CHERNOBYL NUCLEAR ACCIDENT

Following the accident at a nuclear reactor in Chernobyl, USSR, the WHO Regional Office for Europe inaugurated procedures for the systematic collection and dissemination of information. Such were the complexities and uncertainties that it was decided to call a one day consultation of experts at short notice, who would review the situation and provide guidance as to the needs for immediate public health action and also advise on predicted longer term trends.

This meeting was held in Copenhagen on 6 May 1986 and the conclusions and recommendations of the expert group have already been distributed. The present report provides more detailed scientific background in relation to both the short-term recommendations and longer term considerations, together with a description of the course of events, so far as information is available, in the first 12 days after the accident occurred.

Note

C O N T E N T S

PART I - NARRATIVE*

INTRODUCTION

Following the nuclear accident in Chernobyl, USSR, the World Health Organization, both at the Regional Office for Europe in Copenhagen and at the Headquarters in Geneva, was approached by Member States for urgent advice on the existing situation, the prediction of consequences and advice on action to be taken at national level.

The Director General of WHO has entrusted the Regional Office for Europe with follow-up action and a team has been assembled for the period of the emergency.

Following an analysis of the situation, it was decided to urgently convene a group of experts. This group, composed of senior scientists with knowledge in the fields of meteorology, radiation protection, biological effects, reactor technology, emergency procedures, public health and psychology, met in Copenhagen on Tuesday, 6 May 1986, to analyse the development of events and their consequences.

THE CHERNOBYL REACTOR AND THE ACCIDENT

On 26 April 1986, very early in the morning, a reactor unit of 1 000 MW OF THE RBMK type in the Chernobyl Power Station ignited "following an explosion". Soviet authorities officially announced that the reactor fire had ended on May 5 and that the "reaction had stopped". No detailed information has been released on the events leading to the explosion and the subsequent fire.

The reactor unit involved is of the "channel" type, graphite moderated and light-water cooled, using low-enriched uranium. The water boils in the channels and a direct steam cycle to the turbine in used.

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Figure 1 presents schematically the main circuits of a nuclear power station with an RBMK reactor.

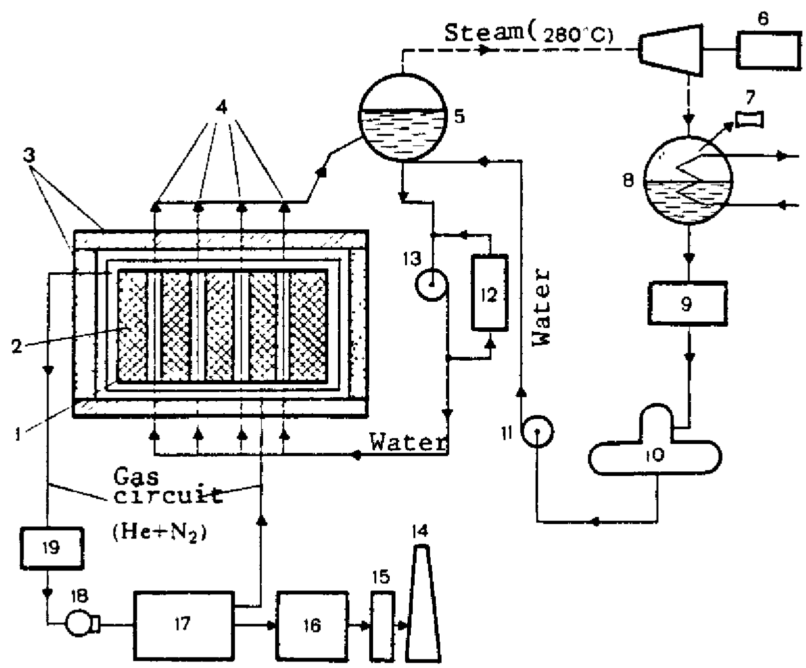


FIGURE 1

1	=	Reactor	11	=	Pump for auxiliary water supply
2	=	Graphite pile	12	=	Removal of impurities by ion exchange
3	=	Biological Shielding	13	=	Main circulatory pump
4	=	Fuel channels	14	=	Ventilator stack
5	=	Drum separator (steam from water)	15	=	Aerosol filter
6	=	Turbine generator	16	=	Gas holding tank (storage for radio-active decay)
7	=	Ejector (turbine)	17	=	Adsorber for CO_2, CO, N_2, NH_3
8	=	Condenser	18	=	Compressor
9	=	Cleaning of condensate radioactivity and impurities	19	=	Aerosol & Iodide filters
10	=	Deaerator			

In the absence of substantive information on the sequence of events leading to the explosion and fire, only conjectural scenarios can be postulated. One possible sequence would start with a rupture of the primary circuit at the level of one main steam collector, followed by turbine and main pump trips, vaporization of the coolant, possibly a zirconium-water reaction in the fuel cladding, with generation of hydrogen, and a partial meltdown of the fuel with release of radioactive materials. The postulated sequence would continue with overheating of the pressure tubes and the graphite, with further zirconium-water and other reactions, loss of reactor leak tightness, entrance of air and ignition of hydrogen and other flammable gases and then of graphite, with temperatures exceeding 2 000°C. At some point of the sequence, a gas explosion could have caused the damage to the reactor building reported by the Soviet media, while the large graphite mass continued burning until the fire was finally extinguished on May 5.

During the episode, substantial amounts of radioactive materials, basically fission products, were released into the atmosphere. Many fission product nuclides were released, but judging from results of measurements of samples obtained many hundred kilometres away, radionuclides of volatile elements prevailed in the release.

TRANSPORTATION AND DISPERSION OF THE RADIOACTIVE MATERIAL IN THE ATMOSPHERE

Due to the high temperature during the release, a substantial plume rise occurred, bringing released radioactive materials to high altitudes of from several hundred metres to over a kilometre.

The released materials would then be dispersed by diffusion and mainly by transportation by the prevailing winds at the different relevant heights.

