G/028

Gorleben Report : Chapter 3

Section

The Effects of Releases to the Atmosphere of Radioactivity from Hypothetical Large-Scale Accidents at the Proposed Gorleben Waste Treatment Facility

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Foreword

This report has been written as one part (section 3.13) of an international review of the proposed Gorleben radioactive waste treatment facility. The report is self-contained but, ideally, should be read in connection with all of Section 3 of the Gorleben International Review (G.I.R.)

This version must be considered preliminary since supporters of the present Gorleben design have not had a chance to criticize the suggestions made for reducing the upper limit risk. Revisions to this report may be made after public hearings are held in Germany at the end of March 1979.

Note that the footnotes to this report include some very technical material.

INTRODUCTION

This Report presents the major consequences following hypothetical airborne releases of large quantities of radioactivity from waste storage tanks and spent fuel storage ponds. The accidents studied here assume release of radioactivity into the air in the form of small particles. The subsequent movement of the radioactive "cloud" is determined by wind and other meteorological factors.

Consequence results are presented as a function of the quantity of material released, up to the maximum which is proposed for temporary storage at Gorleben.

Although the calculations presented here show some possibility of early deaths,[1,2] the major potential consequences appear to be associated with the long-term: delayed lung cancer deaths arising from inhalation of radioactive materials from the passing cloud (primarily ruthenium) and land contamination from the "fall out" of radioactive cesium.

Considerable effort has been put into simplifying the consequence calculations and their presentation. Only the most important isotopes are discussed. Results have been presented in such a way as to minimize the number of assumptions. Instead of restricting the results to specific post-accident scenarios about governmental and individual response (which requires a large number of debatable assumptions), information has been provided which allows for any post-accident population movement. Thus, instead of presenting population doses, calculations are presented in terms of affected land areas - the number of square kilometers over which doses to individuals, if present, would exceed a particular threshold. The presentation is general enough so that the threshold itself can be treated as a parameter. If other observers do not accept the thresholds used here (for illustrative purposes) as indicative of levels at which protective action should be taken, they can use the tables and graphs provided to determine how the results would be modified by other choices.

Hopefully, this general approach will be more useful in the Gorleben debate than presentation of estimated health effects. (Of course, if one is willing to make assumptions about post-accident population behavior and dose-health effects relationships, then the area results can be easily converted to total number of health effects.)

Three types of doses have been singled out as dominating the consequences of an airborne release of waste fission radioactivity[3]: Long-term external doses from radioactivity deposited on the ground, short-term lung doses from radioactivity inhaled at the time of the accident and long-term lung doses from aerosol particles trapped in the lungs. Each will be discussed in turn.

1) External whole-body radiation from cesium deposited on the ground and surface of buildings. The dose received by the individual over, say, a thirty year period depends upon the time spent in contaminated ground, and whether or not any decontamination is attempted.[4]

For illustrative purposes, land which would give a 10 year dose in thirty years is considered contaminated. This dose level is taken as a rough indicator of the criterion which might be used subsequent to an accident.

A 30 year dose of 10 rem would be about a factor of three higher than the average dose from natural background radiation over the same period and might increase the probability of dying from cancer by on the order of a few tenths of a percent.[5] This contamination level was suggested by the U.S. Reactor Safety Study as the level above which decontamination or population relocation would have to occur in rural areas.[6] Choosing a contamination level is rather arbitrary (representing a trade-off between public health and economics) and other levels have been suggested.[7]

It should also be noted that changes in consensus about the health effects of low-level radiation would logically lead to a revision of past estimates.[8]

Furthermore, the U.S. figure was chosen in the context of an accident occurring within the boundaries of one country. Guessing the level that Soviet bloc countries might insist upon for decontamination, should a large release be blown in their direction, is even more difficult.

In any case, information given in the footnotes indicates how to adjust the calculations for other threshold choices.

Fig. I shows a typical, oval contour for land contamination arising from a very large release of radioactivity.[9;9A] The contour determines the area over which the cumulative whole-body radiation dose from cesium 137 would equal or exceed the 10 rem in 30 year threshold. Although the particular shape of the contour depends somewhat upon the meterological model used for calculations, the actual area in square kilometers tends to be model-independent as will be discussed later.

Figs II and III show, superimposed on a map of Europe, two more examples of land contamination - this time following, essentially, the worst possible accident at the presently designed Gorleben spent fuel storage pool. These two examples assume the same amount of released radioactivity (3×10^8 curies of cesium ^{137}), but different meteorological conditions. (It should be noted that, in both cases, the meteorological conditions are typical.)

Fig II and III differ only in the assumed wind direction and in the "deposition velocity" parameter (which measures how fast material "falls out" of the plume).[11] Both assume an average 5 m/sec wind speed and generally overcast conditions.

The direction of the wind occurring at the time of the hypothetical accident would determine over what countries the contamination would fall. It would take many days for the radioactivity to reach the maximum distances shown. In the larger area case, Fig III, the area contour has been terminated after about five days of travel (based on the assumption that

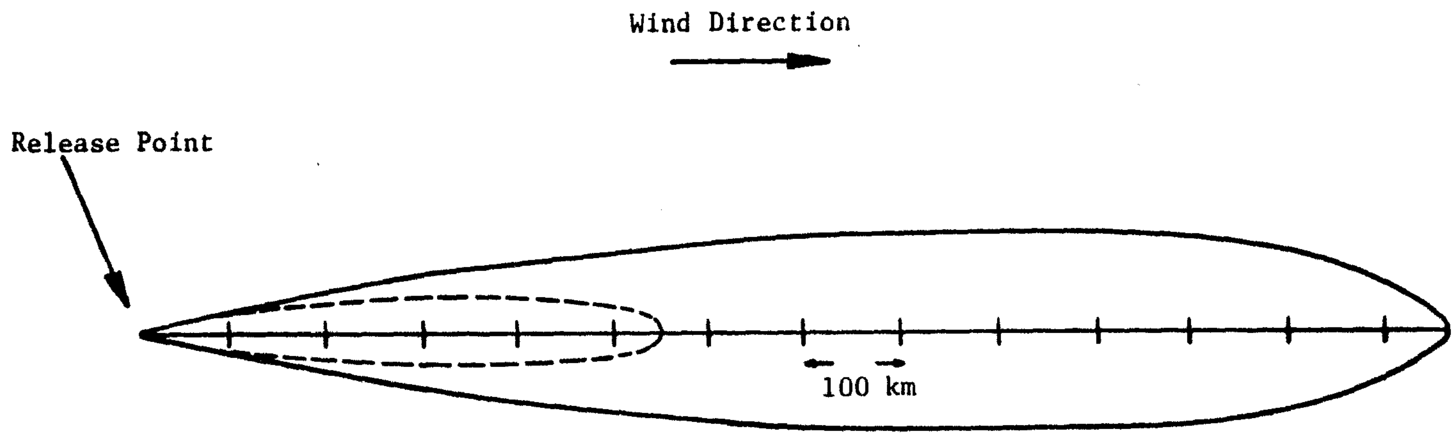

Fig. I. Land Contamination Contours: Worst case release from one high level waste storage tank; 10^8 curies of Cs^{137} released, 5/sec wind speed, .01m/sec deposition velocity; Solid line = 10 Rem dose in 30 years; Dotted line = 100 Rem dose in 30 years contour, or, what is equivalent, 10 Rem/30 years for a 10^7 curie release.

