PUBLIC HEALTH RISKS OF NUCLEAR EMERGENCIES

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What I will present expresses primarily my own opinion and not necessarily that of the Department by which I am employed. I will discuss three things: First, what we knew before Chernobyl about the consequences of large releases of radioactivity into the environment; second, how the released radioactivity was distributed over the USSR and the rest of the world, including the United States; and, third, the events at Chernobyl and the off-site consequences only.

RELEASES OF RADIOACTIVITY INTO THE ENVIRONMENT

To determine the impact of large releases of radioactivity, one must go through a number of steps. These begin with the release itself, include the dispersion of the released material into the environment, and end with the resulting exposure of people. Of course, one is primarily interested in the doses that people have received as a means of estimating the effects of those doses. To help us, a number of models have been developed during the last 40 years. As you know, we have not had any large radioactive releases, so we have worked with trace amounts of radioactivity. Also, the fallout years have taught us much.

The dispersion model now in use has been employed for Chernobyl. Exposure-dose and dose-effect models also have been developed. I believe the Chernobyl release has much to teach us, including the validation of a number of these models. We hope this will be the only such catastrophe, and we should attempt to get the maximum information from it.

Let us look at release factors. This camel-like curve (Figure 1) shows that the uranium atom is very unwilling to split in the middle. This is of extreme importance. It means that products resulting from the fission of uranium lie in two mass areas: one around 90, the other around 130. That explains why isotopes such as cesium-134 and -137 and iodine-131, -132, and -133 are produced in very high yield. But the total number of radionuclides is limited.

Also of importance is what the release fraction of these radionuclides is in, for example, a reactor with a melted core (Figure 2). Clearly the noble gases will be released entirely and the volatile ones, such as the halogens, the heavier metals, and the rare earths, will be released at a much lower fraction. Again, there is fractionation, and it is no wonder that it is the first nine or ten of the listed isotopes that are found most often. These are of public health importance because exposures to them can be rather substantial.

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Some measurements on the fallout from Chernobyl are shown in Figure 3. Without question, the iodines are the most predominant radionuclide group early in the fallout. After the iodines have disappeared, and they disappear rather rapidly, what remains are the radionuclides with very long half-lives, such as cesium-134 and cesium-137.

A large-scale release of radioactivity creates four kinds of hazards (Figure 4): (1) direct radiation exposure from the plume or cloud that rises overhead or in which people are immersed, for example, those close to Chernobyl; (2) radiation from deposited materials; (3) inhalation of radioactivity in the air (iodines also play a predominant role); and (4) contamination of water and food. Contamination of water and food comes relatively late; inhalation is immediate as is exposure to the cloud and to deposited materials.

Instead of going through each of these exposure modes separately, I have summarized what a World Health Organization (WHO) study found after release of radioactivity at Windscale, England in 1957. In the early 1960s, international organizations worked feverishly to analyze the data after every radiation release. With Chernobyl, no doubt analyses of the public health aspects of releases of radioactivity again will appear in many publications.

WHO used the concept of "reference accident," which is related to the inhalation of airborne radioiodine. The reference accident is accompanied by a dose to the thyroid gland of 25 rem from inhalation of radioiodines only. All other risks are compared to that (Figure 5). For example, it is clear that direct gamma or beta radiation or noble gas exposure from the cloud or plume is insignificant compared to radioiodine inhalation. Actually, the doses from these exposures are orders of magnitude (probably at least two orders of magnitude) below the airborne radioiodine dose. The deposited gamma activity is different. It may be significant, ie, the dose could be a large fraction of, or a few times greater than, the dose to the thyroid gland from inhalation.

Milk and food contamination are also significant. When we talk about food pathways, we are talking about deposition that occurs in food crops, is passed on to feed crops, gets into animals, and from meat or milk and processed milk products to man (Figure 6). That is a complex situation, but we have models and I think we have it under control. After Chernobyl, drinking milk contaminated with radioiodine, mostly iodine-131, delivered doses of the same order of magnitude as the ones from airborne radioiodine. If you see a lot of emphasis on radioiodine, it is because there must be much interest in it. This is one aspect that I think is disproportionately handled in Russian reports about Chernobyl. With Chernobyl, even cesium probably will result in doses that are a large fraction of 25 rem, which are comparable to exposures from the reference accident.

Protective measures were required after the release of radioiodine at Windscale (16,000 curies). The British Medical Research Council established dose limits for emergency conditions. Given the isotope and exposure-dose relationships, they could calculate which "maximum permissible intakes" would correspond to maximum permissible doses.

In this country we also had what were called "protective action guides" (PAGs) established by the Federal Radiation Council in the early 1970s. After the meltdown at Three Mile Island, the Food and Drug Administration formed a committee to review PAGs (Figure 7). Two sets of these guides were established: preventive and emergency. The preventive action guide is aimed at preventing exposure to the thyroid of more than 1.5 rad and to the total body of more than 0.5 rad, which are "peace-time" permissible population doses. The emergency PAGs were 10 times higher.

Now look at this particular number, because it will come back: the 15,000 picocuries per liter of iodine-131 in milk against which we will compare other numbers. When somebody said this morning that at Three Mile Island the radioactivity of iodine in milk was 10 picocuries per liter, which was below the PAG, they were not kidding. It was a factor of 1,000 lower than one PAG!

DISTRIBUTION OF RADIOACTIVITY AFTER CHERNOBYL

Figure 8 illustrates how the radioactivity was distributed during the first 48 hours after the release at Chernobyl. The wind blew out of a southwesterly direction, which was quite unusual and quite fortunate, because it meant Kiev was just out of the path of this large release of radioactivity. This is the prediction made by the dispersion model developed by the Atomic Energy Commission and now operated by the Department of Energy's Livermore, California, laboratory, the ARAC System (Airborne Radioactivity Advisory Capability). The ARAC System predicted that the tip of Sweden would be touched by the cloud, and that is exactly what happened. This shows that the model, at least for the first 48 hours, was reliable.

Figure 9 is from the Swedish Radiation Protection Institute. Doctor Lindell showed the same slide. You can see there were large increases of ambient gamma rays (Figure 10). In Sweden, for example, there were increases of up to 1,300 micro-R per hour. In contrast, the average normal background is between 5 and 10 micro-R per hour. These were considerable increases for a relatively short time. The farther from the source, the smaller the numbers get. There are hot spots in different countries: Switzerland, Norway, and Finland show an increase of one or two orders of magnitude.

In the next few days the wind changed direction and started blowing from the northwest. This is when Kiev became involved. The cloud that had just reached Sweden now moved over Poland, Hungary, Austria, Switzerland, and Bavaria (Figure 11). In the case of iodine-131 concentrations--remember the 15,000 picocuries per liter that I mentioned before--the levels were mostly below those needed for protective action. There were some exceptions in Hungary and Switzerland. Some countries used PAGs lower than ours. Nevertheless, in most cases, the milk contamination outside of the U.S.S.R. was manageable.

Within 14 days after the disaster, the British published their population dose assessment (Figure 12). They calculated that the north was somewhat more heavily exposed than the south, primarily because of precipitation. However, overall the doses were low, 2 to 30 millirem with a weighted average of 7 millirem (the data appeared in sievert). The inhalation dose from iodine is less than 1 millirem in terms of an effective dose equivalent. As an organ dose, one must multiply this by 30, so we are talking about something like a 20-millirem dose to the thyroid gland as compared to a whole body dose of something like 7 millirem. Thus it is true that even at long distances inhalation of radioiodine is a factor of some importance. As you can see, the external exposure from the cloud gave rise to relatively low doses. The highest ones are the doses from deposits and ingestion.

The cloud moved over Europe and toward the United States. Figures 13 and 14 are polar projections situated over the North Pole looking down. The cloud went over and around the North Pole and reached the United States exactly where the Department of Energy has a laboratory, so we know exactly when the cloud arrived at the West Coast. The cloud then moved over the nation in a horseshoe-type dispersion pattern (Figure 15). In actuality, the dispersion was somewhat less concentrated, but this is what the model predicted.

We knew the levels of cesium-137 in Stockholm (Figure 16). In Richland, Washington, where the cloud first arrived 12 days after the disaster, the maxima are about two orders of magnitude lower than the one in Stockholm. It has about the same shape with some ups and downs, depending on precipitation.

Figure 17 shows the situation with radioiodine in Stockholm, which is a little south of the maximally exposed area in Sweden, and Richland, Washington. There is a difference of about two orders of magnitude. Figure 18 shows the same iodine curve for Richland compared to the last Chinese nuclear test of September 26, 1976. The pattern is different in that the maximum from Chernobyl is higher by some two orders of magnitude. The meaning is not known. You can see that a nuclear test explosion had a dispersion pattern that was totally different from the release pattern after Chernobyl.