Because of changes in the release rate, meteorological conditions, wind direction and speed, and other factors such as release duration, and changing of conditions along great distances, plume configuration and concentration at early times of dispersion provides little information on the resulting air concentrations many hundreds of kilometres from the accident site. Modelling techniques which are applicable for short distances must then be substituted, for longer distances, by assessments of the movement of air masses.

As summarized in an interim report from the Finnish Center for Radiation and Nuclear Safety, the weather in Europe on the morning of April 26th was dominated by a strong high pressure area over the Western parts of the Soviet Union and a low pressure area that reached from Iceland to North Western Europe. During the day a separate low pressure center was formed in Scandinavia. It moved quickly to the Norwegian sea and this move made room for a very warm air mass that streamed from the south to Finland. This warm air extended almost over the whole country before the morning hours of April 27th.

In the Chernobyl area (51° 17'N, 30° 15'E) the weather was at the starting time of the accident typical of a high pressure situation; winds were very weak and their direction varied strongly, a vast area of fog developed in the night. Higher in the atmosphere the wind field was more clear-cut than on the surface. Already at the height of 1.5 km (850 mb level) the wind speeds were 8 - 10 m/s and they were blowing from the south-east or south. A clear wind canal that reached over the outmost western parts of the Soviet Union directly to Finland is shown in Figure 2. It is a 850 mb level weather map for the situation at 03 Finnish time (00 GMT) on 26 April 1986. The stream velocities varied between 30 and 60 km/h, which means that the emission plumes moved easily in good 24 hours from the accident area to Finland.

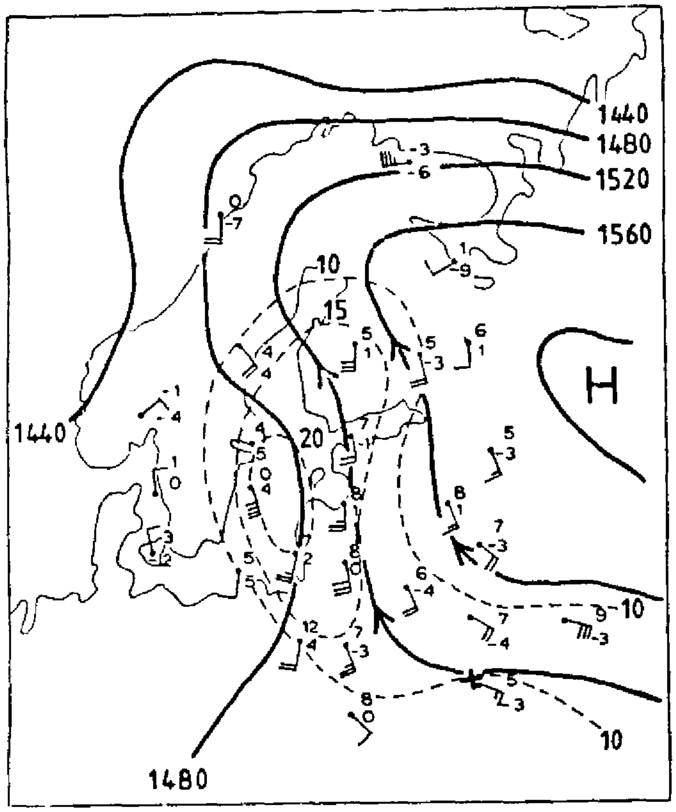


FIGURE 2
850 mb level height analysis in the situation on 26 April at 03 Finnish time (00GMT). The dashed line shows the analysis of wind speeds. The unit of speed is m/s.
(From the Finnish Meteorological Institute).

PLUME DIRECTION CALCULATIONS

The most illustrative picture of the distribution of the radioactive contamination over Europe is given in maps showing the calculated location of the radioactive plume at various times. These are shown in Figures 3 - 7, submitted by the Swedish Meteorological and Hydrological Institute. They have calculated the location of plumes originating at Chernobyl at various times and for each release time they have followed the plume, as it would have moved according to the meteorological information, for five days.

Since it is not known how the release of radioactive material varied with time during the period 26 April to 5 May, the plume locations only indicate the potential for radioactive contamination, but as will be shown in a later section of this report, the measurements of activity concentration in the air and on the ground give results which are fully consistent with the meteorological information.

Calculations have been made for two heights, 1 500 m and 750 m. During the first phase of the accident, most of the radioactive material was most likely brought up to high levels in the atmosphere and the level of 1 500 m may be the most relevant. The extension of the plume at that height has been shaded gray on the maps. Later, the activity was more likely at lower levels, and only the calculated result for 750 m is shown.

The depletion of the atmospheric content of radioactive material is caused by radioactive decay, by gravitational settling of the larger particles, by formation of aerosols close to ground level, and by rainfall. The rate at which radioactive aerosols are brought to the ground depends on the particle size, larger particles being deposited closer to the accident site by gravitational deposition. Rainfall is a most important depletion mechanism, as will be seen later when the results of activity measurements are discussed.

With some simplification, the plume directions may be grouped into the following five periods :