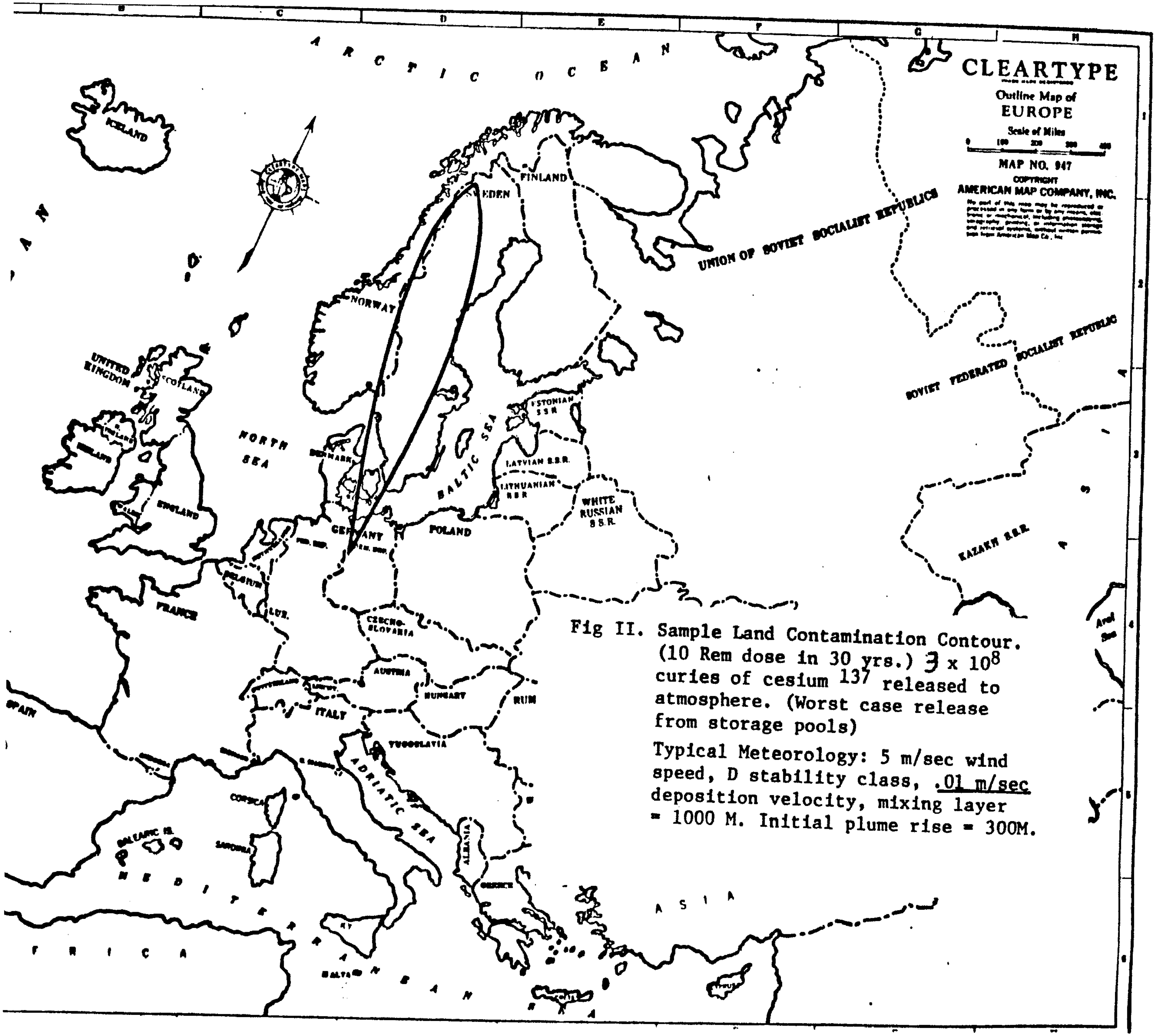

Fig II. Sample Land Contamination Contour. (10 Rem dose in 30 yrs.) 3 x 10^8 curies of cesium 137 released to atmosphere. (Worst case release from storage pools)

Typical Meteorology: 5 m/sec wind speed, D stability class, .01 m/sec deposition velocity, mixing layer = 1000 M. Initial plume rise = 300M.

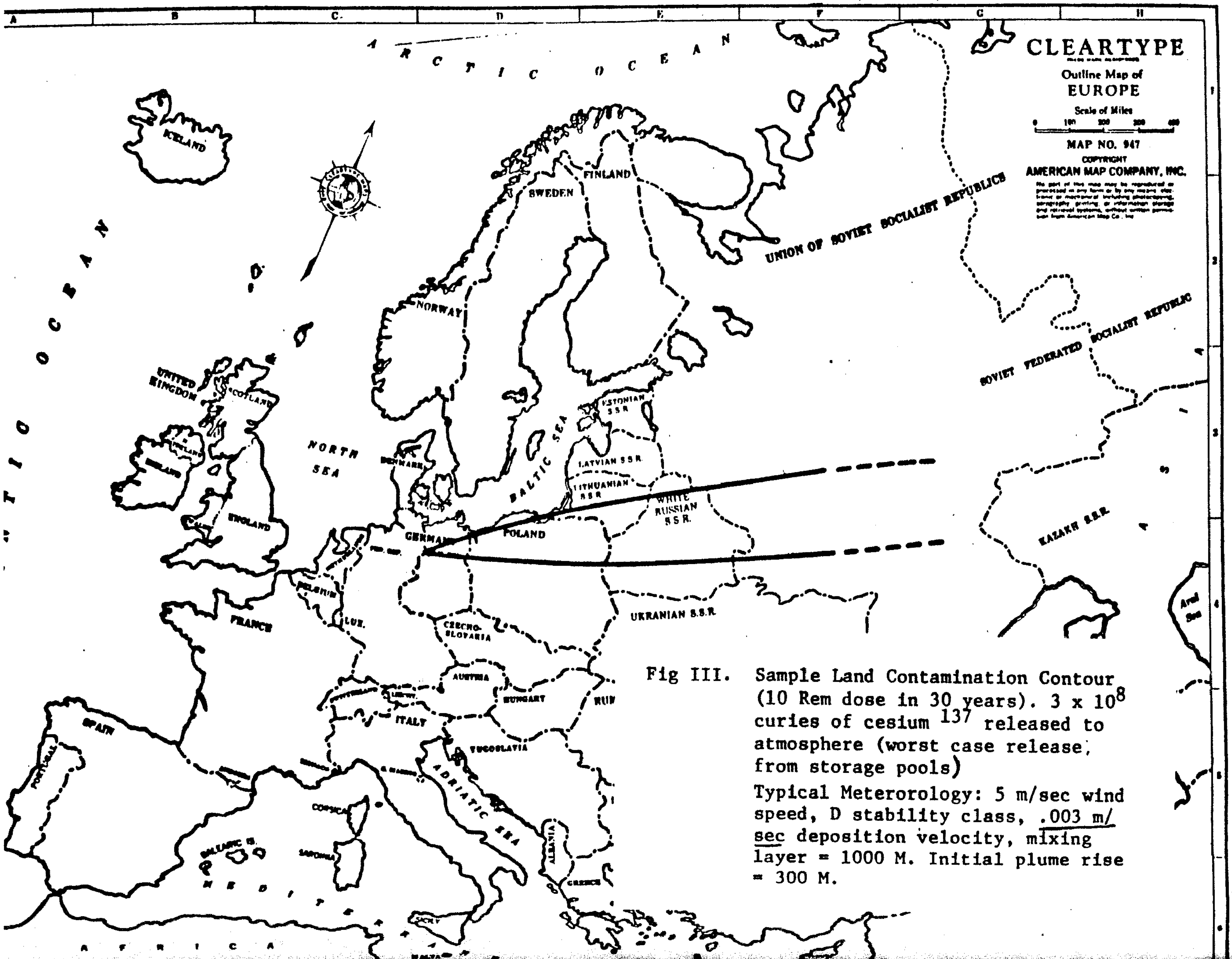

Fig III. Sample Land Contamination Contour (10 Rem dose in 30 years). 3×10^8 curies of cesium ^{137} released to atmosphere (worst case release, from storage pools)

Typical Meterorology: 5 m/sec wind speed, D stability class, .003 m/sec deposition velocity, mixing layer = 1000 M. Initial plume rise = 300 M.

rain washes out the remaining airborne material preventing more distant contamination). In any case, hundreds of thousands of square kilometers would be polluted.

Another consequence of the long travel time is the fact that wind direction changes may be significant and reduce the maximum distance which is contaminated. This is important when considering winds initially blowing towards the west. One should not "rotate" the entire contours in fig. II or III to point West, without considering the meteorological probability of the wind blowing in that direction for many days.

However, every part of the F.R.G. is close enough to the site so that wind persistency considerations are not important as far as German soil is concerned.

Figs II and III are very dramatic pictures. They indicate that very bad accidents at Gorleben could literally change the map of Europe. (The extent of the contamination is perhaps not so surprising when one realizes that the cesium 137 radioactivity released in the accident shown is equivalent to that which would be released by 60 reactor cores melting down simultaneously[12]).

Because the pictures shown are so dramatic, they may well receive wide publicity in the F.R.G. The level of debate will be lowered if these curves are sensationalized and their significance over stated. The level of land contamination is not such that the effects would be easily detected, even if no mitigating measures were to be taken subsequent to the accident. The land would be polluted in the same way that land in the past has been polluted from chemical carcinogens

There would be a slight increase in the rates of cancer, illness, spontaneous abortions and birth defects. (In absolute numbers, however, the increases would be very disturbing, potentially causing great anxiety among the affected population.)

It is important to note that the probability of such accidents is probably very low. The low probability, as well as the dramatic consequences, must be weighed in decisions about Gorleben.