In the United States, milk concentrations really did not amount to anything. As you can see (Figure 19), the levels are higher than those with the Three Mile Island incident, but they all are nearly a factor of 100 or more lower than the PAG. Other than in Oregon, where some action was taken, I believe that nowhere in the U.S. were any protective measures taken. Certainly they were not necessary.

OFF-SITE CONSEQUENCES OF CHERNOBYL

At the August 1987 meeting of the International Atomic Energy Agency (IAEA), the Russians produced an extensive list of numbers they had collected or calculated within four months. I think it must be taken into account that any number you see here, no matter how good it looks, has a tendency to look better than it actually is. I think Doctor Gale mentioned the factor of 50%, but I am not so sure they are within a factor of two or three of the real value. You simply cannot look at the large area less than 30 km from Chernobyl and characterize it entirely in a matter of four months. Figure 20 lists the numbers. A total of 134,000 people were evacuated. The Pripyat population had a lower average dose equivalent because they were not initially exposed to the cloud. Some of the people who were 7 to 10 km, 10 to 15 km, and 15 to 20 km from Pripyat received much larger doses. About 24,000 people between 3 and 15 km received an average dose of 45 rem. This is a substantial number.

The Russians Indicated that more than 30 km from Chernobyl, in the Ukraine and in White Russia with a total population of about 60 million people, the average individual dose equivalent was 0.5 rem (Figure 21). However, I cannot believe that 60 million people were equally exposed or that most of them were significantly exposed. I suspect that perhaps 20 million were exposed to a much larger extent than the remaining 40 million, which would mean an average individual dose that is higher, perhaps a few rem. Nevertheless, if you want to predict the cancer numbers that would result, it would be about 2,900. These are the estimated exposures, some external and some internal, for that population. There was tremendous confusion at the IAEA meeting in Vienna when the number of 210 million person-rem was reported. There is no question that it is out of proportion with any of the other numbers. The Russians later reduced the number by a factor of ten. They did not want to be accused of being too optimistic about their estimates, and thus used a conservative model rather than a more realistic model. I think that even a 21 million person-rem number is somewhat high, because it does not take into account any protective measures.

In the case of iodine-131, the Russians predicted a 1% increase in mortality from thyroid cancer, which amounts to something like 200 deaths. By any analysis of the likely thyroid exposures, that appears to be low, but we have no other information. For example, exposures to iodine-132 and iodine-133, which are relatively short lived but certainly in a close-in population are of considerable importance, may be even more important than the exposure to iodine-131 on which the Russian estimate was based.

A discussion on whether there was more or less cesium released at Chernobyl than by all the nuclear test explosions together appeared recently in the newspaper. The amount of radiocesium released at Chernobyl is something like one-tenth of the amount released by all test explosions together, an immense amount.

In Figure 22, population exposures from the nuclear tests and from Chernobyl are listed. If you look at them from a population's standpoint, there should not be that much of a difference between the different proportions. The absolute numbers are something else, but the proportions should be about right. The collective dose of external exposure should be approximately twice as high as from internal exposure, judging from experience with test explosions. You can see that the number, 210 millirem, is clearly out of proportion. Compared to the 29 one would estimate, about half of that number would be expected. Radiocesium is interesting, and there will be many studies of it, but this is clearly not a predominant radionuclide in the food chain.

Figure 23 summarizes the data from Hiroshima and Nagasaki. It is these data upon which most of our estimates are based. There are about 300,000 survivors and the average exposure was 16 rads. The total excess number of cancers is about 500. The epidemiologic program that follows this population is very intensive. To find an increase of 500 cancers against a background of tens of thousands of cancers is no mean accomplishment. It is interesting in terms of Chernobyl to consider whether there is any sense in following up that population. The increase in the number of cases of leukemia in Japan was 100%. This is the type of cancer to look for first. In comparison, all other cancers show a 3% increase above the expected number.

If you look at the main USSR population, the number evacuated from Pripyat versus others was 45,000 versus 89,000 (Figure 24). We know that 134,000 people received an average of 12 rads. On the basis of the Japanese risk estimates, about 156 is the excess number of cancers among some 22,500 cases. That is less than a 1% increase and impossible to detect. However, if you look at the 24,000 people exposed to 45 rads, there may be 110 excess cancers among 4,000 cases---a 5% increase. We should be able to find and measure it. It would require something like the Radiation Effects Research Foundation in Hiroshima and Nagasaki. If the dose is higher and if the exposed group is larger, it would be much easier. One looks at leukemia first and makes the assumption that the Japanese risk estimates would hold with more extensive and expanded exposure.

Figure 25 shows the thyroid cancer number in the downwind population. Assuming a dose of 100 rad, I cannot believe the numbers. I multiplied them by a factor of between two and ten. I still believe that is not impossible among the close-in population. If you look at the number of people that we have receiving radiation therapy for thyroid cancer and thyroid nodules, it is clear that an increase of between 80 and 100 over the 250 expected should be easily detectable. There is no question that the thyroid cancer and nodule situation should be investigated.

Without question there is enough work to be done for the next ten years. The Russians appear to be willing to engage in a collaborative effort. We, of course, would be very much interested in that. There is a lot of science to be studied. There also is much public health to be studied in order to better predict the consequences in the U.S. of a release such as that at Chernobyl.

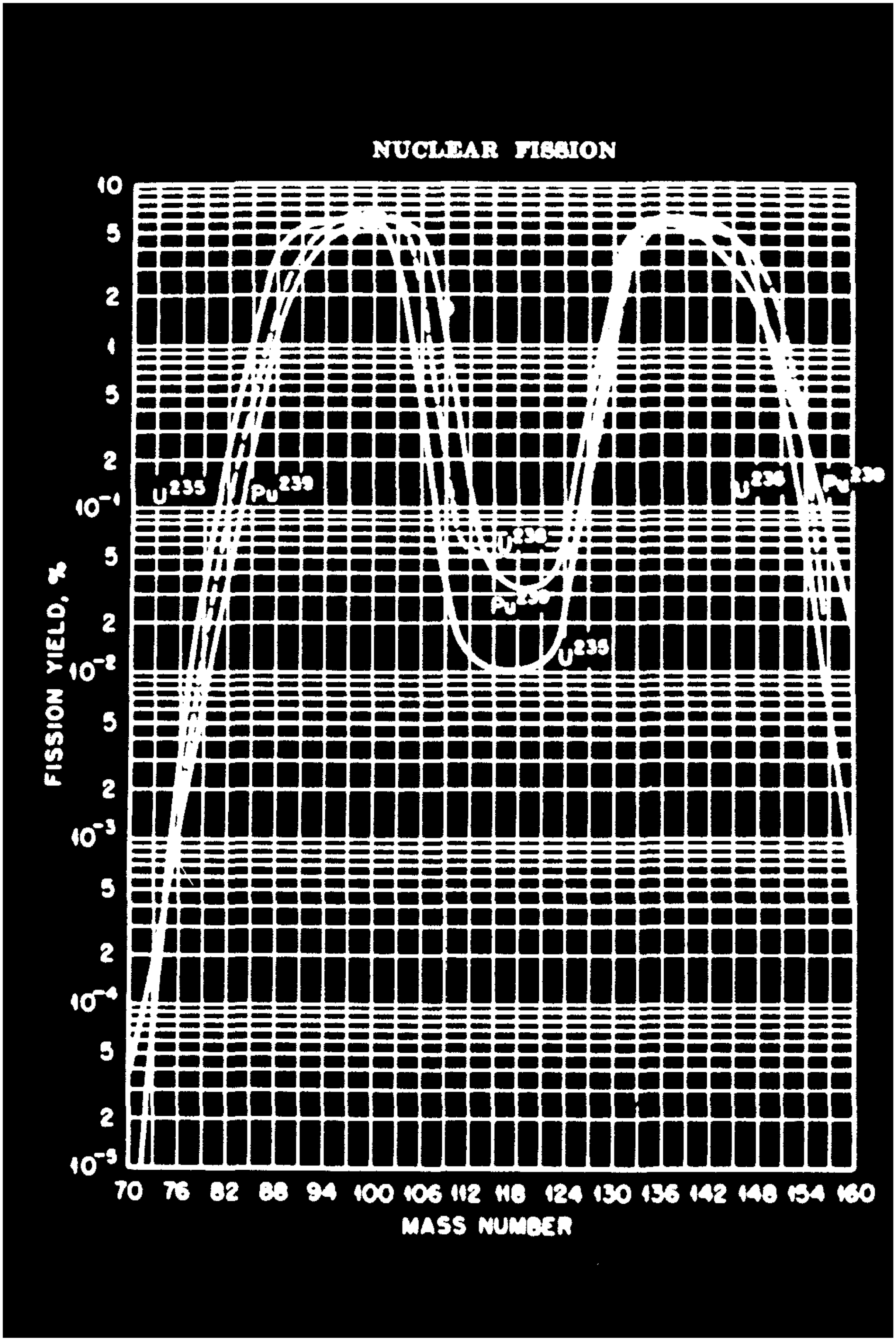

NUCLEAR FISSION
FISSION YIELD, %
MASS NUMBER
10
5
2
1
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁵
70 76 82 88 94 100 106 112 118 124 130 136 142 148 154 160
U235
Pu239
U235
Pu239
U235
Pu239

Figure 1.