1. Area : Scandinania, Finland, Balticum
   Emission during : 26 April; arrived 27 - 30 April

2. Area : Eastern central Europe, Southern Germany, Italy, Yugoslavia
   Emission : 27 April; arrived 28 April - 2 May

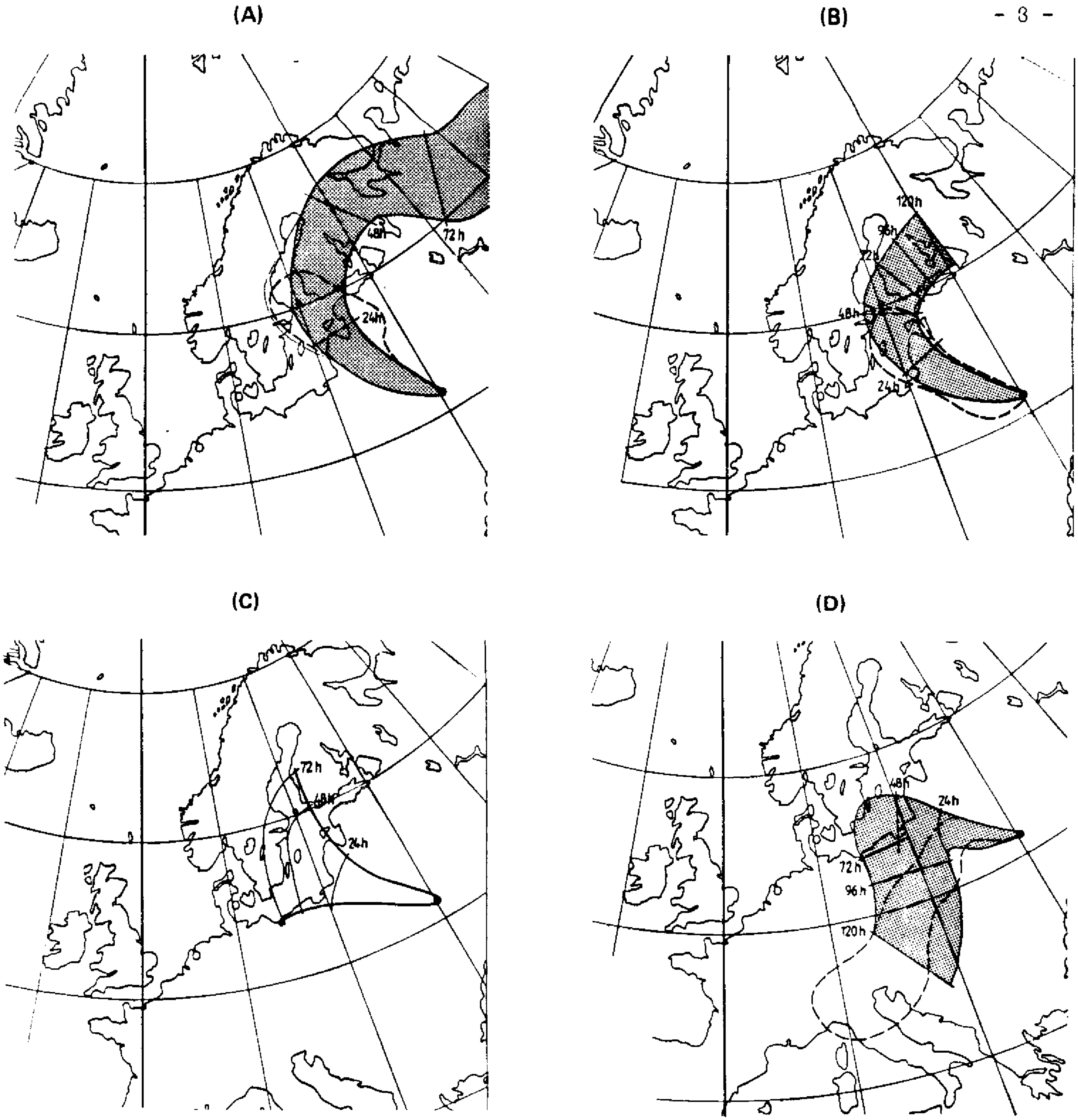
3. Area : Ukraine and eastwards
   Emission : 28 - 29 April; arrived 28 April - 2 May

4. Area : Balkan, Romania, Bulgaria
Emission : 29 - 30 April; arrived 1 - 4 May

5. Area : Black Sea, Turkey
Emission : 1 - 4 May, arrived 2 May and later.

It is not unlikely that most of the release occurred in the first two periods, so that the corresponding plumes (Figures 3 a-d and 4 a) are the most significant as regards movement of radioactive material.

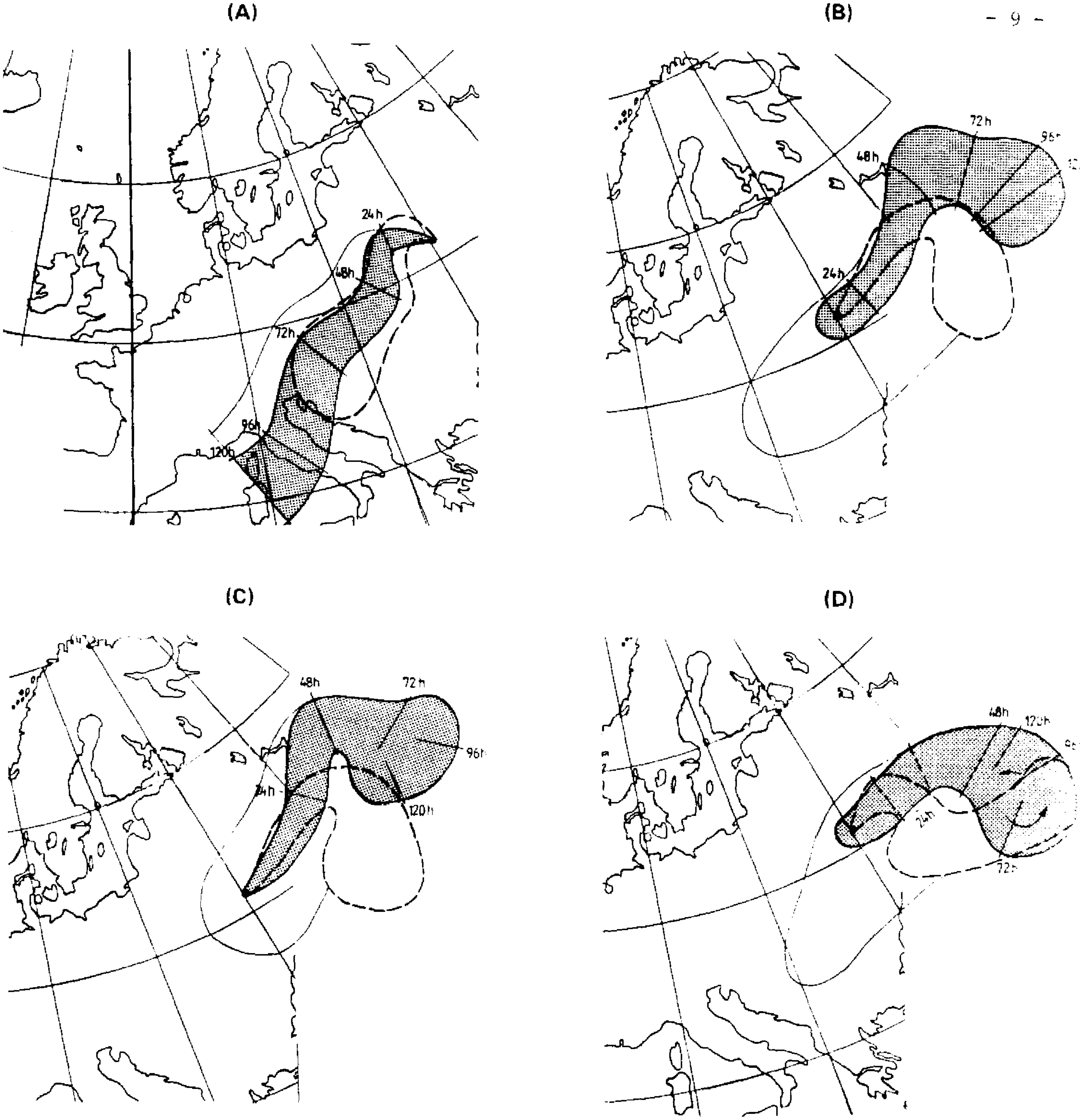
The plume calculations end at 120 hours (5 days) because of the uncertainties of calculations for longer movement periods. The later movement and dispersion of radioactive material already in the atmosphere is more difficult to assess. However, for each plume shown on the maps, there is also remaining activity from earlier plumes. Figure 7 indicates general wind directions on the evening of 5 May, the day when the releases had ceased according to USSR reports. It illustrates how older material may have moved towards the northwest. This explains why countries such as the Benelux, United Kingdom and Denmark have had some contamination although they have been outside the immediate plumes.