Nevertheless, in spite of these mitigating factors, there is no way to avoid the fact that such accidents would be environmental disasters of an unprecedented sort. Many people will find these pictures disturbing regardless of full explanations and assurances that the probabilities are believed to be very low. It is thus of interest to consider whether there are any options, short of not building Gorleben, which could rule out such large accidents. Such possibilities are considered at the end of this report.

Fig II and III assume, essentially, worst case releases. What about the size of areas effected by lower release quantities? Since it is too cumbersome to show contour plots for a wide variety of releases, the areas of the contours in square kilometers have been tabulated instead. Table I shows a tabulation of areas for contours equivalent to Figs II and III, for lower initial amounts of released cesium 137.

Fig IV shows a graphical presentation of the dependence of area upon release quantity. A typical meteorological case is shown as well as upper and lower limits. These limits have been obtained by varying meterological conditions over a wide range of wind speed.[12A] Note that typical conditions produce a curve close to the upper limit curve. Fig IV can be used to estimate the range in land contamination that would result from a wide range of hypothetical accidents.

TABLE I. AREAS AND MAXIMUM DISTANCES REACHED FOR DIFFERENT QUANTITIES OF RELEASED CESIUM 137
(5 m/sec wind speed, ground shielding = .25 , D stability, 1000m mixing level, 300 m initial plume rise, 10 Rem/30 year threshold.)

	.01 m/sec deposition velocity		.003 m/sec deposition velocity	
Cesium 137 Curies	Area	Maximum Distance Reached	Area	Maximim Distance Reached
4×10^8	430,000 km^2	1900 km	740,000 km^2	2400[a)]
3×10^8	370,000	1800	680,000	2400[a)]
1.4×10^8	237,000	1500	410,000	2300
1×10^8	190,000	1400	290,000	2000
4×10^7	100,000		100,000	1100
1.2×10^7	34,000		17,000	470
3×10^6	7,100			
1.2×10^6	2,300			
4×10^5	550			

a) Cut off at 2400 km, assuming rain occurs and washes out radioactivity, preventing more distant contamination.

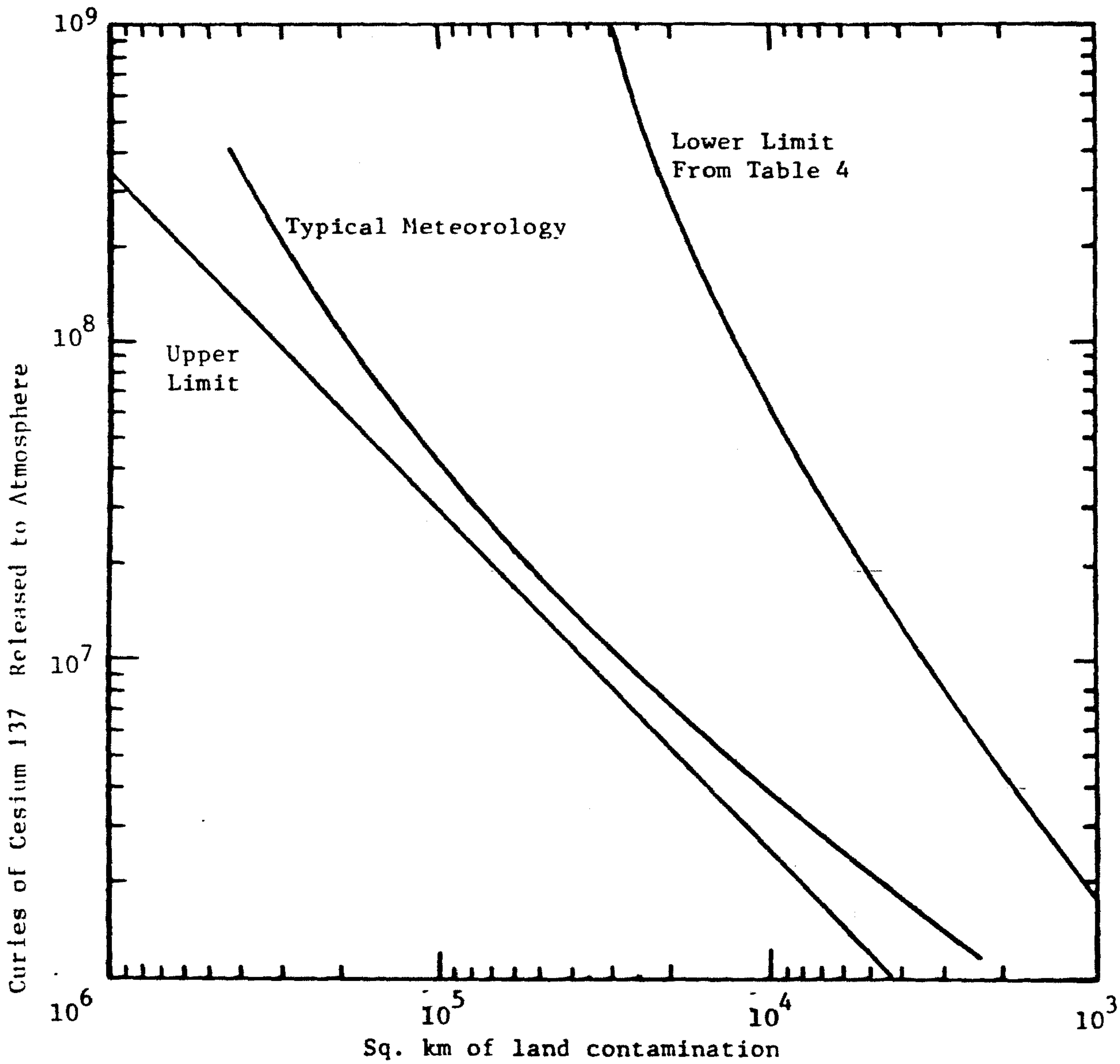

Fig IV. CONTAMINATED AREA AS FUNCTION OF RELEASED CURIES OF CESIUM
The "typical meteorology" curve assumes 5 m/sec wind speed, D stability class, .01 m/sec deposition velocity, 1000 M mixing layer, 300 m inital plume rise. The upper and lower limits are taken from Table 4. See note 12A. The upper limit takes into account all possible variations in wind speed and deposition velocity.

Footnote 12B indicates how area numbers corresponding to different assumptions about thresholds can be extracted from Fig IV and how different assumptions about post-accident behavior can be taken into account.

An additional advantage of presenting the results in square kilometers. is that the results become much more model-independent. As a result, there should be less debate about the adequacies of the particular model assumed. Calculations have been made using both a standard gaussian plume model[9A] (which requires a computer) and a simplified wedge model[17] (which can be used to anaytically explore the effects of parameter variations).

In the wedge model one can show that the upper limit is independent of atmospheric stability conditions, wind speed, and deposition velocity. It amounts to about 20% of the physical upper limit one would get by simply spreading the cesium uniformly to the threshold level.[17b]

The fact that the numerical value of affected areas approach each other in the two models when areas are large, means that the upper limit areas tend to be model independent. This is an important result in the policy context, since one does not want technical conclusions to be uncertain or debatable due to model inadequacies.

Based on Fig IV (and its relative model-independence), it appears that the key variables for debate are the release quantities, the contamination threshold, and the amount of decontamination and relocation which would be possible in the post-accident environment. Once these variables are fixed, the consequences are fairly definite. Meteorological probabilities do not appear to be a major factor as they have been in some past considerations of reactor accidents.[4a]

Long-term Internal Lung Dose

The second type of dose which has been emphasized here is long-term internal lung dose caused by inhalation of radioactive particles (primarily Ruthenium-106). Some of this radioactivity remains in the lung delivering a dose over a period of many years. Whether or not an individual receives such a dose depends only upon where the individual was during the passage of the airborne radioactive material. If the individual can be evacuated before cloud passage, no lung dose results.