Figure 2.

RELEASE FRACTIONS VARY FOR DIFFERENT ELEMENTS

FISSION PRODUCT	MELTDOWN RELEASE FRACTION
Xe, Kr, I, Br	0.9
Cs, Rb	0.75
Te, Se, Sb	0.15
Sr, Ba	0.10
Ru, Mo, Rh	0.03
La, Ce, Y, Zr, Pu	0.003

Figure 3.

SOME OF THE MORE IMPORTANT PARENT RADIO-NUCLIDES MEASURED IN AIR IN FINLAND

Nuclide	Half-life, days	mBq/m^3
Zr- 95	64.03	390
Nb- 95	34.98	800
Ru-103	39.42	3140
Ru-106	372.60	750
Ag-110m	249.8	100
Sb-125	1007.4	250
I-131	8.04	226000
Te-132	3.26	36000
I-133	0.87	60000
Cs-134	753.73	7640
Cs-136	13.10	3190
Cs-137	11012.05	12500
Ba-140	12.76	6600
Am-241	157680	20

Paakkola *et al.*, STUK-B-VALO (1986)

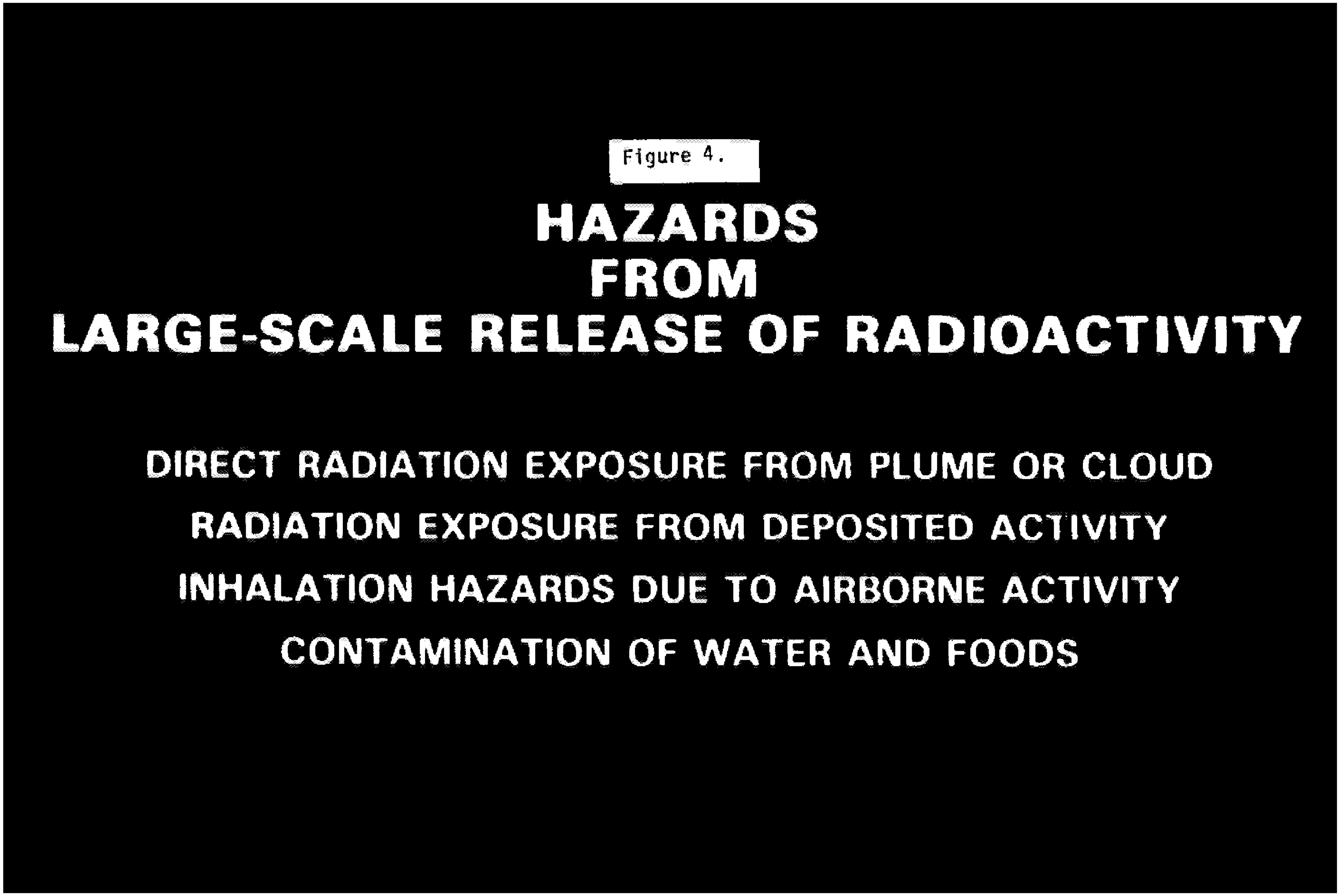

HAZARDS
FROM
LARGE-SCALE RELEASE OF RADIOACTIVITY
DIRECT RADIATION EXPOSURE FROM PLUME OR CLOUD
RADIATION EXPOSURE FROM DEPOSITED ACTIVITY
INHALATION HAZARDS DUE TO AIRBORNE ACTIVITY
CONTAMINATION OF WATER AND FOODS

Figure 4.

Figure 5.