Figures 3 a, b, c and d illustrate the movement in the atmosphere of any radioactive material that might have been released from the Chernobyl reactor during the first days after the accident. The approximate location of plumes originating at Chernobyl at various times have been calculated from the meteorological information by the Swedish Meteorological and Hydrological Institute. The four diagrams represent the following assumed emission times at Chernobyl:

(a) Saturday, 26 April, 00.00 hours GMT
(b) Saturday, 26 April, 12.00 hours GMT
(c) Saturday, 26 April: transition stage 12 - 24 GMT
(d) Sunday, 27 April, 00.00 hours GMT

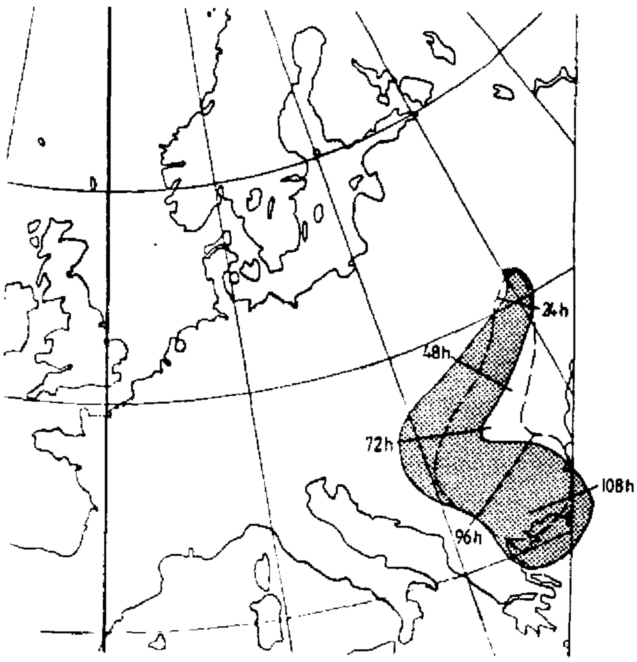
Full lines indicate the level 1500 m, dashed lines 750 m. The transport time is indicated for the level 1500 m. The thin line in Figure 3 a indicates an uncertainty area due to weak and variable winds.



<u>Figures 4 a, b, c and d</u> illustrate the movement in the atmosphere of any radioactive material that might have been released from the Chernobyl reactor during the period Sunday, 27 April to Tuesday, 29 April. The notations are the same as in Figure 3, with the transport times given for the level 1500 m. The four diagrams represent the following emission times at Chernobyl:

(a) Sunday, 27 April, 12.00 hours GMT
(b) Monday, 28 April, 00.00 hours GMT
(c) Monday, 28 April, 12.00 hours GMT
(d) Tuesday, 29 April, 00.00 hours GMT

(A)



