THE CHERNOBYL REACTOR ACCIDENT SOURCE TERM: DEVELOPMENT OF A CONSENSUS VIEW

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I INTRODUCTION

In August 1986, scientists from the former Soviet Union provided the nuclear safety community with an impressively detailed account of what was then known about the Chernobyl accident [1]. This included assessments of the magnitudes, rates, and compositions of radionuclide releases during the ten days following initiation of the accident. A summary report based on the Soviet report, the oral presentations, and the discussions with scientists from various countries was issued by the International Atomic Energy Agency [2] shortly thereafter.

Ten years have elapsed since the reactor accident at Chernobyl. A great deal more data is now available concerning the events, phenomena, and processes that took place. The purpose of this document is to examine what is known about the radioactive materials released during the accident. The accident was peculiar in the sense that radioactive materials were released, at least initially, in an exceptionally energetic plume and were transported far from the reactor site. Release of radioactivity from the plant continued for about ten days.

A number of more recent publications and results from scientists in Russia and elsewhere have significantly improved our understanding of the Chernobyl source term. Because of the special features of the reactor design and the pecularities of the Chernobyl accident, the source term for the Chernobyl accident is of limited applicability of the safety analysis of other types of reactors.

II CORE INVENTORIES

There have been a number of attempts to estimate the radionuclide inventories of the Chernobyl reactor at the time of the accident. Early attempts were handicapped by imprecise knowledge of the fuel burnup in the reactor. Begichev et al. [3] have clarified the burnup history of fuel in the reactor. Their estimate of burnup average is 10 910 MWd/t. Sich [4] has assembled data on samples of core debris remaining in the reactor and concludes that in average the burnup is about 11660 ± 650 MWd/t.

Various estimates of the radionuclide inventories are listed in Table 1. Inventories attributed in this table to Warman [5] were derived from data provided by INSAG [2] which were based on the Soviet report [1]. These estimates have been critically reviewed by Clough [6] and by Devell [7], who noted that typographical errors may be responsible for overestimation of the ^{99}Mo inventory by a factor of 10 and underestimation of the ^{239}Np inventory by a factor of 10. Corrected values are shown parenthetically in the table. Clough provided comparison inventories obtained with the FISPIN code assuming average fuel burnups of 10300 and 13500 MWd/t. He also cited results obtained with the ORIGEN2 code by Anttila [8], who assumed an average burnup of 10000 MWd/t for fuel in seven burnup ranges from 2500 to 17500 MWd/t. Kichner and Noack [9] used the ORIGEN code to obtain inventories for fuel with an average burnup of 12850 MWd/t. Little [10] used the ORIGEN code and an average burnup of 10300 MWd/t to estimate core inventories. Begichev [3] used varying burnups according to reactor operation to obtain estimates of the core inventories of radioactive materials. These burnup histories and the WIMS/CACH2 codes were

Table 1. Estimates of radionuclide inventories at the time of accident initiation. [a)]

Nuclide	Inventory (Bq) by						
	USSR [1] INSAG [2] Warman [5]	Clough [7]	Anttila [8]	Kirchner & Noack [9]	Little [10]	Sich [4]	Begichev et al. [3]
^{85}Kr	3.3E16	--	--	--	2.5E16	2.8E16	3.3E16
^{133}Xe	7.3E18	--	--	--	6.2E18	6.5E18	6.3E18
^{131}I	3.1E18	2.9E18	2.9E18	2.4E18	3.0E18	3.1E18	3.2E18
^{134}Cs	1.9E17	1.1E17	1.6E17	1.4E17	2.0E17	1.7E17	1.8E17
^{136}Cs	--	--	--	9.0E16	9.6E16	6.3E18 (1.1 E17)	--
^{137}Cs	2.9E17	2.4E17	2.2E17	2.7E17	2.3E17	2.6E17	2.8E17
^{132}Te	3.3E18	4.1E18	4.4E18	4.4E18	4.1E18	4.5E18	2.7E18
^{89}Sr	2.3E18	3.6E18	4.0E18	3.2E18	3.0E18	4.0E18	2.3E18
^{90}Sr	2.0E17	2.0E17	1.8E17	2.0E17	1.7E17	2.3E17	2.0E17
^{140}Ba	5.3E18	5.8E18	5.6E18	5.5E18	5.4E18	6.1E18	4.8E18
^{95}Zr	--	5.8E18	--	5.3E18	5.1E18	5.8E18	5.6E18
^{99}Mo	7.3E19 (7.3E18)	5.5E18	5.7E18	--	5.2E18	6.1E18	4.8E18
^{103}Ru	5.0E18	4.3E18	4.0E18	4.6E18	4.5E18	3.8E18	4.8E18
^{106}Ru	2.0E18	8.9E17	7.9E17	1.1E18	1.2E18	8.6E17	2.1E18
^{141}Ce	5.6E18	5.6E18	5.4E18	--	5.1E18	5.6E18	5.6E18
^{144}Ce	3.2E18	3.9E18	3.4E18	3.8E18	3.4E18	3.9E18	3.3E18
^{238}Pu	1.0E15	--	--	7.3E14	1.6E15	1.3E15	1.0E15
^{239}Pu	8.5E14	--	--	8.0E14	9.6E14	9.5E14	8.5E14
^{240}Pu	1.2E15	--	--	1.6E15	1.6E15	1.5E15	1.2E15
^{241}Pu	1.7E17	--	--	1.9E17	1.8E17	1.8E17	1.7E17
^{239}Np	3.6E18 (3.6E19)	4.7E19	5.1E16	6.1E19	6.7E19	5.8E19	2.7E19
^{242}Cm	2.5E16	--	--	3.3E16	3.3E16	4.3E16	2.6E16