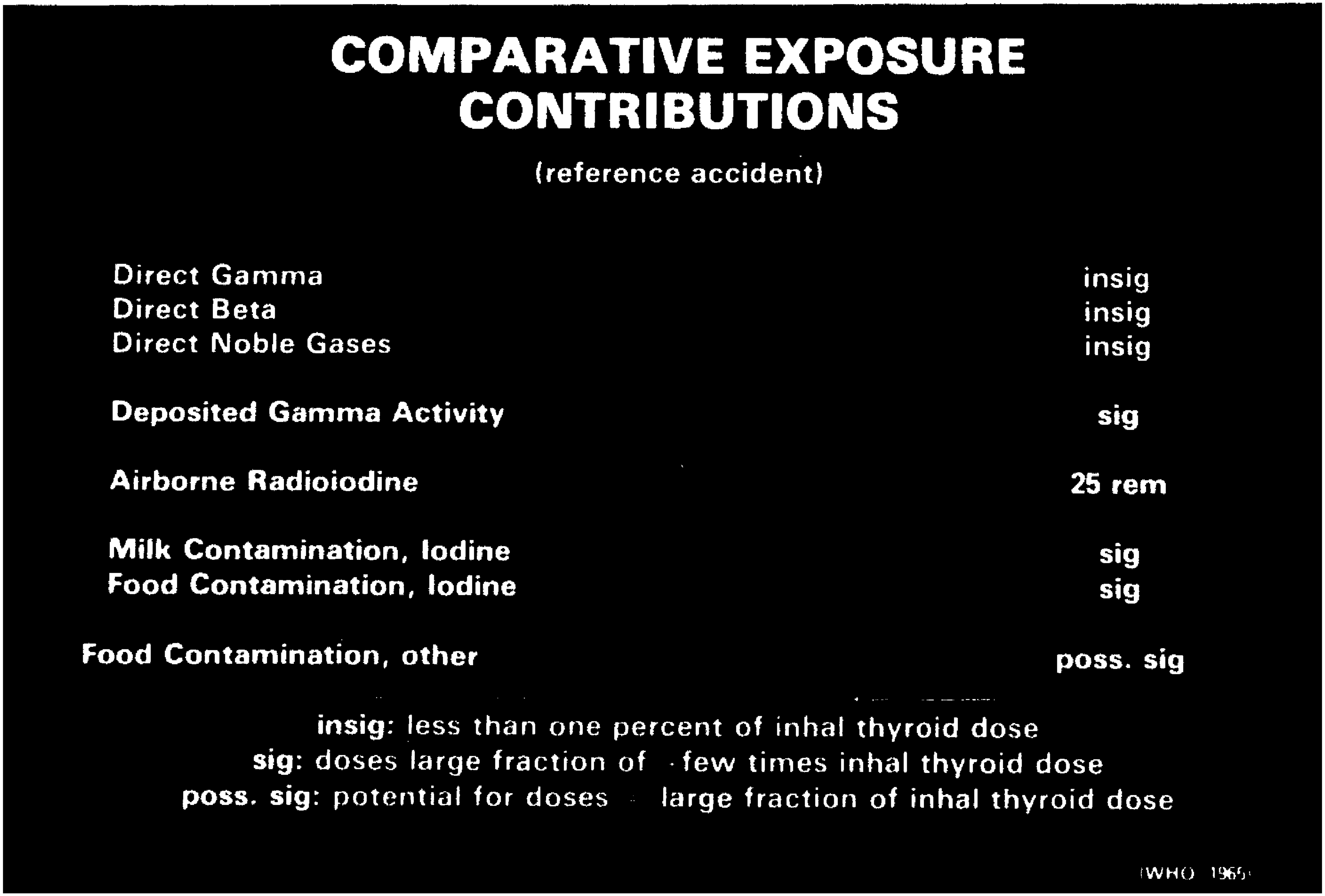

COMPARATIVE EXPOSURE CONTRIBUTIONS
(reference accident)
Direct Gamma
insig
Direct Beta
insig
Direct Noble Gases
insig
Deposited Gamma Activity
sig
Airborne Radioiodine
25 rem
Milk Contamination, Iodine
sig
Food Contamination, Iodine
sig
Food Contamination, other
poss. sig
insig: less than one percent of inhal thyroid dose
sig: doses large fraction of · few times inhal thyroid dose
poss. sig: potential for doses large fraction of inhal thyroid dose
(WHO 1965)

Figure 6.

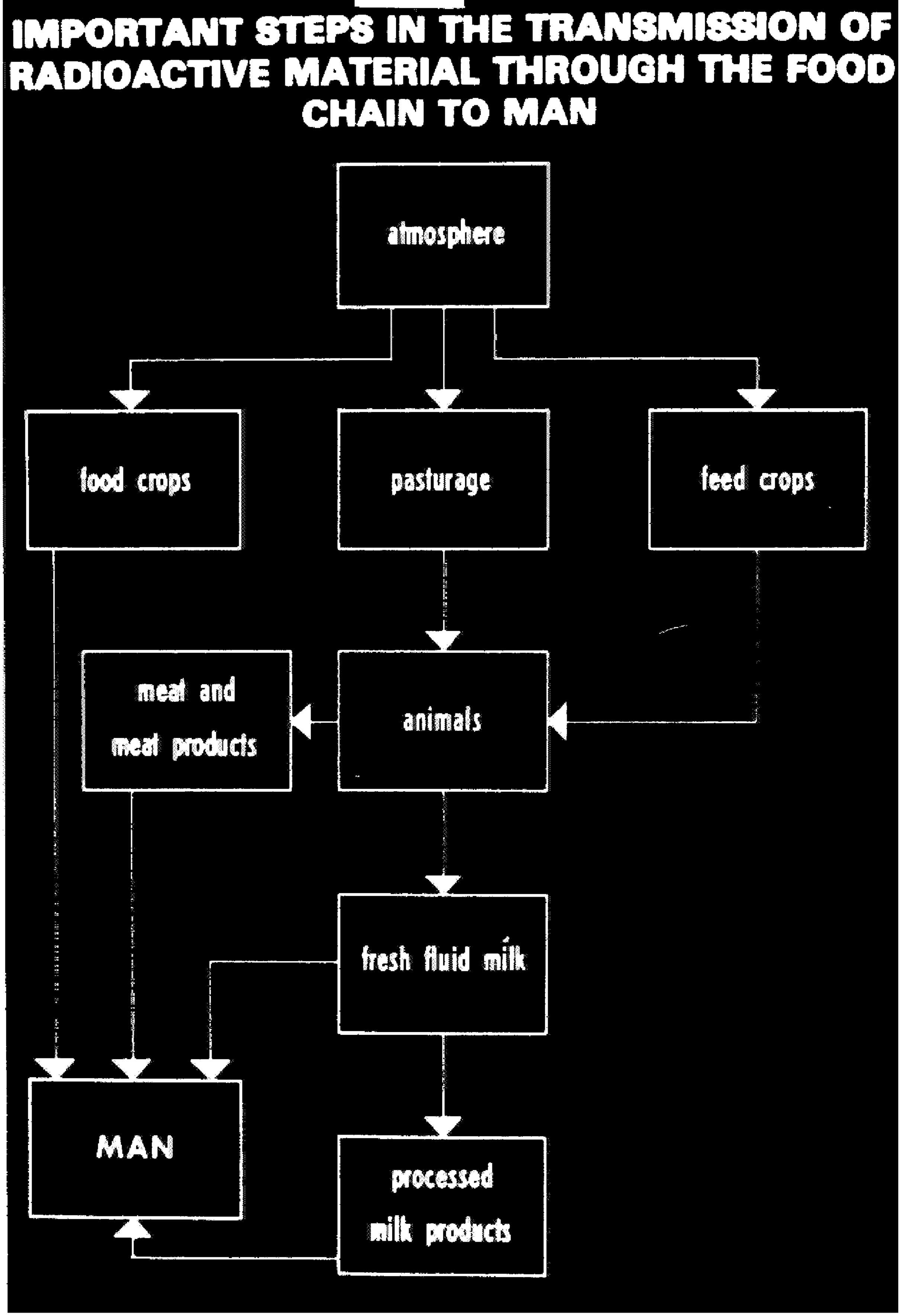

IMPORTANT STEPS IN THE TRANSMISSION OF RADIOACTIVE MATERIAL THROUGH THE FOOD CHAIN TO MAN
atmosphere
food crops
pasturage
feed crops
meat and meat products
animals
fresh fluid milk
MAN
processed milk products

Figure 7.

FDA'S RESPONSE LEVELS FOR THE PREVENTIVE PAG

(FEDERAL REGISTER VOL. 47, NO. 205, 47073-47083, OCTOBER 22, 1982)

RESPONSE LEVELS FOR PREVENTIVE PAG	I-131	Cs-134	Cs-137	Sr-90	Sr-89
INITIAL ACTIVITY					
AREA DEPOSITION (MICROCURIES/SQUARE METER)	0.13	2	3	0.5	8
FORAGE CONCENTRATION (MICROCURIES/KILOGRAM)	0.05	0.8	1.3	0.18	3
PEAK MILK ACTIVITY (MICROCURIES/LITER)	0.015	0.15	0.24	0.009	0.14
TOTAL INTAKE (MICROCURIES)	0.09	4	7	0.2	2.6