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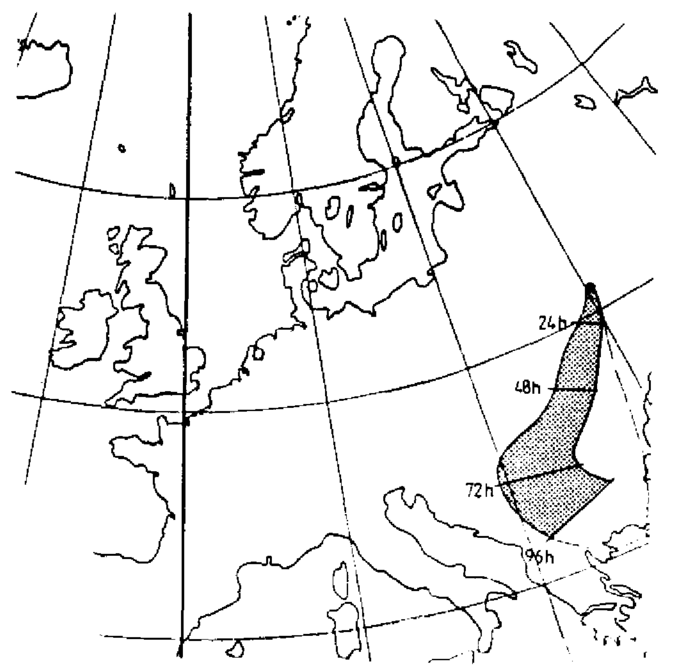
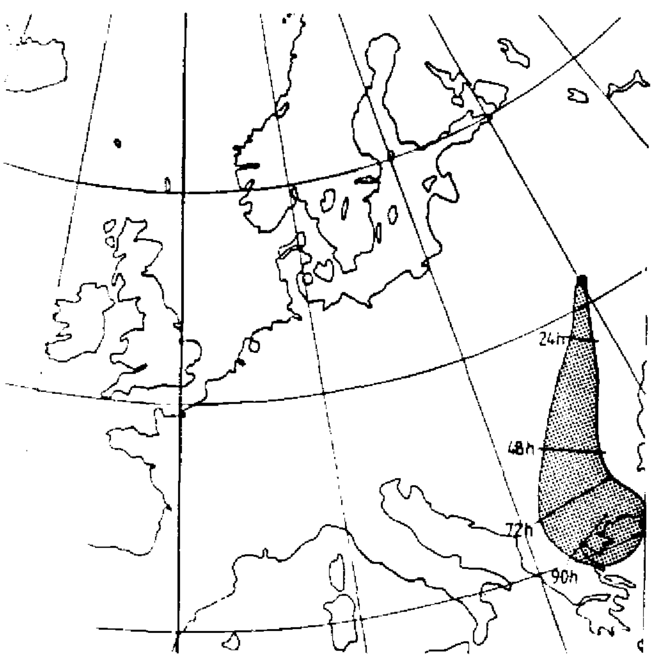


(C)



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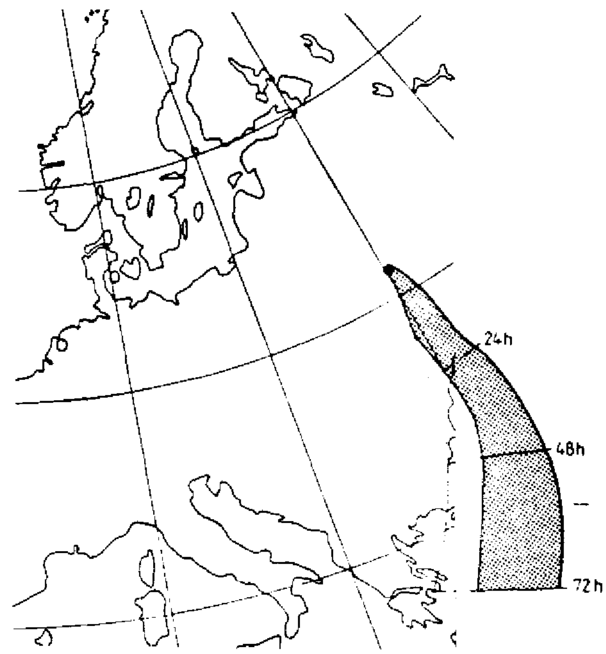
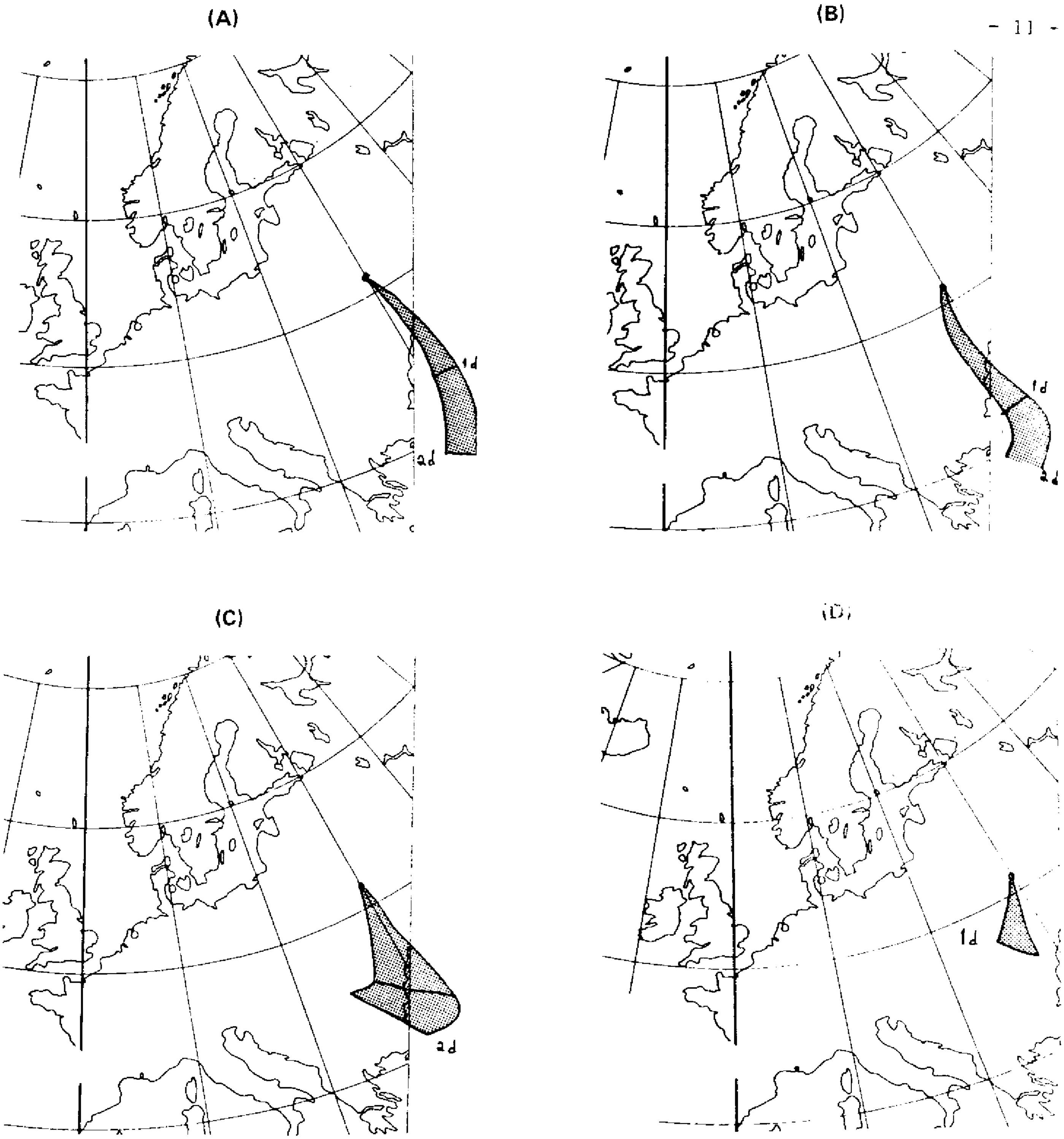