[a)] Figures in paranthesis are the final corrected values.

used by Sich [4] to estimate inventories. A corrected value for ^{136}Cs [11] is shown parenthetically in Table 1.

There is general agreement among the various estimates of core inventories shown in Table 1. There are, however, large-enough variations that some caution is needed when inventories are used to calculate release fractions. Estimates of inventories made by Begichev et al. [3] may be the most reliable since they were calculated with the most detailed fuel history. Notable differences between results obtained by Begichev et al. and others are that the ^{132}Te and ^{89}Sr inventories are 30 to 40 percent lower and the ^{106}Ru inventory is 40 to 50 percent higher.

III RELEASE CHARACTERISTICS

The pattern of radioactivity release during the Chernobyl accident has been discussed by many authors [1-5, 12]. There was an initial, intense, release of radioactivity during the dynamic events following the reactivity insertion that started core disruption. This initial release included fragments of fuel as well as other types of aerosol particles, radionuclide vapors and noble gases. Though the released, radioactive material was lofted high above the reactor in an energetic plume, much of the material and especially the fragmented fuel particles, deposited within the borders of the former Soviet Union. Nevertheless, substanstial amount of radioactive material, including material composed of fuel fragments, was carried beyond these borders.

The initial, intense phase of the accident was not the end of radioactivity releases from Chernobyl. Releases of radionuclides continued for several days after the initial core disruption. The rates of radioactive material release declined rapidly after the initial dynamic stage of the accident. A broad minimum in the radioactive material release rate was reached about April 29. Then, radioactive material releases began to increase despite heroic efforts at the reactor site to mitigate and manage the accident. On or about May 5, some 9-10 days after accident initiation, the radioactive material release rates dropped by about 3 orders of magnitude. Release rates that had been on the order of 10^{16} Bq per day fell to an average estimated by Cambrey et al. [13] to be 9 x 10^{11} Bq per day, though there may have been episodic eruptions over the next few weeks [1, 4]. Buzulukov and Dobrynin indicate significant releases of radioactivity occurred 20-21 and 25-30 days after accident initiation [14]. These indications may have been the result of vaporization of dust-suppression solutions admitted to the reactor vault. The releases are thought not to have added greatly to the total radioactivity release from the plant.

Quantitative descriptions of the radioactivity releases during the accident were presented by Soviet scientists in 1986 based on air sampling and surveys of ground contamination within the Soviet Union [1]. Materials that went outside the borders of the Soviet Union were not included.

It has been assumed that the variations in the rates of radioactivity release could be explained by the behaviour of core debris within the reactor. It has long been known that a fairly vigorous natural circulation of air up through the damaged portion of the reactor provided an efficient transport of radionuclides released from the core debris. Further interpretation of the release has been complicated by uncertainties concerning the behaviour of the graphite moderator and the effects of many tons of lead, borax, clay, and sand dropped into the reactor vault to smother the burning graphite.