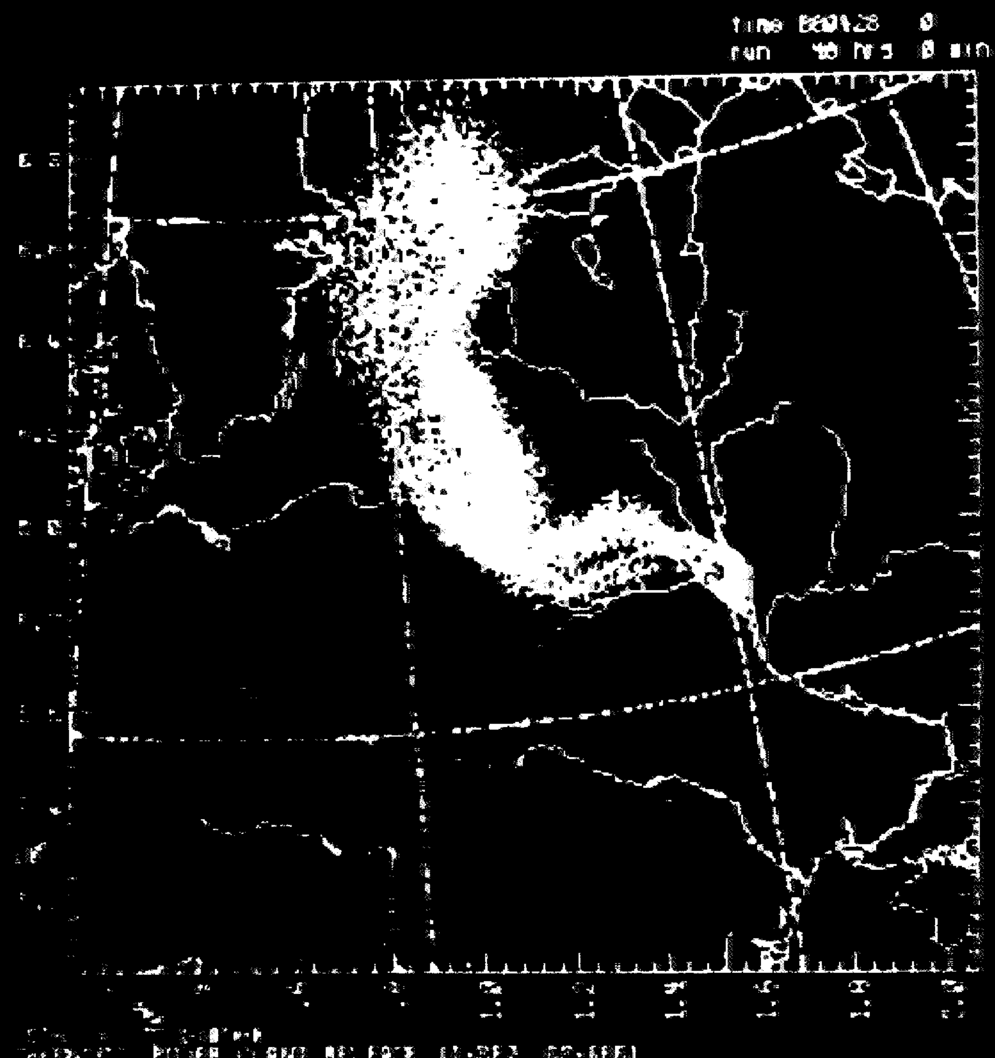


Figure 8.

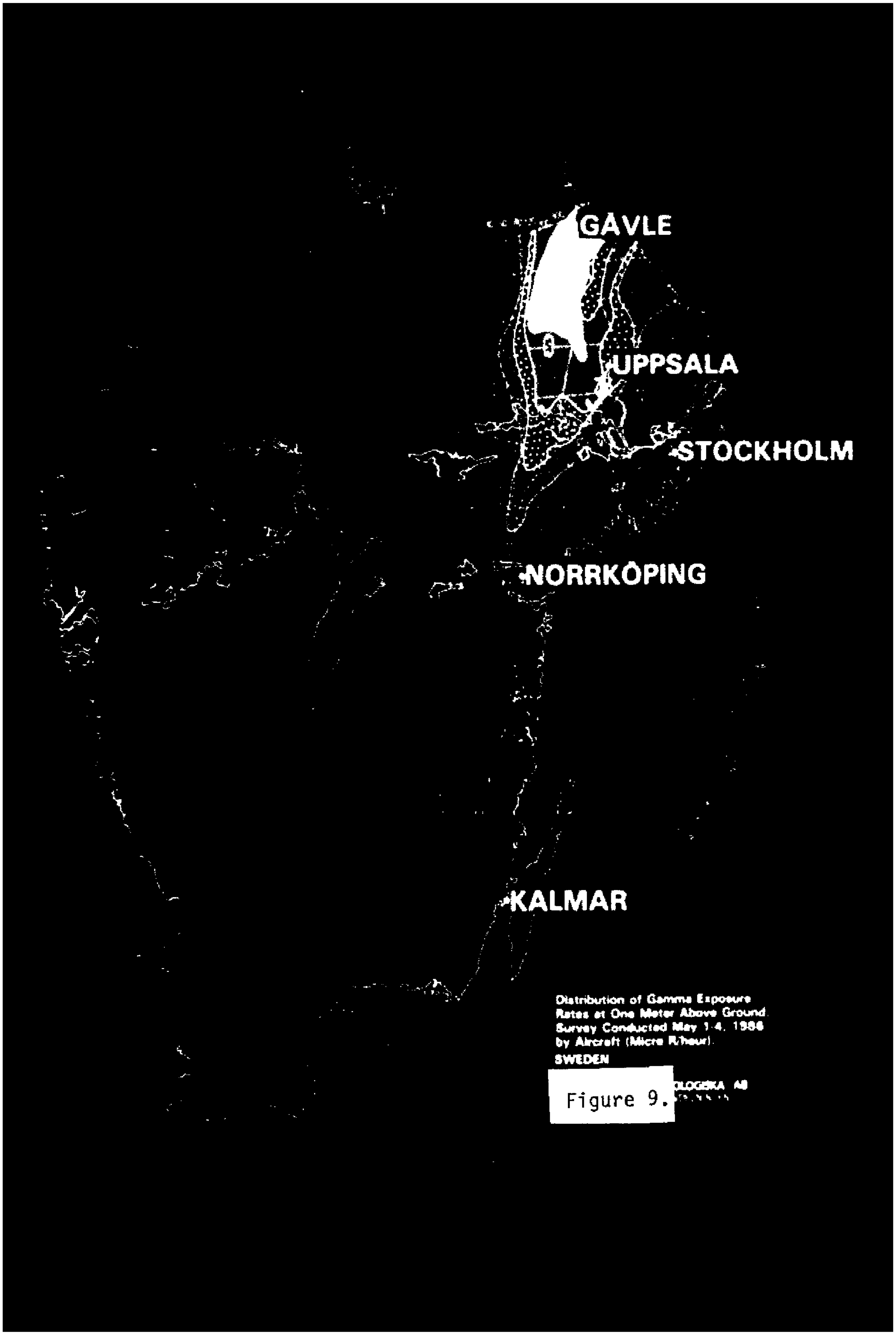

GÄVLE
UPPSALA
STOCKHOLM
NORRKÖPING
KALMAR
Distribution of Gamma Exposure Rates at One Meter Above Ground. Survey Conducted May 1-4, 1986 by Aircraft (Micro R/hour).
SWEDEN

Figure 9.

Figure 10.

Typical Gamma Exposure Rates in European Countries Following the Chernobyl Accident

Country	Dates	Gamma Exposure Rates (micro R/hr)
Sweden	4/29 to 5/8/86	5 - 1300
Finland	4/28 to 5/4/86	5 - 385
Denmark	4/26 to 5/3/86	7 - 8
Austria	5/4 to 5/86	18 - 220
Norway	5/4/86	11 - 22
Hungary	5/5-8/86	21 - 35
Switzerland	5/4/86	5 - 130