Lung doses of this sort contribute to the risk of delayed lung cancer. Roughly speaking, a 100 rem lung dose will cause 1 to 10 delayed cancer deaths per thousand exposed population[18]. Figures V and VI show the areas within which long-term lung doses would exceed 100 rem for the same "worst case" examples shown for land contamination in Figs II and III. (5×10^8 curies of Ruthenium-106 released.)[18a] These are the areas for which public officials might order immediate evacuation in order to prevent inhalation of radioactivity. (Since the radioactivity is traveling relatively slowly, there would be time for evacuation. The number of people involved, however, would be incredibly large.)[9x]

People beyond these areas, who would not be evacuated, would receive lung doses smaller than 100 rem. These doses would contribute to a large number of delayed lung cancer deaths (between 3000 and 100,000[19]), but the individual risk would be small since the exposed population would range from 30 to 100 million. Evacuation for this second set of people might not be desirable, even if logistically possible, because the number of accidental deaths incurred in the evacuation process might exceed those from the inhaled radiation.[20]

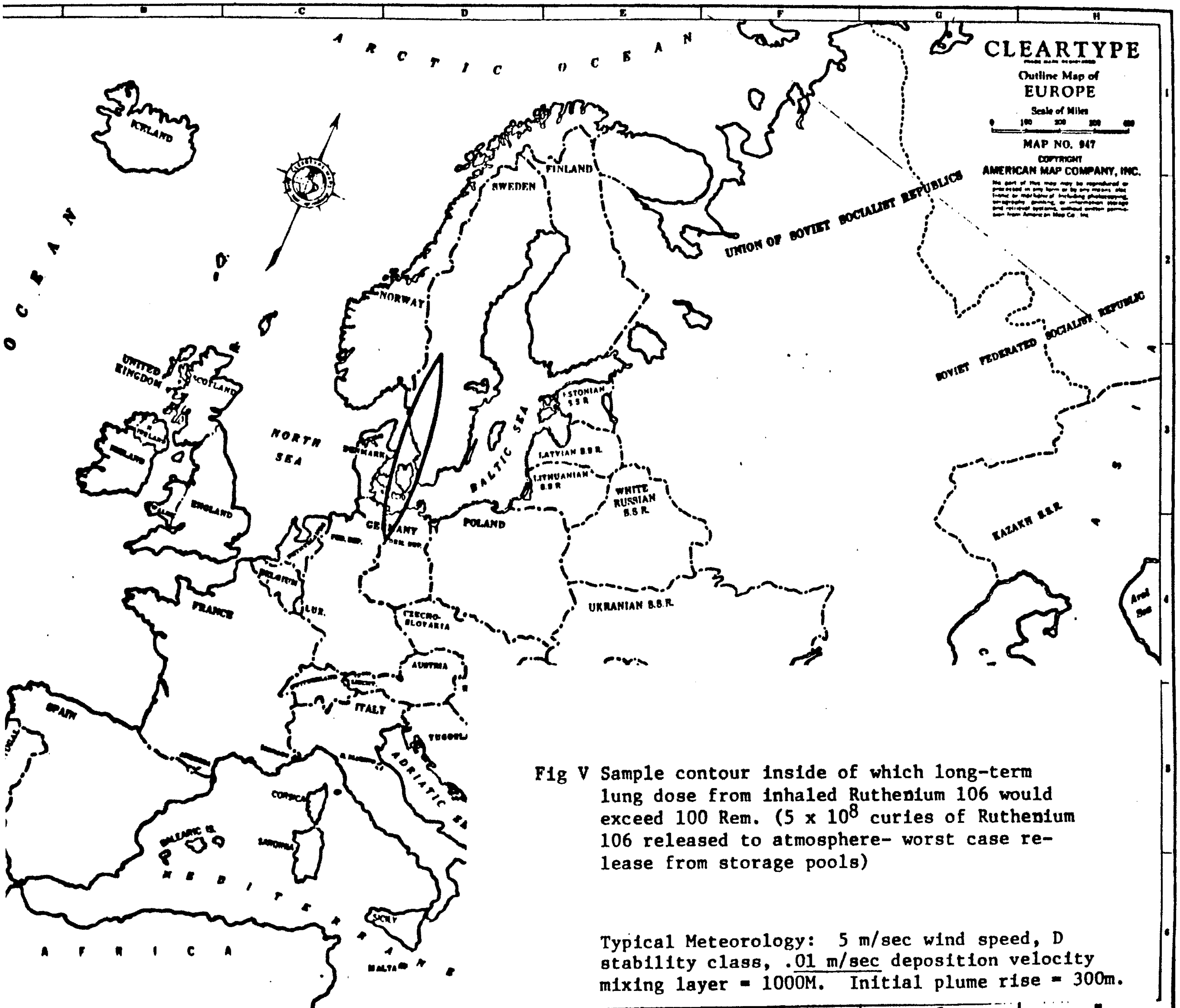

Fig V Sample contour inside of which long-term lung dose from inhaled Ruthenium 106 would exceed 100 Rem. (5×10^8 curies of Ruthenium 106 released to atmosphere- worst case release from storage pools)

Typical Meteorology: 5 m/sec wind speed, D stability class, .01 m/sec deposition velocity mixing layer = 1000M. Initial plume rise = 300m.

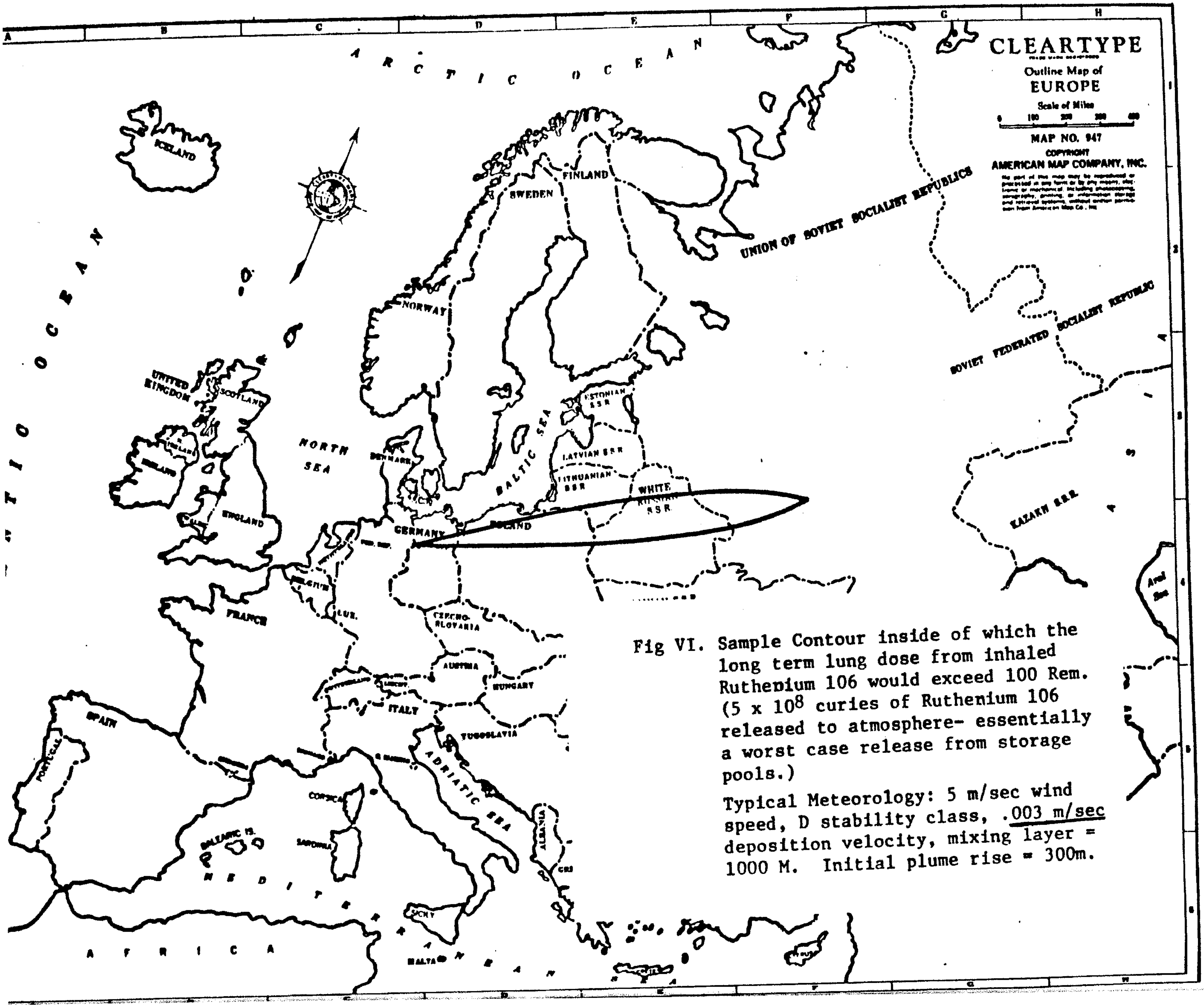

Fig VI. Sample Contour inside of which the long term lung dose from inhaled Ruthenium 106 would exceed 100 Rem. (5 x 10^8 curies of Ruthenium 106 released to atmosphere- essentially a worst case release from storage pools.)

Typical Meteorology: 5 m/sec wind speed, D stability class, .003 m/sec deposition velocity, mixing layer = 1000 M. Initial plume rise = 300m.

Table II shows tabulated areas for contours corresponding to releases lower than the worst case. A graphical presentation is shown in fig VII. In the inhalation case, the results are not as model-independent as the land contamination case. Here the upper limit depends upon the lowest deposition velocity which is considered possible.[21] Thus, rather than show upper and lower limits, one additional deposition velocity case has been shown.