In recent years, it has been possible to re-enter the reactor, take samples, make measurements, and clarify some of the effects of deposited materials and to determine the fate of the core debris. Sich and Borovoi [4, 15] have published an account of these investigations. More recent investigations have been performed and updated figures of core debris distribution have been presented [16].

The most remarkable feature of the core debris is that some fraction of it melted and dissolved into the serpentine concrete lower biological shield of the reactor. This molten mass flowed into lower portions of the reactor where it froze. Apparently [4], little of the materials dropped from helicopters into the reactor vault actually landed on core debris. Consequently, these efforts at accident management little affected core debris behaviour or the releases of radioactive materials from the reactor.

Another remarkable finding of post-accident inspections of the reactor is that most of the graphite moderator has burned and disappeared. In 1986, it was thought that only about 20 percent of the graphite had burned, though some familiar with the damaged reactor claimed more had burned.

Based on these findings, Sich [4] has developed qualitative hypotheses concerning the behaviour of core debris following the initial dramatic events of the accident. He suggests that initially much of the fuel accumulated as a rubble bed intimately mixed with fragmented moderator graphite in the reactor vault. Combustion of the graphite in the rubble bed allowed fuel to segregate into an uncoolable mass. This mass heated sufficiently to penetrate into the lower biological shield. Eventually, a fairly fluid core debris-concrete mixture was able to flow out of the reactor vault and quench in lower regions of the reactor building. When this happened, radionuclide releases were abruptly reduced. Sharp rises in the radionuclide concentrations above the reactor on May 7-9 and May 16 may indicate core debris relocation events.

It appears that there is now sufficient evidence about core debris behaviour that predictions of the quantitative details of fuel behaviour including predictions of radionuclide release could be formulated. Following the initial, transient events, fuel would have been exposed to rather low oxygen potentials dictated by the equilibrium:

$$O_2 + 2C(solid) \Leftrightarrow 2CO(gas)$$

These conditions would favour the vaporization of radionuclides such as barium and strontium which are most volatile in the elemental state. Transport of vaporized species would be limited by the natural convection flow through a porous, gas-generating bed. As combustion of the graphite progressed, the porosity of the rubble bed would increase and fuel would be exposed to higher oxygen partial pressures. At higher oxygen partial pressures, radionuclides such as ruthenium, molybdenum, and technetium, which are most volatile in the oxidized state, would vaporize. Vaporization of the volatile oxides would become progressively less efficient as fuel segregated from the rubble of the moderator and attacked the biological shield at the base of the reactor vault. Partitioning of metallic fission products such as ruthenium and molybdenum from the fuel into the molten, steel liner of the biological shield would further affect vaporization of these elements.

Exposure of the fuel to high partial pressures of oxygen from the air would be expected to cause oxidation to U_3O_8. Strains produced in solid fuel by this oxidation will cause fracture and decrepitation. This fragmentation of the fuel by oxidation could be responsible for evidence of mechanical release of radionuclides late in the accident.

IV RADIONUCLIDE RELEASES

The fractional releases of individual radionuclides estimated to have occurred over the course of the Chernobyl accident in 1986 are shown in Table 2. The "initial estimate" in this table is that presented in 1986 by Soviet scientists [1]. The "current estimate" listed in the table is mainly adopted from Bedyaev et al [17], supplemented with results and comments by authors of this paper. The release of noble gases (krypton and xenon) was estimated to be 100 percent of the core inventory. The initial release estimates for the volatile radionuclides iodine, tellurium and cesium based on ground contamination in the Soviet Union varied between 10 and 20 percent. About 3 percent of the fuel and associated low volatility radionuclides were estimated to have been dispersed from the reactor building. Barium and strontium were indicated to have been released slightly more than the fuel material.

Initial release estimates shown in Table 2 were based on materials deposited only within the borders of the former Soviet Union. At the time the initial estimates shown in Table 2 were prepared, Soviet scientists did not have access to data on radionuclides deposited in other countries. In the discussion at the Vienna meeting in August 1986 it was accordingly suggested that the total release must be significantly higher.