<u>Figures 5 a, b, c and d</u> illustrate the movement in the atmosphere of any radioactive material that might have been released from the Chernobyl reactor during the period Tuesday 29 April to Thursday, 1 May. In b, c and d, the curves relate to the height of 750 m, because it is no longer likely that much of any released material would reach higher levels. The four diagrams represent the following emission times at Chernobyl:

(a) Tuesday, 29 April, 12.00 hours GMT
(b) Wednesday, 30 April, 00.00 hours GMT
(c) Wednesday, 30 April, 12.00 hours GMT
(d) Thursday, 1 May, 00.00 hours GMT



Figures 6 a, b, c and d illustrate the movement in the atmosphere of any radioactive material that might have been released from the Chernobyl reactor during the period Friday, 2 May to Monday, 5 May. The curves relate to a level of 750 m. The four diagrams represent the following emission times at Chernobyl:

(a) Friday, 2 May, 00.00 hours GMT
(b) Saturday, 3 May, 00.00 hours GMT
(c) Sunday, 4 May, 00.00 hours GMT
(d) Monday, 5 May, 00.00 hours GMT

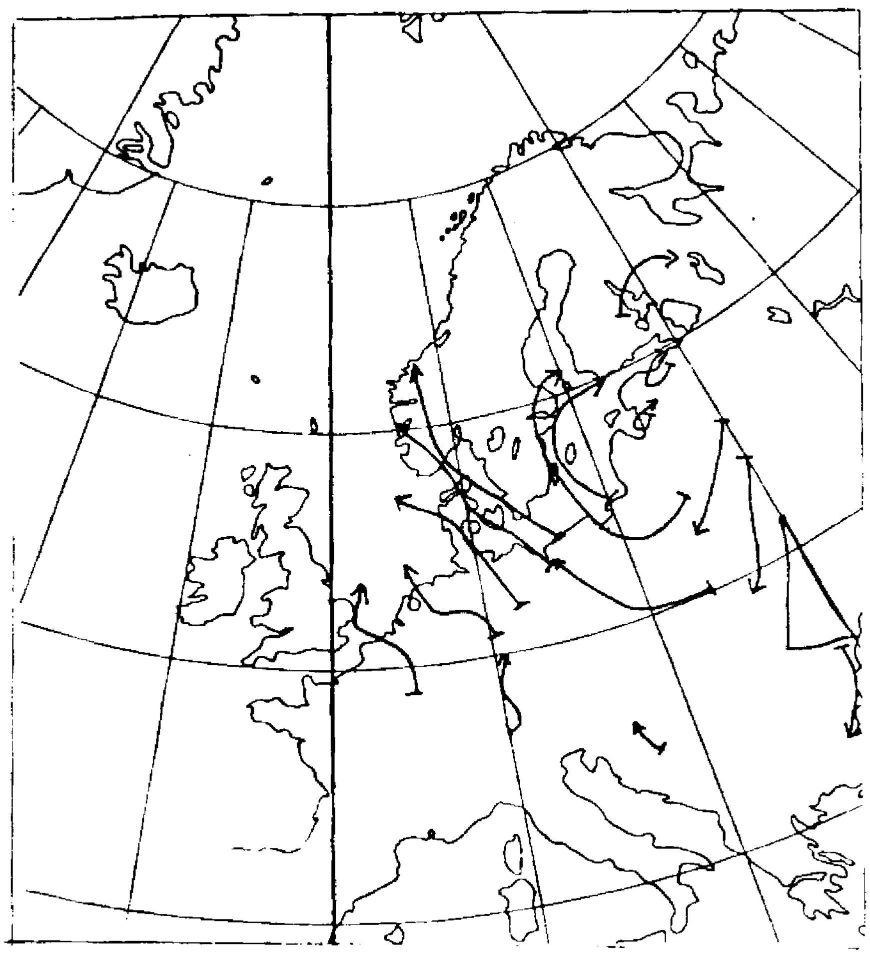


Figure 7: Indication of movements of air masses in Europe on 5 May at 18.00 hours GMT. Some radioactive material from early releases moves towards northeast.

CONSEQUENCES INSIDE THE USSR

According to the USSR Investigation Commission, two workers died immediately from the accident, but not from radiation injuries. One died from severe heat burns, the other when part of the reactor building collapsed from the accident. About 200 workers were brought to hospital and it is reported that 18 of these have been exposed to such high radiation doses that their condition is severe. Evacuation of the Chernobyl area was said to have commenced on Sunday, 27 April at 14:00 hours (the accident was reported to have occurred at 01.23 hours on Saturday, 26 April). According to other USSR reports, some 40 000 persons were then evacuated and several days later a further 40 000 were moved out of the area. There is not yet enough information to make it possible to assess the short-term radiological consequences of the radiation in the close to the accident or elsewhere in the Ukraine.