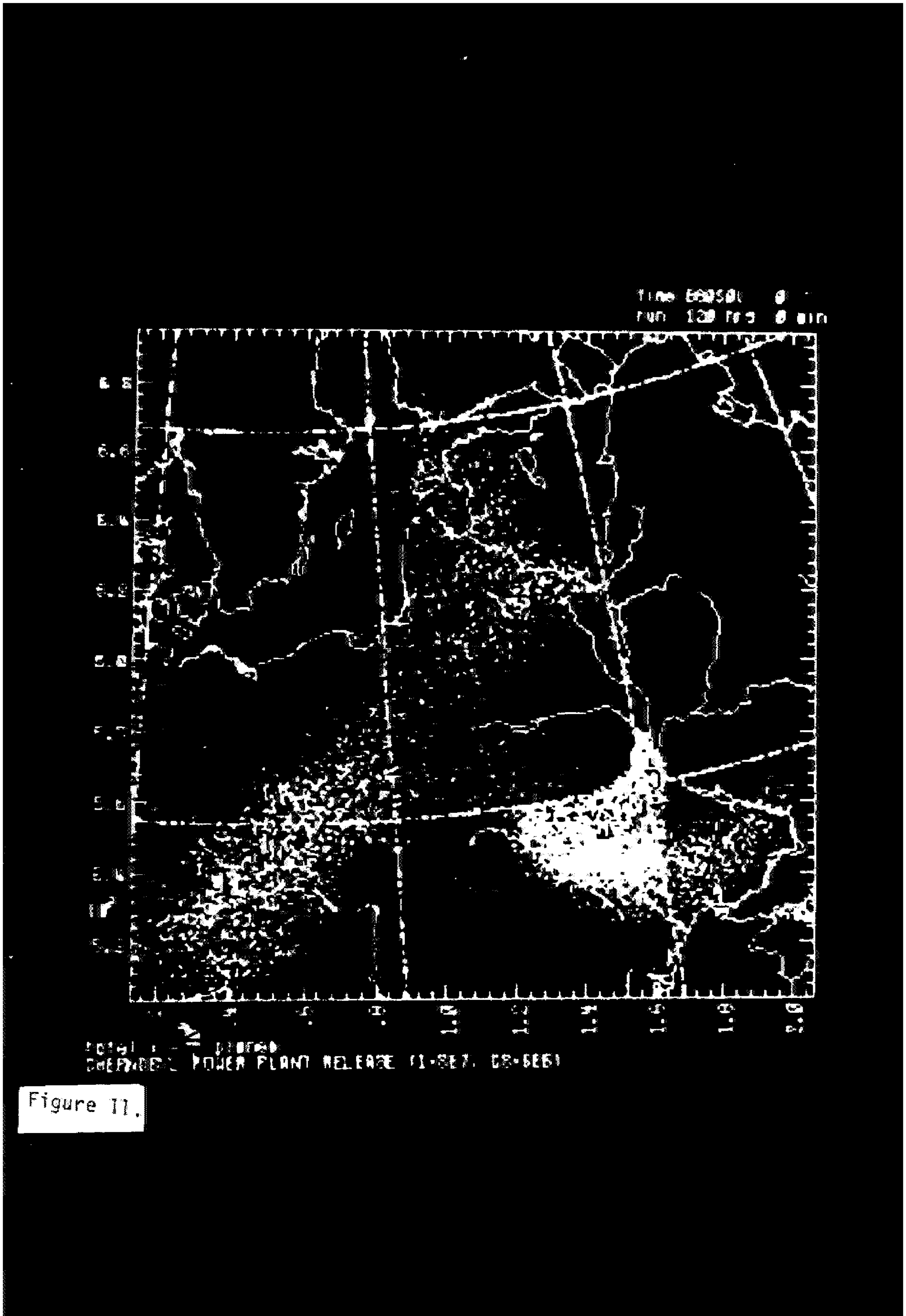


Figure 11.

Figure 12.

DOSE ASSESSMENT, UNITED KINGDOM
MAY 1986 — APRIL 1987
(MREM C.E.D.E.)

	SOUTH		NORTH	
EXPOSURE MODE:	INFANT	ADULT	INFANT	ADULT
EXT. EXPOSURE FROM CLOUD	.01	.01	.01	.01
INHALATION	.7	.8	.7	.8
SKIN CONTAMINATION	.003	.003	.1	.1
DEPOSITED ACTIVITY	1	1	16	16
INGESTION	3	.4	70	10
ALL EXPOSURE MODES	5	2	90	30
DO., WEIGHTED FOR AGE DISTR.	2		30	
DO., WEIGHTED FOR POP. DISTR.	7			

(ADAPTED FROM NATURE 321 194, MAY 15, 1986)

Figure 13.

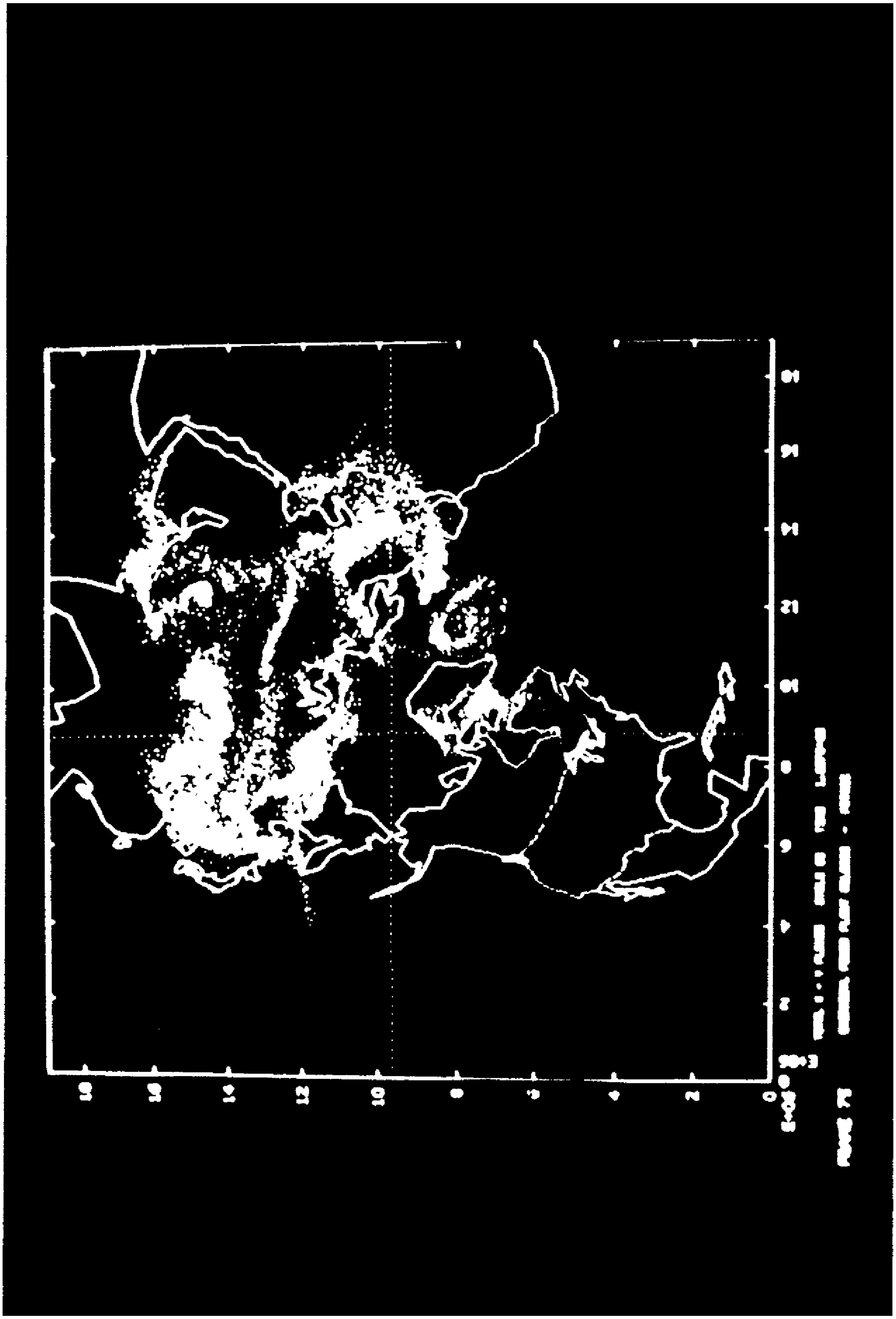
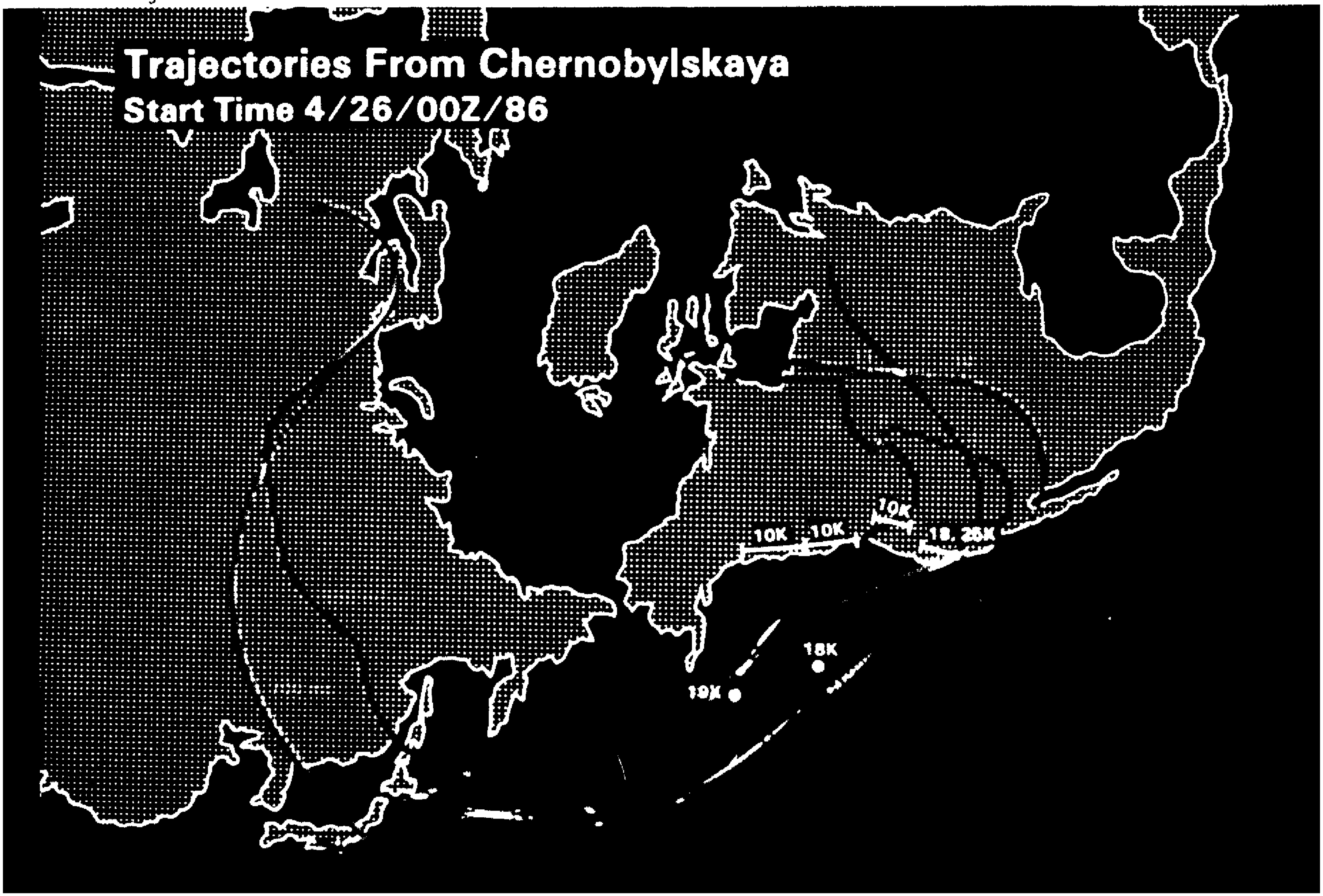


Figure 14.