Warman [5] was among the first to publish revised, quantitative estimates of the Chernobyl reactor accident source term that included materials deposited outside the Soviet Union. Global dispersion codes (PATRIC, MESOS, GRID, ARAC) and compositions of samples obtained in various countries were used to estimate total iodine releases of 40-60 percent [18] of the initial core inventory. Tellurium and cesium releases were estimated to be between 30 and 50 percent of the initial core inventory. Confirmation of estimated releases of fuel and low volatility radionuclides could not be done by this technique since most of these materials deposited within the Soviet Union. A more recent, more comprehensive analysis of the long-range transport of radionuclides outside the former Soviet Union has been published by Gudiksen et al [19]. They conclude release fractions for cesium and iodine were 40 and 60 %, respectively. They estimated the release fraction of tellurium to be only 10 %. Release fractions for other, condensable radionuclides are estimated to be small since most of these materials deposited within the Soviet Union relatively near the reactor site and were not included in their worldwide transport analysis.

Current, best estimate releases of radionuclides from the Chernobyl reactor have been prepared by Bedyaev et al. [17] and are listed in Table 2. The 33 % release fraction of cesium was first announced 1989 by A.A. Borovoi [20]. The cesium release fraction, 33 ± 10 percent, has also been given by Buzulukov and Dobrynin [14] and is consistent with the observed release of 47 percent of the cesium from residual fuel in the reactor and the observed cesium retention within

Table 2. Estimates of Radionuclide Releases During the Chernobyl Accident

Radionuclide	Percent of Core Inventory Released	
	Initial Estimate [1][(a)]	Current Estimate[(b)]
^{85}Kr	100	100
^{133}Xe	100	100
^{131}I	20	50-60
^{132}Te	15	10-60 (c)
^{134}Cs	10	33±10
^{137}Cs	13	33±10
^{140}Ba	5.6	3.5-6 (d)
^{95}Zr	3.2	3.5
^{99}Mo	2.3	3.5-6 (e)
^{103}Ru	2.9	3.5-6 (e)
^{106}Ru	2.9	3.5-6 (e)
^{141}Ce	2.3	3.5
^{144}Ce	2.8	3.5
^{89}Sr	4	3.5-4.5 (d)
^{90}Sr	4	3.5-4.5 (d)
^{239}Np	3	3.5
^{238}Pu	3	3.5
^{239}Pu	3	3.5
^{240}Pu	3	3.5
^{241}Pu	3	3.5
^{242}Cm	3	3.5

(a) Based on integration of deposited materials within the borders of the Soviet Union only.
(b) Comments by authors of this paper given in notes c-e.
(c) Air samples above the reactor and in Nordic countries and deposition indicate a release fraction up to 2 times that of cesium.
(d) Selective releases of strontium in addition to releases caused by fuel fragmentation have been detected. The range given for barium doesn't reflect any new results.
(e) Air samples in Nordic countries indicate extensive Mo and Ru release relative to Ce and Zr in the late phase of the accident. From comparison of deposition of Ru with that of Ce as well as that of Cs the total release is estimated to 3.5-6 %.

the damaged reactor [17]. It is also consistent with analyses of the worldwide dispersion of cesium from the accident [5, 19]. Release fractions for iodine have been estimated to be as high as 80 percent, but the most likely range is between 50 and 60 percent. Tellurium release remains uncertain. Air sampling data and deposition in Nordic countries suggest that the release fraction for tellurium could have been up to two times higher than that for cesium [21, 49].

Estimated releases of barium and strontium are judged not be less than the releases estimated for low volatility elements such as cerium and zirconium. Evidence from solubility measurements of particle samples taken at various distances from the Chernobyl site [22] show there was, indeed, some selective release of strontium. On the other hand fuel material released was depleted to some extent in strontium and some other elements. These results indicate a total 3.5 - 4.5 % strontium release [49].

From the earliest days of the Chernobyl accident, it has been known that many of the radioactive particles transported outside the former Soviet Union were nearly pure ruthenium [23]. The appearance of ruthenium particles was unexpected and the mechanism of release has been the subject of discussion [12, 24]. It is likely that ruthenium was released from the fuel as RuO_3 and RuO_4 vapors that condensed to form metallic particles. Kashparov et al. [25] suggest the reducing agents that caused the ruthenium oxides to be converted to ruthenium metal were particles from structural materials in the reactor.