Results for other plume rises are tabulated in Table V at the end of the report. In figs VIII and IX, the land contamination contours are joined with the 100 rem lung dose contours to show the relative size of the areas affected .

TABLE II. 100 REM LUNG DOSES: AREAS AND MAXIMUM DISTANCES FOR DIFFERENT QUANTITIES OF RELEASED RUTHENIUM 106.[a)]

	.01 m/sec deposition velocity		.003 m/sec deposition velocity	
Ru 106 curies	Area	Maximum Distance Reached	Area	Maximum Distance Reached
5×10^8	77,000 km^2	900km	280,000 km^2	1900 km
1.7×10^8	26,000	550	77,000	1000
5×10^7	6,700	270	12,000	390
1.7×10^7	1,800	140	2,500	170
5×10^6	250	67	280	72

a) 5 m/sec wind speed, D stability, 1000 m mixing layer, 300 m initial plume rise, breathing rate = 2.7×10^{-4} m^3/sec, 3.9×10^6 Rem lung dose received in 10 years per curie inhaled.

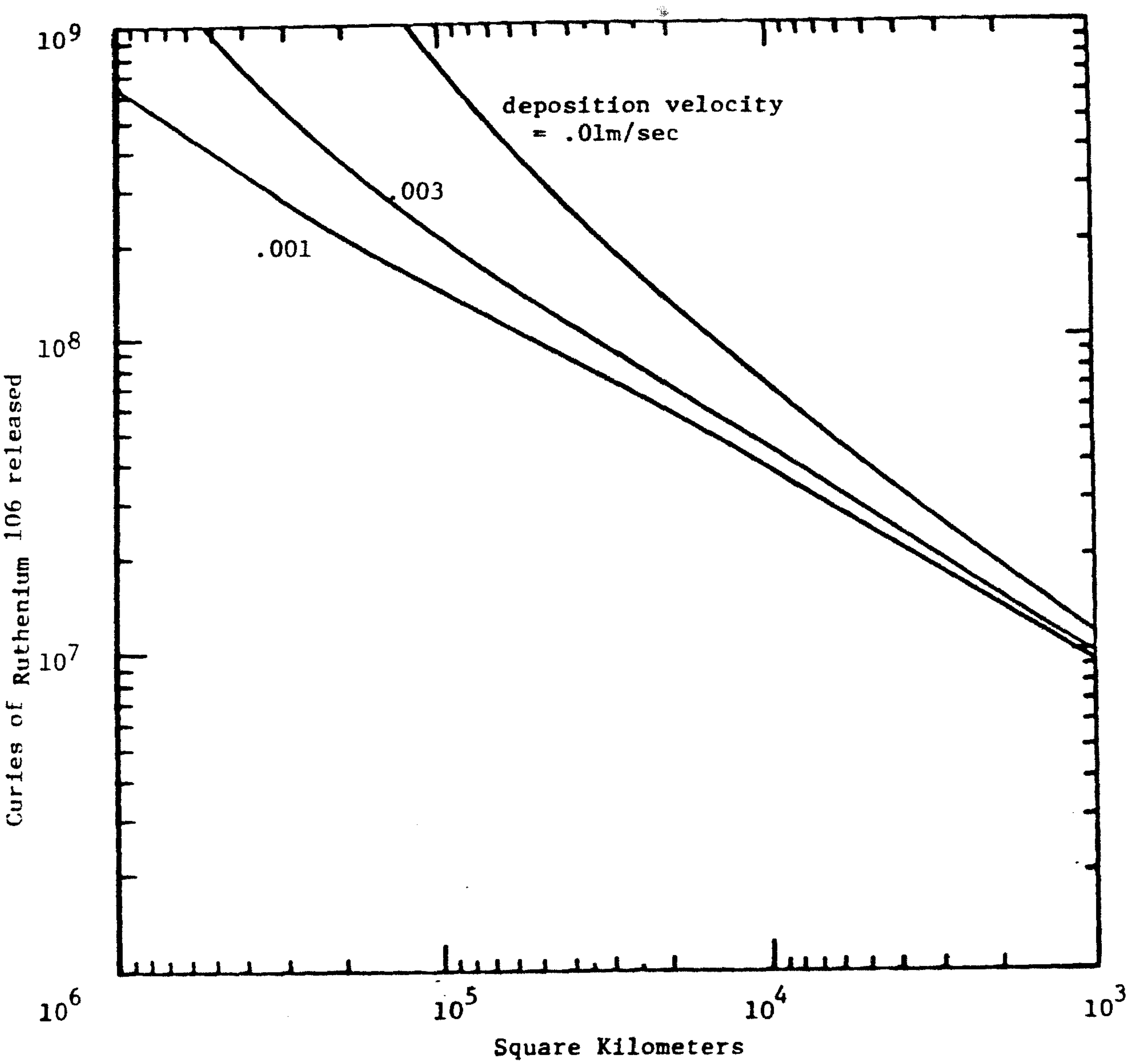

Fig VII. AREA OVER WHICH 10 YEAR LUNG DOSE EXCEEDS 100 REM AS A FUNCTION OF RELEASED CURIES OF RUTHENIUM 106

(5 m/sec wind speed, 300 meter initial plume rise, 1000 meter mixing level, breathing rate = 2.7×10^{-4} m^3 /sec, 3.9×10^6 Rem per curie inhaled)

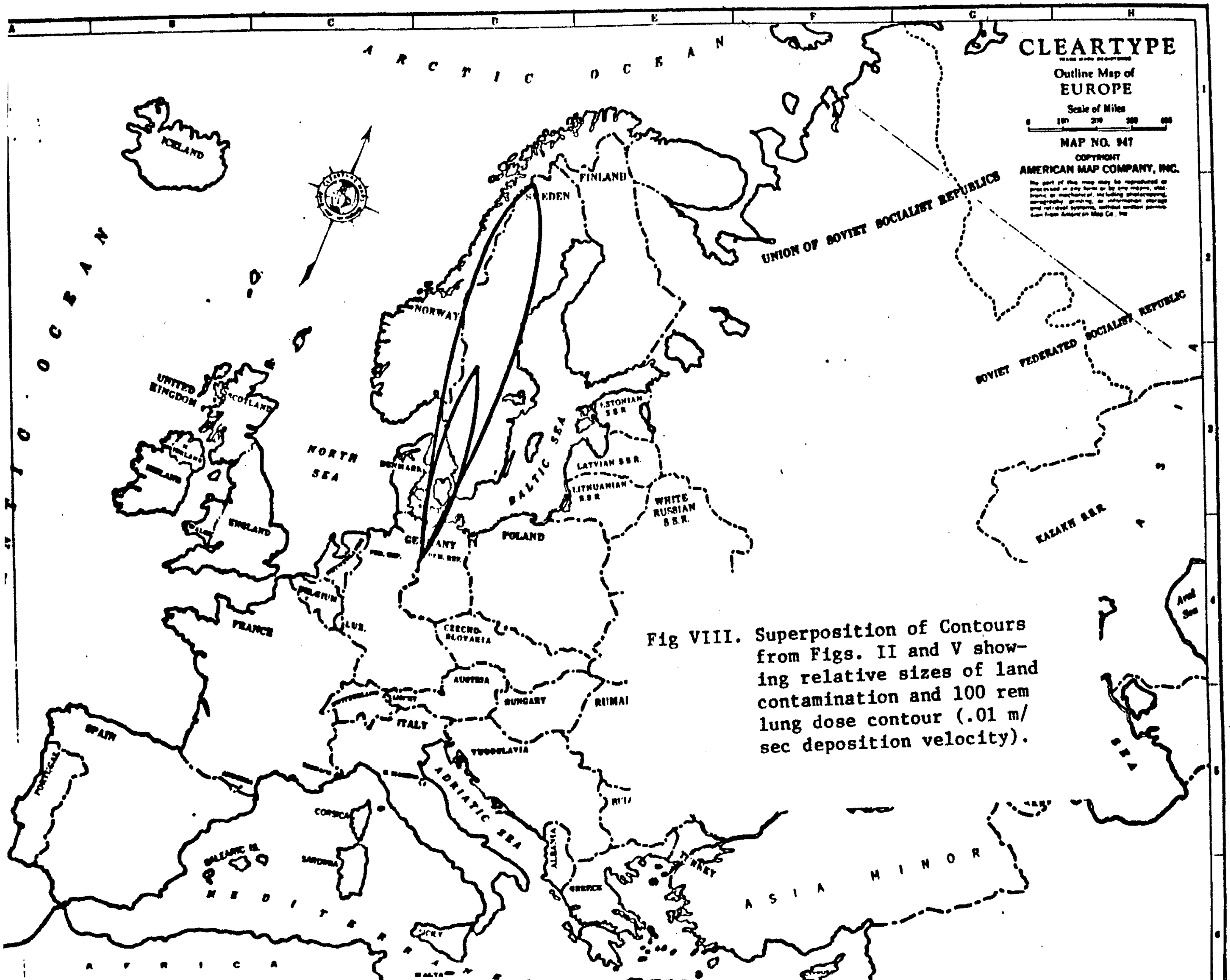

Fig VIII. Superposition of Contours from Figs. II and V showing relative sizes of land contamination and 100 rem lung dose contour (.01 m/sec deposition velocity).

