7-9, 1987, Berkeley, Gloucestershire, England (in press).

10. M. F. OSBORNE, J. L. COLLINS, and R. A. LORENZ, "Experimental Studies of Fission Product Release from Commercial Light Water Reactor Fuel Under Accident Conditions," *Nucl. Technol.*, 78, 157 (1987).

11. D. O. CAMPBELL, A. P. MALINAUSKAS, and W. R. STRATTON, "The Chemical Behavior of Fission Product Iodine in Light Water Reactor Accidents," *Nucl. Technol.*, 53, 111 (1981).

12. E. A. WARMAN, "Soviet and Far-Field Radiation Measurements and Inferred Source Term from Chernobyl," paper presented at the New York Chapter Health Physics Society Symposium on the Effects of the Nuclear Reactor Accident at Chernobyl, Brookhaven National Laboratory, April 3, 1987.