One of the authors of the present report [21, 26] has shown that, indeed, there were two periods of ruthenium release. The first was during the initial phase of the accident when mechanical, rather than chemical, processes were probably responsible for the release of substantial amounts of radionuclides as fine aerosol particles of fragmented fuel. The second phase of ruthenium release occurred several days later when it is possible that fuel was exposed to high oxygen partial pressures to form volatile ruthenium oxides. He argues that overall ruthenium and also molybdenum releases were higher than the release of fuel material because there was a sharp increase in the concentrations of ruthenium and molybdenum relative to concentrations of cerium and zirconium in air samples taken during later stages of radionuclide release [21, 26, 49]. The hypothesis of two phases of ruthenium release is consistent with the results of leaching tests by Kruglov et al. [22] that show there to be two physicochemical forms of ruthenium in particles deposited within the former Soviet Union. The relative abundance of the low solubility physicochemical form of ruthenium, which is presumably ruthenium in fuel fragments, decreases with distance from the Chernobyl site. The magnitudes of ruthenium and molybdenum releases have been estimated [49] to fall in the range 3.5 - 6 %. Only 4 percent of the initial core inventory of ruthenium remains in damaged fuel in the reactor [27], but this could be indicative of both ruthenium release and partitioning of ruthenium into structural metals. Detailed studies of ruthenium particles as well as fuel particles [28] and the depletion of cesium and ruthenium from the latter have been reported [29].

Releases of the low volatility elements such as cerium, zirconium, neptunium and plutonium occured by fuel fragmentation rather than by vaporization. Consequently, the release fractions for these low volatility elements are equal to the fraction of fragmented fuel dispersed from the reactor. As discussed further in the next section, this does not mean releases of the low volatility elements were confined to the initial, energetic, phase of the reactor accident. It appears that mechanical release of fuel fragments persisted throughout much of the accident. Radiochemical analyses of land contamination of ^{144}Ce, which is expected to have vaporized little from the fuel, are interpreted now to indicate 3.5 ± 0.5 % of the reactor fuel was dispersed from the plant as fragments.

V CHEMICAL AND PHYSICAL FORMS

Characterization of a severe accident source term includes description of the chemical forms of vapors and the physical forms of aerosol particles. Attentions to these aspects of the Chernobyl source term have been based on samples of contaminated materials collected far from the reactor. Much attention has been devoted to the chemical form of iodine. The available data [13, 21, 23, 26. 30] show that much of the iodine was in gaseous form (I_2 or CH_3I). The fraction of iodine that was gaseous varied. Devell reported the gaseous fraction of the iodine to be 60 to 80 percent during the two weeks after accident initiation [26]. Winkelmann et al. [30] report that in the later stages of the accident 40 percent of the iodine was associated with aerosol particles, 35 percent was gaseous elemental iodine, and 25 percent was organic iodide. With time, the organic iodide fraction increased. Cambrey et al. [13] found about 75 percent of the iodine that reached the United Kingdom was in gaseous form. There clearly is no close chemical association between cesium and iodine. Data by Georgi et al [31] show there to be an exchange between gaseous iodine and iodine associated with particles. Furthermore, based on the chemical form of ^{132}I produced by decay of ^{132}Te, the time constant for iodine reaction to form organic iodides in the atmosphere is about 1 day [21, 30, 32].

Cesium in the released material from the Chernobyl accident did not remain entirely in a water soluble form. Salbu [33] found that only 35 percent of cesium in water was present as cations. The rest was bound to colloidal particles. Certainly, by the time the radioactive material reached Salbus's location (Norway), cesium was no longer present entirely as CsOH or CsI. This alteration of cesium to an insoluble form as well as the alteration of iodine from a particulate to a gaseous form may have generically applicable implications concerning the consequences of radionuclide dispersal into the environment.

One of the authors [21, 32] has reviewed the state of understanding concerning aerosol particles produced by the Chernobyl accident. Again, much of the published information has come from samples collected in the West or particles collected from ground deposits. As a consequence, there is little known about size distributions, compositions, and the like for particles as they were emitted from the reactor. Particles that have been studied [22, 23, 25, 28-31, 34-45] fall into three classes:

- o fuel fragments that contain fission products but have been depleted of volatile species such as iodine, cesium, and ruthenium;
- o mono-element (mostly ruthenium) particles; and
- o particles of condensed volatile radionuclides including cesium, tellurium and iodine.

Fuel fragments were certainly formed and lofted from the reactor building during the initial, energetic events of Chernobyl accident. Larger fragments (>50 μm) were deposited near the Chernobyl site. Smaller fragments (<20 μm) were carried well beyond the site and even beyond the borders of the former Soviet Union and have been detected in Poland [29], Greece [40], Bulgaria [46], Hungary [47], as well as the Nordic countries [23, 39, 42, 44, 45]. Interestingly, fragments have been found that include carbon which may have come from the reactor moderator [37].