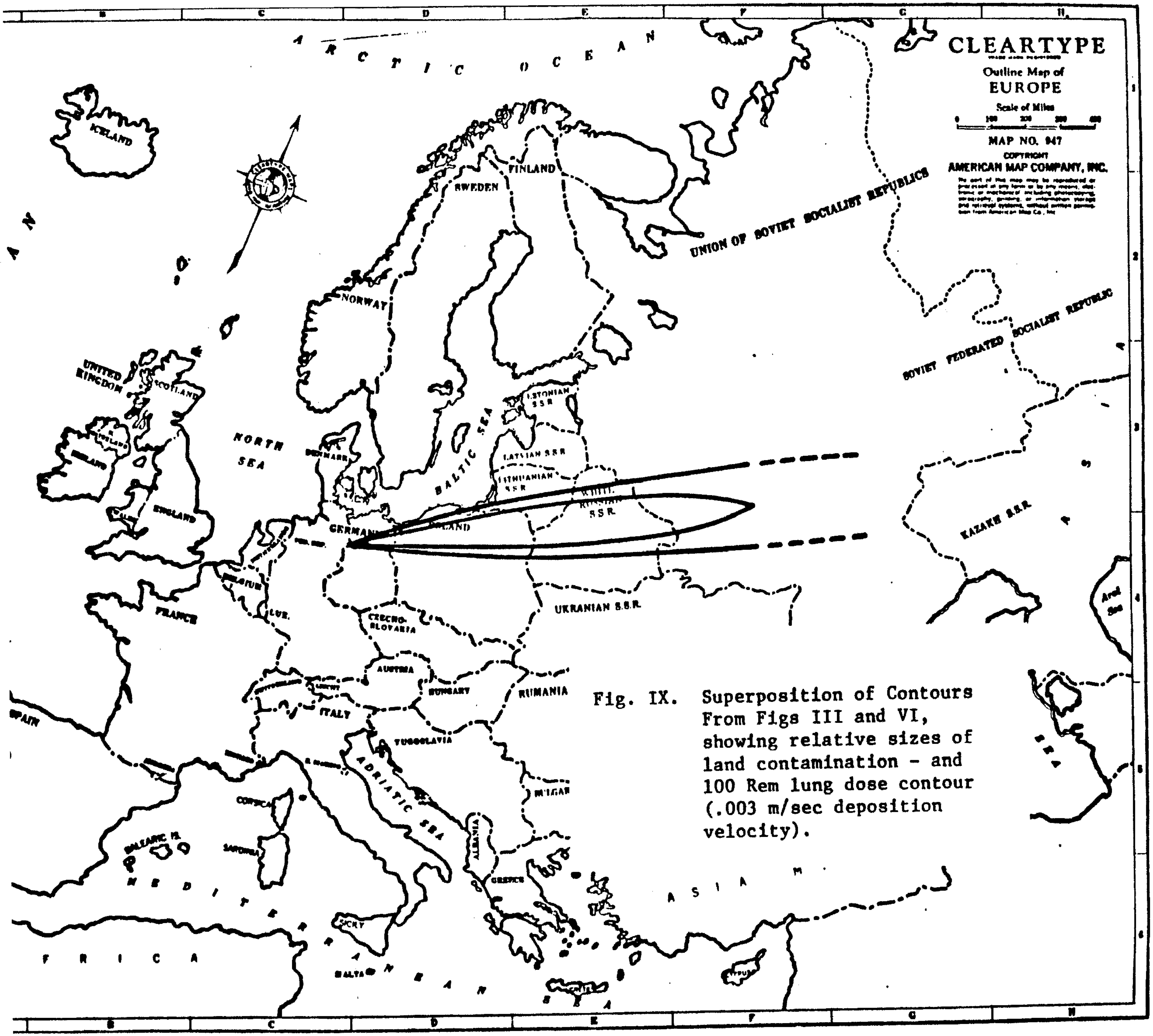

Fig. IX. Superposition of Contours From Figs III and VI, showing relative sizes of land contamination - and 100 Rem lung dose contour (.003 m/sec deposition velocity).

Short-Term Lung Dose

The third type of dose which must be considered is the short-term lung dose. Very high lung doses (of the order of 10,000 rem) received over a relatively short period (one year) will introduce a risk of early death.

The areas affected are much smaller than those already discussed for land contamination and 100 rem lung doses. Nevertheless, investigating the possibility of early death (within 1 year) is important. Table III shows calculated areas for 10,000 rem or higher doses for typical meterology. A 10,000 rem dose might mean a 10% chance of early death.[22] Only for the highest releases will a 10,000 rem lung dose be received anywhere under typical meteorological conditions.

To get 10,000 rem doses for lower releases, either the wind speed must be low or the initial plume rise must be low, as shown in Table IV.

Actually, the lower radioactivity releases might correspond to low heat releases which would make a lower plume rise plausible. However, further accident modeling is required to estimate a reasonable plume rise range and thus estimate the possibility of early death for low radioactivity releases.

Since early death possibilities for all but the worst releases are likely to be model and meteorology dependent, and thus subject to considerable technical debate, this aspect of accident consequences is likely to be a difficult one for policy makers.

Fortunately, the policies and design changes which serve to reduce the worst case releases for land contamination (discussed later) also reduce the inventory responsible for short-term deaths.

Table III. 10,000 REM LUNG DOSE: AREAS AND MAXIMUM DISTANCES REACHED FOR DIFFERENT QUANTITIES OF RELEASED RUTHENIUM 106[a)]

	.01 m/sec deposition		.003 m/sec deposition	
Ru 106 Curies	Area	Maximum Distance Reached	Area	Maximum Distance Reached
		(5 m/sec wind[b)])		
5×10^8	100 km^2	42 km	118 km^2	45 km
2.5	-	<4	-	<4
		(2 m/sec wind[b)])		
5×10^8	490 km^2	70 km	720 km^2	90 km
2.5×10^8	150	45	200	53 km
8.3×10^7	-	<4	-	<4
		(25 m plume rise, 5 m/sec wind)		
5×10^8	240 km^2	46 km	340	57
2.5×10^8	110	30	140	36
8.3×10^7	27	15	33	17
5×10^7	14	11	15	12
1.7×10^7	2.6	5.9	3	6.2

a) D stability, 1000 m mixing layer, breathing rate = $2.7 \times 10^{-4} m^3/sec$, 2.5×10^6 Rem to lung in one year per curie inhaled.

b) 300 m initial plume rise

Reasonableness of the release quantities.

Is the information presented here more than a mathematical exercise?

Clearly, releases which have been discussed are possible in wartime. However, it is nothing new to point out that the consequences of war can be disastrous. Gorleben, as presently designed, certainly would not add a new level of war-related risk. (It might however increase the upper limit risk in a limited nuclear war fought with tactical nuclear weapons.[23])

Short of a full-scale bombing, it is necessary to have loss of cooling to achieve an airborne release, either due to an accident or sabotage. Unlike a reactor core meltdown, melting times following loss of services at Gorleben would be measured in days and weeks.[24] If the site were not already contaminated and social conditions were stable, there probably would be time for repairs before melting. However, these conditions might not be met so there does exist the physical possibility of large releases. Probability considerations would have to be invoked by advocates of the present design to rule out serious consideration of such occurances. The upper limit of the risk spectrum is as high as discussed here; the probabilities are unknown.

Thompson, in a companion report for the Gorleben International Review,[25] has discussed accident sequences plausible enough to suggest the probabilities are not negligible. He points out that a small accident might contaminate a storage area to such an extent that proper maintenance would be prevented for a period of time sufficient to lead to loss of cooling and subsequent airborne release.

In any case, the areas affected by a large release at Gorleben are so enormous that many observers will find the possibility of such accidents unacceptable, regardless of assurances that the probability is acceptably low.