In accident scenarios that have been used in various countries for the purpose of emergency planning, the dominating long-term consequence is due to the deposition of cesium-137 (half-life about 30 years) over large agricultural areas, causing contamination of various farm products, but also causing external exposure from the ground. Experience from studies of the world-wide radioactive fallout from the atmospheric nuclear weapons testing gives useful information on critical pathways and transfer factors through the various food chains.

RADIOLOGICAL CONSEQUENCES OUTSIDE THE USSR

Exposure routes

The exposure of man due to the atmospheric contamination by radioa stances is caused by a number of routes, the most impor

- External exposure from the radioactive cloud;
- Internal exposure from radioactive substances taken into the body by inhalation during the passage of the cloud;
- External exposure from radioactive substances deposited on the ground;
- Internal exposure from radioactive substances taken into the body by ingestion of contaminated food (and in rare cases water).

Except for noble gases, which only expose by gamma and beta radiation from the cloud and contribute little to the total dose, the deposition pathways dominate the exposure. The main nuclides that have been found in the air and deposited on the ground after the accident are :

Zr-95	half-life	65	days
Nb-95		35	days
Mo-99		2.8	
Tc-99m		0.38	
Ru-103		40	
Te-132		3.3	
I-132		0.1	
I-131		8.05	
I-133		0.88	
Cs-134		767	
Cs-136		13	
Cs-137		11 000	
Ba-140		12.8	
La-140		1.7	
Ce-141		32.5	
Ce-144		285	
Np-239		2.4	

Most of these are isotopes of relatively volatile elements. In fresh fallout from nuclear weapons tests Zr-95/Nb-95, which are not considered volatile, were more important in contributing to the total external gamma dose than in the case of the present accident where the relative abundance of these nuclides is not so high. In the fresh material, Te-134/I-132 and Ba-140/La-140 were important contributors to the dose, in addition to iodine-131. The long-lived Cs-137 was present in relatively high proportions with activities between 1 and 10 per cent of those for iodine-131 during the first few days.

For short-term internal exposure, the iodine isotopes are the most important, dominated by iodine-131. The exposure route is through milk but also by inhalation. Iodine is taken up by the thyroid and infants consuming fresh milk receive the highest radiation doses, mainly because the iodine is retained in a smaller size thyroid than in adults, thus giving a higher concentration and a higher radiation dose. It should be noted that the radiation dose is the energy absorbed per unit mass of irradiated tissue.

Biological effects

Outside the USSR, radiation levels from the accident, as reported, are too small to cause any acute radiation effects. The remaining possible biological effects are therefore late effects, namely cancers, genetic and teratogenic effects. Iodine in the thyroid increases the probability of thyroid nodules and cancer in this organ. The current assumption is that there is no threshold dose below which the late effects cannot occur and that, therefore, any small dose will cause a proportionally small probability of incurring some effect. For cancer this will not happen until after a latency period of tens of years. Teratogenic effects will be evident after birth and genetic effects may appear in one or more generations of offspring to the exposed individuals. The normal frequency of the various late effects is the result of a variety of causative influences of which radiation is only one. The additional probability of being affected by some late effect caused by an incremental radiation dose is therefore not easily derived from comparisons with the natural background radiation.

The Chernobyl accident has caused an uneven deposition of radioactive material in the countries reached by the radioactive plumes, with local high values substantially exceeding the average for the country. The question arises whether epidemiological studies could be expected to show increased frequences of late effects. On the basis of the assumption that, for cancer and genetic effects which appear at random with a probability that is proportional to the effective dose equivalent (a quantity used in radiation protection to make different exposure situations intercomparable), the expected number of persons affected would be proportional to the product of the number of people exposed and their average effective dose equivalent. The effective dose equivalent is measured in sievert (Sv) or millisievert (mSv). The risk factor is of the order of 10^{-5} per mSv for deaths by cancer.

Doubling the natural background for one year would mean an extra radiation dose of 1 mSv and would be expected to lead to some 100 cancer deaths appearing over a period of several decades in a population of 10 million people. Even if a much more pessimistic risk factor were used, the expected increase in the annual cancer rate would be difficult to detect. If infants consume milk at the iodine-131 action level of 2000 Bq/l used in a number of countries, their effective dose equivalent accumulated over the contamination period would be a few mSv. Considering the documented uneven distribution of iodine deposition, the number of infants exposed near the action level in any one country would only be expected to be a few hundred or at most a thousand. The expected number of lethal cancer would then be less than one, i.e. it is more likely than not that there will be no such case, in the most exposed sub-group, although some case of thyroid cancer or nodules cannot be ruled out.

Within the first week after the accident a number of measurements have been made on activity concentrations in milk and exposure rates outdoors. The results of these measurements are only indirectly related to the health consequences. The probability of cancer and genetic effects is assumed to be proportional to the total radiation dose committed by the event, i.e. would be proportional to the time integral of the concentrations and exposure rates. This is illustrated schematically in Figure 8.

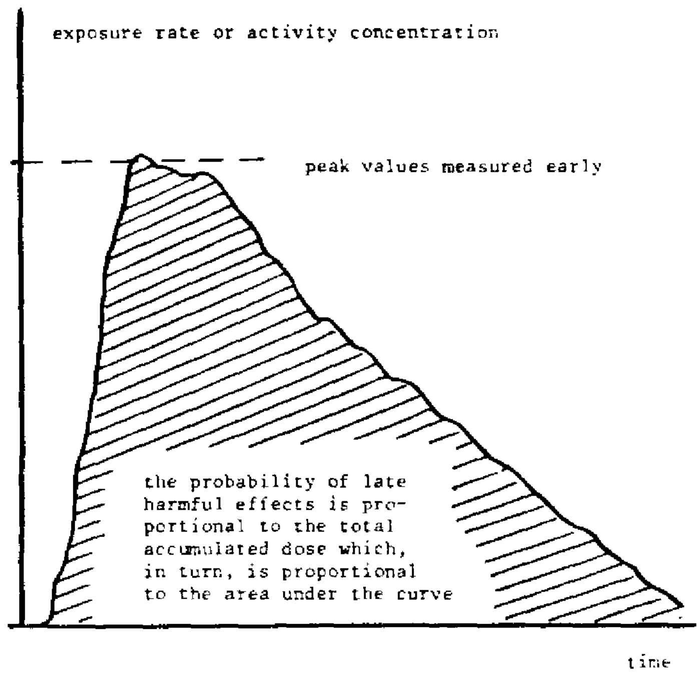


FIGURE 8 : Illustration of the relation between rates or concentrations and the total accumulated dose.