Trajectories From Chernobylskaya
Start Time 4/26/00Z/86
10K
10K
10K
18, 25K
18K
19K


Estimated Plume Position

Figure 16.

Airborne ^{137}Cs Concentrations at Stockholm, Sweden and Richland, Washington, Measured at Ground Level Following the Chernobyl Accident

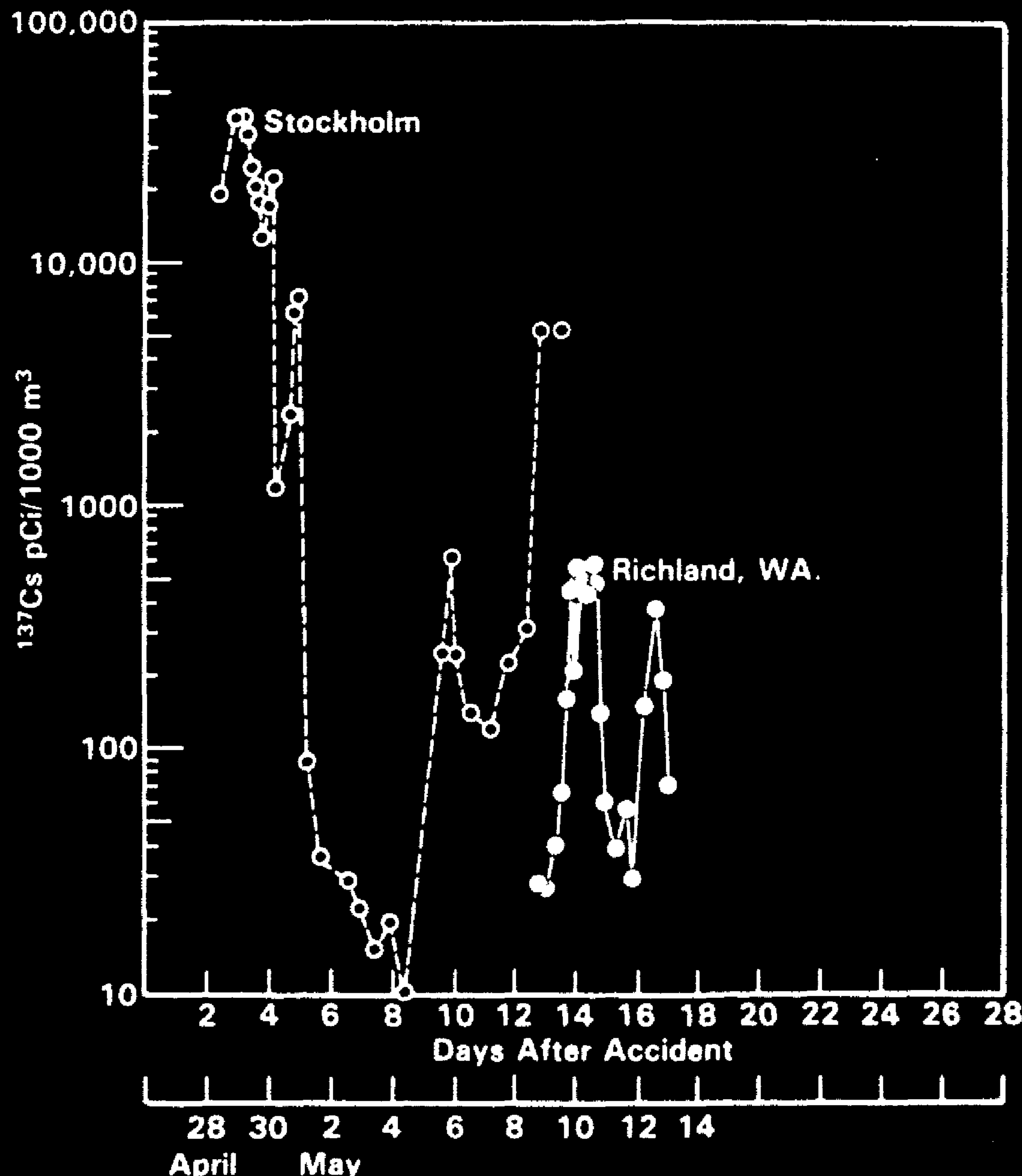


Figure 17.

Particulate Airborne Radioiodine Concentrations at Stockholm, Sweden and Richland, Washington Following the Chernobyl Accident

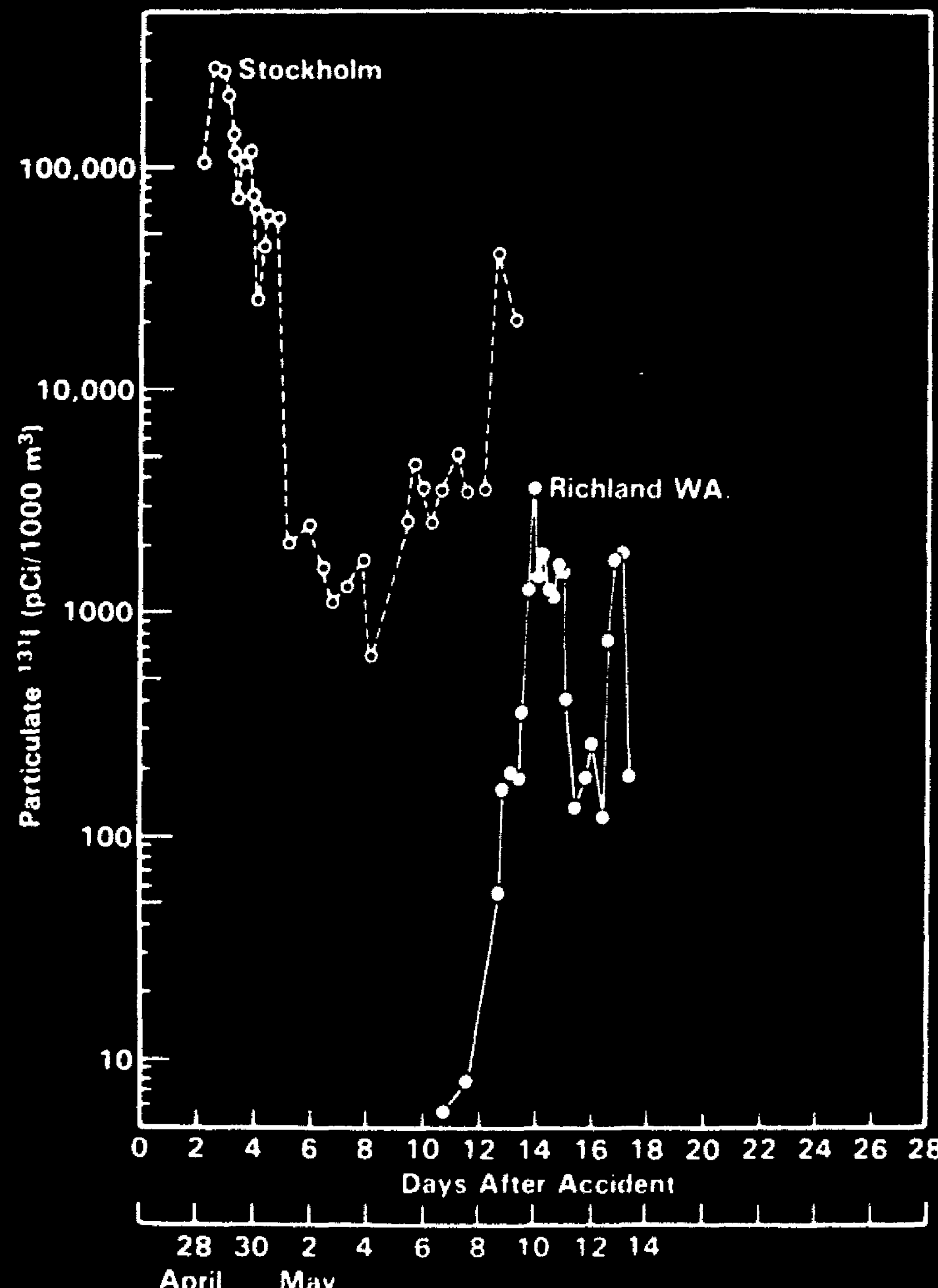


Figure 18.