Mitigating Measures

Because the present Gorleben design envisions storage of radioactive cesium up to the equivalent of sixty reactor core inventories, constructing the storage pond as designed would amount to increasing the upper limit of the civilian nuclear risk spectrum by a factor of sixty.[26,27]

Certainly the introduction of a factor of sixty increase in the upper limit civilian risk warrants unusual critical attention to assurances of safety and claims of benefits. (Note that these considerations also apply to large "away-from-reactor" storage pools as well, not just to Gorleben.) At the very least, alternative designs which would not introduce such an increase should receive thorough technical and economic analysis before proceeding with the present design.

There are two alternatives which appear attractive:[28] (A combination of the two would be preferable.[29]

1. Natural cooling, and

2. Reduction of the critical isotope inventory at any facility to that present in a single reactor core.

The first method eliminates the possibility of large releases except in the case of war. (Thompson has suggested combining this option with underground sites.) The second method reduces the upper limit risk to that which already exists. (This would not prevent dedicated nuclear opponents from opposing Gorleben as they might any new nuclear power installation, but it should reduce Gorleben as a priority in their eyes as far as surface accidents are concerned.)

Thompson has discussed natural cooling; I will concentrate on reduction in inventory.

1) Storage Pool

Reducing the inventory here is relatively simple. It is a scheduling problem. Assume that the storage pool is restricted to 120 metric tons, and that 1500 tons have to be processed each year. The operators simply have to schedule deliveries from reactor storage pools in sequence, so that 120 tons arrive each month. This does introduce management problems, and by reducing the storage, may introduce some delays. These delays have to be estimated and compared with the benefits. Of course, it would not be consistent to allow large inventories to build up at existing reactor storage sites. The upper limit risk could increase from this alone. A consistent philosophy requires prevention of large inventories anywhere in the fuel cycle prior to final storage.

2) High level waste tanks

Reducing the inventory of a high level waste tank to reactor-size inventories does not appear to be a minor change. It could be very costly, although not necessarily excessive when compared to the total project cost.

Before rejecting such a possibility, it would be helpful to see detailed engineering cost estimates for a design with storage tanks (either liquid or solid) which are 1) one tenth the capacity of the present design,2) spaced one kilometer apart,and 3) hardened against air crashes.

Of course, if the radioactive inventory is split into many separate facilities, it would be possible for a terrorist group to attack all of them simultaneously. However, the same could be said for nuclear plants. A terrorist group could attack all nuclear plants in an upper limit scenario, so the upper limit risk is the same in both cases.

It will be said in response to these suggested changes for spent fuel and high level waste storage that such changes are either uneconomic or present engineering problems which cannot be solved. Such counter-arguments would amount to "having it both ways." Those unsolved engineering and economic problems which stand in the way of nuclear technology are considered to be solvable at some future date; those unsolved engineering and economic problems which would make the technology safer but slow it down are considered impossible.

Ideally, "surface accidents," such as those which have been discussed in this report, should be a minor consideration in deciding about the feasibility of long term storage. However, unless the design is changed, concern about these hypothetical surface accidents may play a decisive role in the political decision to go ahead with Gorleben.

Table IV. LAND CONTAMINATION AREAS FOR DIFFERENT WIND SPEEDS, PLUME HEIGHTS AND CESIUM 137 CURIES RELEASED (10 Rem in 30 year threshold, .01 m/sec deposition velocity, 1000 m mixing layer, D stability, .25 ground shielding factor)

Wind Speed (m/sec)	25	300	600
		4×10^8 curies released (Release height meters)	
25	$1.1 \times 10^6 km^2$	$1.2 \times 10^6 km^2$	$1.3 \times 10^6 km^2$
10	650,000	790,000	960,000
5	330,000	430,000	540,000[a)]
2	88,000[a)]	118,000[a)]	133,000[a)]
1	23,000	37,000[a)]	42,000[a)]
		1.2×10^8 curies released)	
25	310,000	340,000	320,000
10	270,000	330,000	380,000
5	160,000	217,000	290,000
2	48,000	88,000[a)]	110,000[a)]
1	13,000	31,000[a)]	37,000[a)]
		4×10^7 curies released)	
25	62,000	66,000	54,000
10	96,000	120,000	130,000
5	68,000	97,000	125,000
2	24,000	49,000	79,000[a)]
1	7,500	23,000[a)]	31,000[a)]
		4×10^6 curies released)	
25	2400	2100	220
10	5100	6000	4200
5	6700	10,000	10,000
2	4400	10,000	15,000
1	2100	6600	13,000

a) Area truncated after 5 days of travel

Table V. 100 REM LUNG DOSES: AREAS FOR DIFFERENT INITIAL PLUME HEIGHTS AND RELEASE QUANTITIES OF RUTHENIUM 106

Ru106 Curies	(.01 dep. velocity) Release Height (meters)			(.003 dep. velocity) Release Height (meters)		
	25	300	600	25	300	600
5×10^8	53,000 km^2	76,000	96,000	254,000	283,000	300,000
5×10^7	4800	6700	6200	11,000	12,000	9,000
5×10^6	310	250	0	420	280	0

Addendum
Added March 1979
~~Added March, 1979~~

Theoretical Initial Plume Rise due to heat released during accident (D stability class)[a)]

Thermal Release Rate (megawatts)	5 m/sec wind speed	2 m/sec wind speed
.12	13 meters	18 meters
.44	17	27
1.2	23	41
4.4	38	79
12	60	130
44	120	280
120	210	500
240	310	760
440	450	1100
1200	790	2000

a) Based on theoretical calculations as formulated by the U.S. Reactor Safety Study in its computer program manual, CRAC. These numbers are appropriate for releases from smokestacks and should only be used as rough indicators for plume rise under accident conditions.

The material is assumed to be released from the structure at a height of 10 meters.

Footnotes and References

1) (This note corrected March, 1979.) An environmental group in Germany (B,B.U.) attempted to calculate health effects, based on doses given in a secret government report (IRS 290), following a waste storage accident. (See ref. 2 for a discussion of the history of the controversy.) The B.B.U., however, incorrectly used a 600 REM early death threshold in connection with long-term doses given in IRS 290. As a result, they calculated an enormous number of deaths (30 million).

Although one cannot estimate the number of early deaths which would result based on IRS 290 alone, it is possible to correctly estimate the number of long-term cancers which might result.

It is a 10,000 Rem, whole-body, long-term dose which will give a high probability of fatal cancer, not 600 Rem As a result, the B.B.U. made an over estimate of deaths.

To do the calculation properly, the dose region has to be broken up into a region where the dose is greater than 10,000 rem (where essentially everyone eventually dies of cancer) and a region where the dose is lower than 10,000 rem (where the linear hypothesis can be used.)

Furthermore, it is not valid to extrapolate the doses in IRS 290 to further distances than shown without caution. From examination of the IRS 290 dose/distance dependence, a low value of deposition velocity must have been used. But beyond 100 km, depletion of the plume by "fall out" must begin to have an effect on the dose/distance relationship.

Assuming that 90% of the radioactivity has been depleted by 1000 km, and taking into account the factors previously mentioned, it is possible to make a rough estimate of the total number of fatal cancers. I have done so for the whole-body dose and have concluded that the B.B.U. number should have been about one million.* Although this number is much smaller than 30 million, it is still startling. Furthermore, if the low level cancer dose coefficients which are conventional (10^{-4} chance of death per rem) should prove optimistic by a factor of ten (see Note 8), then the number would be larger. Note that this kind of calculation assumes no evacuation of the population.

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*Assuming a uniform population density of 200 people per km^2, I obtained 100,000 cancer deaths within 70 km, 125,000 deaths between 70 and 100 km, and 1 million deaths between 100 and 1000 km. The probability of cancer death was taken as 1.3×10^{-4} rem. The whole body dose up to 100 km was taken from IRS 290, Table 4.3 (D stability). Beyond 100 km, the dose (in rem) was taken as $7000\ (100/X)^2$, with x in km. The wedge opening angle was taken as .25 radians. The contribution to total person rem beyond 1000 km was ignored.

Even if one took a very low number for cancer probability, the number of deaths would exceed 100,000.

2) Political Ecology Research Group Report #OR2.3 (Available from P.E.R.G., P. O. Box 14, Oxford, England).

3. Long-term ground contamination is dominated by the gamma-emitting cesium isotopes CS 134 and CS 137. Cesium 134 has a short half life and makes a relatively small contribution for old fuel. (The 30 year dose from cesium 134 is approximately equal to the 30 year dose from cesium 137 for fresh reactor fuel.) Rather than restrict the generality of the results by assuming an age distribution for the Gorleben Wäste, the cesium 134 contribution has been dropped.

The lung dose contribution is dominated by Ruthenium 106 and cerium 144. However, based on volatility arguments, a smaller release of cerium than ruthenium would be expected and the cerium contribution has been ignored to avoid tying the results to a debatable cerium/ruthenium release ratio.