In order to assess the integrated quantity, which is assumed to be proportional to the probability of harmful effects, it is necessary to know the shape of the curve showing the variation with time. For exposure from the ground, this can be deduced from knowledge of the composition of gamma-emitting radionuclides and their half-lives. The early deposition in Finland and Sweden had a large share of short-lived radionuclides : Mo-99, Tc-99m, I-133 and Np-239 have half-lives shorter than three days, and only Sr-90, Cs-134, Cs-137 and Ce-144 of the more important radionuclides have half-lives longer than three months. Only a fraction of the initial dose-rate can therefore be expected to remain over a long time.

In a corresponding way, it is necessary to find the relation between the expected integrated intake of iodine-131 and the peak concentration of the nuclide in milk. This relation is only partially determined by the half-life of iodine and depends on local conditions.

The third type of late effects, the teratogenic effects, cannot be related to the total accumulated dose, since the period of exposure is of importance.

For irradiation in utero, there is no evidence of teratogenic effects during the first few weeks of gestation for fetal doses less than 100 millisievert (mSv). However, recent evidence suggests the random induction of severe mental retardation, with a probability of 0.04 per cent per millisievert of fetal dose, in the period of about 8-15 weeks after conception, and with no indication of a threshold dose. The risk seems to be clearly smaller after 15 weeks and may then have a threshold. Prior to 8 weeks no such risk has been detected.

The above considerations are particularly relevant for external gamma exposures from deposited radionuclides. Taking into account the decay of the deposited radionuclides, the time spent indoors and the shielding afforded by houses, and the relationship between outdoor exposures in air and fetal dose, it appears that the continuous presence of pregnant women in an area of ground deposition, during the 8-15 week post conception period would not significantly increase the normal risk of mental retardation, if the peak exposure rates in air do not exceed a few hundred microroentgen per hour. Therefore, in areas where exposure rates are smaller than this value, no special precautions are needed.

THE FIRST OBSERVATIONS

The first observation of the fallout is reported to have been made at the radiation monitoring station of Kajaani in Finland, where external exposure rates between 70 and 100 μR/h were measured on the evening of 27 April, 1986. This is consistent with a release at Chernobyl in the night between Friday and Saturday, 25-26 April (cf. Figure 3 a). A heavy shower of rain had caused the fallout.

It was thought that the radiation might have been caused by one of the radon peaks that had been detected in previous years when snow melted in the spring. However, on Monday, 28 April, the Rescue Department of the Ministry of the Interior asked for results from its own monitoring stations. It was found that some stations had results that were 1.2 - 2.5 times the normal values.

In Sweden, the contamination was first observed at the Forsmark nuclear power station on the Baltic coast about 100 km north of Stockholm. An activity deposition was detected in the morning, within the site of the station. No reason for the contamination was found within the power station and the Swedish Radiation Protection Institute was alerted.

It was soon found that the gamma spectrum of the air activity, which could be also be measured at a number of other places along the Swedish east coast, indicated relative amounts of cesium-134 and cesium-137 that made it unlikely that the activity came from a nuclear explosion. The conclusion was that there must be some abnormal release from a reactor southeast of Sweden and Finland. Meteorological trajectories were drawn back towards the Black Sea, but the first guess was that the source was a large nuclear power plant in Latvia. However, at 21.00 hours on Monday, 28 April, the USSR news media acknowledged that an accident had occurred at the Chernobyl nuclear power plant.

Between 12 GMT on Saturday, 26 April and 00 GMT on Sunday, 27 April, the direction of the air masses from Chernobyl shifted (cf. Figure 3c) and radioactive material released from the accident site on Sunday, 27 April moved, first west and then south, over the German Democratic Republic, Poland, Czechoslovakia, Hungary, Austria, the southern part of the Federal Republic of Germany, Switzerland and northern Italy (Figures 3 d and 4 a).

In southern Germany, a heavy rainfall caused a localized activity deposition in the Munich area in the afternoon of Wednesday, 30 April. This is consistent with a release on Sunday, 27 April (cf. Figure 4 a), i.e. more than one day after the accident. Within a few hours the exposure rate increased from the normal 8 μR/h to about 110 μR/h. The activity deposition was dominated by Te-132/I-132 and I-131, but Cs-137 was present in an activity that was about 1/4 of the activity of iodine-131. This means a cesium-137 deposition of about 40 kBq/m^2 which is quite remarkable, considering that the total accumulated deposition of cesium-137 from the atmospheric nuclear weapons testing was about 5 kBq/m^2 in the 40-50° latitude band (according to the 1982 UNSCEAR report).

The two events : the Scandinavia-Finland contamination and the Central-East Europe contamination dominate the European exposure situation after the accident. Any radioactive material released from Chernobyl after Sunday, 30 April, has moved eastwards or south, involving Ukraine, Balkan, Romania, Bulgaria, Turkey and the Black Sea region. Contamination found in other countries has essentially been secondary, by movements of air masses with radioactive material more than five days old, counted from the time of the release.

INTERPRETATION OF MEASUREMENT DATA

Extensive data on measurement results have been reported to the WHO from twenty-two countries. WHO also asked a number of laboratories and public health authorities specifically to provide data that can be used for the assessment of health consequences. Of special value is the information on the deposition of various radionuclides and particularly of iodine-131 and cesium-137. Such data are the basis for a general assessment of the situation.

Useful in this respect is also data on the external exposure rate, provided that they are supplemented by some information on the nuclide composition of the deposition.