Fragmentation of the fuel may have persisted throughout the accident. Hot particles consisting of fuel fragments have been detected in Greece which was not exposed to the energetic plume formed during the initial phase of the Chernobyl accident [40]. A possible mechanism for fuel fragmentation late in the accident is air oxidation of relatively cool (< 1000°C) fuel. Air oxidation of uranium dioxide to form U_3O_8 is known to cause decrepitation. Fine fuel fragments, depleted in volatile radionuclides but still containing nearly the initial concentrations of low volatility radionuclides such as zirconium and cerium, could have been dispersed by the strong updraft known to have developed through the core. Certainly, Sich [4] notes that the entire Chernobyl site is heavily contaminated with dust particles he attributes to the oxidation and decrepitation of fuel

Kashparov et al. [25] have shown that aerosol particles with a bimodal size distribution are produced when Chernobyl fuel is heated to 673 to 1173 K in air. Size distribution data for these particles can be fit assuming two lognormal distributions with mean diameters of 5.6 μm (s_g=1.21) and 11.4 μm (s_g=1.19). The proportion of fine particles increases with the duration of heating. After about 16 hours of heating, more than 60 percent of the aerosol emissions were found to belong to the smaller size mode.

The test results obtained by Kashparov et al. certainly show that it is possible for fuel fragment release to have continued well after the initial core disruption event at the Chernobyl accident. That is, fuel fragments detected at later times outside the Soviet Union need not have been resuspended fragments produced by the initial energetic events of the accident.

Volatile fission products (cesium, iodine and tellurium) were found in very small particles (0.5 - 1 μm) that have compositions different than fuel. Jost et al. [35] found that iodine was associated with smaller particles than cesium, ruthenium, or tellurium. Georgi et al [31] observed a similar phenomenon.

VI CONCLUSIONS

A consensus is emerging concerning the general features of the Chernobyl accident and the releases of radioactive materials to the environment during this accident. Knowledge of the radioactive releases has advanced considerably since 1986 as a result of further analyses of environment samples taken worldwide as well as the results of further examinations of the destroyed reactor and analyses of core materials.

It can be concluded now that:

- The release of radioactivity extended over more than a week with two pronounced, intense, emission periods. The first intense, emission period was associated with the accident initiation. The second emission period occurred about a week later when damaged reactor fuel may have been exposed to oxidizing conditions. The exact pattern of radioactive material releases between these two intense periods is not known. About 9 or 10 days after accident initiation, releases of radioactivity fell to very low levels.
- There is a better understanding of the total release of radioactivity to the environment. Releases consisted of gases, vapors, aerosols, fragmented and probably reacted fuel. Current best estimates of the release fractions of various isotopes (see Table 2) are somewhat different than previous estimates and may be revised further in the future.
- More than half the initial core inventory of iodine is thought to have been released. As a result of integration of worldwide deposition and analyses of core debris within the reactor, the release of cesium is thought to amount to about one-third the initial core inventory.
- A peculiar feature of the radioactive material release during the Chernobyl accident is the release of a substantial amount (3.5 percent) of the fuel to the environment as fragments. Release of fuel as fragments occurred during both periods of intense release of radioactivity. Release of fuel fragments late in the accident may be the result of core debris oxidation. Low volatility elements such as cerium, zirconium and the actinides were retained in the fuel fragments and no selective release of these elements by vaporization can be detected. Fuel fragments deposited faster and closer to the reactor site than did cesium and iodine but were detected in e.g. Poland, Bulgaria, Hungary, the Nordic countries and Greece.
- Another unexpected feature of radionuclide release during the Chernobyl accident was the appearance of particles composed almost totally of ruthenium isotopes. The probable mechanism for the formation of these particles is the vaporization of ruthenium oxides from the fuel and the subsequent condensation and reduction of the vapors to form metallic particles.
- Air samples indicate that the releases of molybdenum and ruthenium were substantially higher in the late phase of the radionuclide emission period than were releases of fuel fragments which suggests selective release of molybdenum and ruthenium by oxidation to volatile forms.
- The composition and the characteristics of radioactive materials released from the reactor changed during transport due to gravitational settling, wet and dry deposition, decay and chemical transformations. Chemical transformation of released materials such as the formation of gaseous iodine and water-insoluble forms of cesium could have generic implications for the estimation of the consequences of nuclear reactor accidents.

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