Particulate Airborne Radioiodine Concentrations Measured at Ground Level at Richland, Washington Following a Chinese Nuclear Test and the Chernobyl Accident

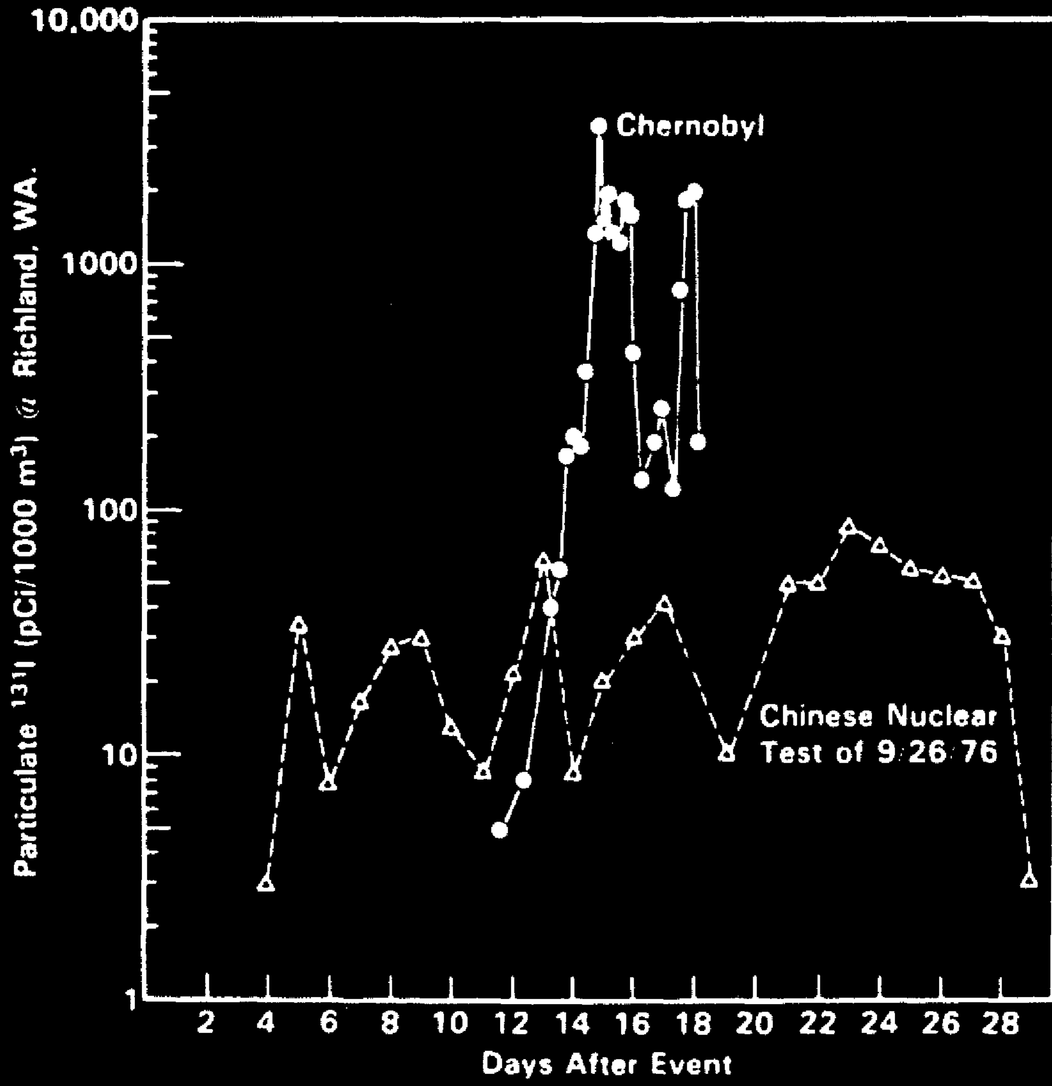


Figure 19.

Iodine-131 in Pasteurized Milk
(EPA National Monitoring Network)

Date	Location	Concentration (pCi/liter)
May 14	La Crosse, WI	36
May 15	Salt Lake City, UT	43
May 15	Syracuse, NY	17
May 15	Seattle, WA	59
May 16	Portland, ME	35
May 16	Helena, MT	54
May 16	Cleveland, OH	21
May 16	San Francisco, CA	36
May 16	Spokane, WA	136
May 16	Oklahoma City, OK	27

Figure 20.

EXTERNAL GAMMA EXPOSURE

<30 km FROM CHERNOBYL

REGION	POPULATION	PERSON-REM	AVE.INDIV.D.E.	"CA.DEATHS"
PRIPYAT	45,000	150,000	3.3	15
3 – 7 km	7,000	380,000	54.3	38
7 – 10 km	9,000	410,000	45.6	41
10 – 15 km	8,200	290,000	35.4	29
15 – 20 km	11,600	60,000	5.2	6
20 – 25 km	14,900	90,000	6.0	9
25 – 30 km	39,200	180,000	4.6	18
TOTAL	134,000	1,560,000	11.6	156

(ADAPTED FROM USSR/IAEA, 1986)

Figure 21.

POPULATION EXPOSURES — ALL SOURCES

CATEGORY	COLLECTIVE D.E.	AVE. IND. D.E.	"CA. DEATHS" CONSERV.	"CA. DEATHS" REALISTIC (?)
EXTERNAL <30 KM	1,600,000	11.6	156	< 156
EXTERNAL >30 KM	29,000,000	0.5	2900	< 2900
INTERNAL Cs-137,-134	210,000,000	3	21,000	< 1500
INTERNAL I-131, ETC.	?	?	200	> 200

(ADAPTED FROM USSR/IAEA, 1986)

Figure 22.

RADIOCESIUM FROM WEAPONS TESTING VERSUS CHERNOBYL

(Collective and Average Doses Northern Temperate Zone)

	Nuclear Tests (all through 1980)	Chernobyl (April 26 — May 6)
Ingestion		
Collective:	16 million person-rad	210 million person-rad*
Average:	28 millirad	3300 millirad*
External		
Collective:	33 million person-rad	29 million person-rad**
Average:	60 millirad	500 millirad

* : later lowered by a factor of ten; ** : all gamma radiation

(from UNSCEAR 1982, and USSR/IAEA 1986)

Figure 23.

CANCER MORTALITY IN JAPANESE A-BOMB SURVIVORS

(Radiation Effects Research Foundation data)

Number of Survivors (Oct.1, 1950):	283,498
Ave. Dose (T65D):	16.1 rad
Total leukemia mortality through 1978:	387
Est'd Excess (number /%):	190.6 / 100%
90% Conf. Limits:	174.0 — 207.2
Total all other cancer mortality:	10,421
Est'd Excess (number /%):	335.7 / 3%
90% Conf. Limits:	253.7 — 417.7

(From Kato & Schull, 1982)

Figure 24.

CANCER IN DOWNWIND USSR POPULATION

(from USSR data)

Number evacuated (Pripyat/other):	45,000 / 89,000
Given 11.6 rad ave. dose to 134,000 people:	
radiation-induced cancer deaths:	156*
non-radiogenic cancer deaths:	22,500
$< 1\%$ --> not detectable	
Given 45 rad ave. dose to 24,000 people:	
radiation-induced cancer deaths:	110*
non-radiogenic cancer deaths:	4,000
5% --> possibly detectable	

*: assuming Japanese risk factors applicable

Figure 25.

THYROID CANCER IN DOWNWIND USSR POPULATION

(assumptive)

Assume 100 rad ave. thyroid dose to 100,000 population:

radiogenic thyroid cancer cases	: 80 – 800	*
radiogenic thyroid nodules	:200 – 2000	**
normal lifetime TC incidence	: 250	*

--> easily detectable

*: using data from NCRP 80, 1985; **: Marshallese experience; ranges given: chronic exposure vs. acute exposure