Strontium 90 contamination has not been studied. Strontium 90 would contaminate food grown on contaminated land. Long-term bone doses from plutonium in spent fuel have not been considered based on volatility arguments. However, Thompson has considered bone doses from releases of six tons of plutonium nitrate which would be stored separately at Gorleben. (See G.I.R. 3.5)

4. An average decontamination factor of 20 was assumed possible in the U.S. Reactor Safety Study[4A] at an average cost of 60,000 U.S. dollars per sq. km of open farmland and 400,000 U.S. dollars per sq. km of developed land.[4C]

Decontamination in rural areas was assumed to be carried out by overturning or by scraping and removing soil. The ecological effects of such a drastic procedure over very large areas was not investigated. Recent experience with decontamination of Bikini Atoll suggests decontamination may not be effective in preventing an uptake of fission products in the food chain. The island was almost completely bulldozed, yet measured body burdens have exceeded projections. For a review of the Bikini situation see The Radiological Status of the Bikini People, Robert Conard, Brookhaven Laboratory, Upton Long Island, September 1978, unpublished report.

Doses can also be reduced by keeping people out for a specified period of time (interdiction). A ten year interdiction is equivalent to reducing the initial release by a factor of about two. (The choice of keeping people out or decontaminating the land becomes an economic decision.) After ten years, the process of leaching of the cesium-137 deeper into the soil has stopped and subsequent thirty year cumulative doses fall off with the Cs 137 half life of 30 years.

4a. Nuclear Regulatory Commission, Reactor Safety Study (WASH-1400, or NUREG-75/014,1975) Appendix VI p.11-20.) The reader of this reference should be aware that the uncertainties in the quoted quantitative results are often very much greater than stated here. See ref. 4b.

4b. Risk Assessment Review Group Report to the U.S. Nuclear Regulatory Commission, NUREG/CR-0400, 1978.

4c. Based on costs per acre given in Table VII 12-9 and P VI 12-5 of Ref 4a.

5. UN Scientific Committee on the Effects of Atomic Radiation, Sources and Effects of Ionizing Radiation (New York, United Nations, 1977).

6. Ref. 4a, Table VI 11-6. Note that 9% of the (10 rem) dose is delivered in the first year, 6% in the second. The yearly dose rate decreases due to radioactive decay and migration into the soil. See note 9.

7. See e.g. A Study of Some of the Consequences of Hypothetical Accidents at Barseback, Jan Beyea, 1978, Report to the Swedish Energy Commission, DsI 1978:5.

8. Radiation dose-effect coefficients in the low dose region continue to be the subject of great controversy. The reasons why the number arrived at by the UN committee in Ref 5 might be conservatively high are discussed in its report. Some knowledgeable scientists believe, however, that these numbers might be perhaps an order of magnitude too low. See e.g. the recent review by K.W. Morgan, Bulletin of the Atomic Scientists, September 1978, p. 30, and the Gorleben Review contribution by Alice Stewart.

9. This release of 10^8 curies of cesium^{137} corresponds to a high percentage release from one 1400 metric ton equivalent HAW tank. At 10^5 curies of Cs^{137} per metric ton for 3 year old fuel (Ref 10A), each tank can hold about 1.4×10^8 curies of cesium 137.

Thompson has considered release scenarios for HAW tanks (G.I.R. 3.7). He points out that an accident at one tank would prevent access to all five, leading to loss of services and eventual release from all of them. Assuming a 90% release of cesium gives numbers ranging from 1 to 1.4×10^8 curies of cesium 137 per tank. The variability is due to assumed differences in age of the fuel in the different tanks.

Different ages of fuel means different heat loads, as well as different numbers of curies. As a result, Thompson calculates intervals of days between releases from each tank. (He estimates each release to last a few hours.)

Because of the long interval between releases, one cannot from a meteorological perspective simply add the inventories from all five tanks and assume a release of 6.7×10^8 curies. Instead, five ovals similar to the one shown in Fig. I would result,each pointing in different directions from the Gorleben site. Since there would be some overlap of areas, the total contaminated area would lie between one and five times the area of a single oval.

9a) <u>Details of the Calculations:</u> Calculations have been made using the Gaussian plume model as described in Ref 4a and Ref 7. However, instead of using the "Tophat" approximation used in those references (which gives triangular-shaped contamination areas), full gaussian calculations have been made.

In the gaussian plume model the airborne concentration is assumed gaussian in both horizontal and vertical directions. As in Ref. 4a, we have placed a vertical "lid" on the plume (here, 1000 meters) to account for an average mixing layer. Depletion of the plume due to deposition is assumed, for calculational simplicity, to occur uniformly above each ground point (i.e. rapid vertical mixing). An average shielding factor of .25, a release duration of 3 hours, time invariant weather, and stability class D are assumed. (In the wedge model to be discussed later, stability class D corresponds to a wedge opening angle of about .25 radians.) Note that land contamination is not particularly sensitive to stability class (wedge opening angle).

Dispersion parameters are the same as those used in Refs 4a and 7, with the horizontal dispersion coefficient multiplied by 1.8 to account for a 3 hr release duration. Note that the area results are not particularly sensitive to these parameters except in the case of the high threshold,short-term lung dose to be discussed later.

The initial plume rise, due to heat released during the initiating event, has been taken to be 300 meters. Plume rise calculations are uncertain (see Ref 7). Fortunately, the results in this paper are not significantly sensitive to this parameter (except in the short-term lung dose case). This can be seen from Tables 4 and 5, where calculations for 25 and 600 meters do not show highly significant differences in calculated areas.

Dose From Cesium: Cesium 137 has a half-life of 30 years; The gamma dose rate to the bone marrow (measured in rads/year) above undisturbed soil per $\mu Ci/m^2$ of Cs^{137} deposited by fallout has been fit by the the approximate expression

$$D(t) = 0.08\ (0.63\ \exp-(1.15t) + 0.37\ \exp\ (-0.03t)).$$

The initial rapid rate of decline is apparently associated with the increasing shielding of the gamma radiation resulting from movement of the Cs^{137} into the top 10 centimeters of soil during the first few years. Thereafter, however, the vertical distribution of Cs^{137} in the soil stabilizes and the continued slow decline in the dose rate is due primarily to the radioactive decay of the Cs^{137}. The dose rate integrated to 30 years approximately equals 0.64 rad per $\mu Ci/m^2$. Allowing for shielding this dose has been reduced by approximately a factor of four to .16 rem/μCi/m^2. See Ref 4, App. VI, P E-4, and Table VI C-2.

Thus, the cesium concentration at the edges of the contour amounts to an initial activity of about 60 μci/m^2.

9x. Evacuation from contaminated land need not be rapid in most of the contaminated area since the doses of concern would be accumulated over many years.

10. The capacity of the ponds at Gorleben is projected to be 3000 metric tons. Multiplying 3000 tons by 10^5 curies of Cs^{137} per metric ton for 3 year old fuel (Ref 10a) gives an inventory of 3 x 10^8 curies. Assuming a loss-of-coolant accident as discussed by Thompson (G. I.R. 3.8) followed by a zircalloy-hydrogen reaction, a large fraction of this volatile cesium might be driven off. A 90% release would give 2.7 x 10^8 curies which, when rounded off to 3 x 10^8 curies, becomes the number assumed for Figs II and III.

Note that the contour in Fig I, which assumes a 10^8 curie release, would correspond to a 33% release of the storage pool capacity.

10a. Updated Projections of Reductive Wastes to be Generated by the U.S. Nuclear Power Industry, C. W. Kee, A. G. Croff, J. O. Blomeke, Oak Ridge National Laboratories, Report ORNL/TM-5427, Table A.2

11. Deposition velocity is a very uncertain parameter, uncertain to a factor of 100 for the stability class considered here (Ref 4a, p. B-9). Different mid-range values have been used by different investigators. The value used by the U.S. Reactor Safety Study and a Danish group (Ref 11a) was .01 M/sec, while a value of .003 has been used in Great Britain and Sweden (Ref 11b).

Rather than argue about which is more typical, I have made calculations for both values.

11a) Calculation of the Individual and Population Doses on Danish Territory Resulting from Hypothetical Core-melt Accidents at the Barsebäck Reactor, Jensen, Petersen, Thykier-Nelson, and Vinther, Risø National Laboratory Report No. 356 (1977).

11b) Haveristudie-Barsëback, Konsekvensberakning, Ove Edlund, Christina Gyllander, Studsvik Laboratories Report HS-77 (1978).

12. 5×10^6 curies of cesium 137 is a typical reactor inventory. See Ref. 4a, appendix VI, p 3-3.

12a) See Table 4 at the end of the report for the range of wind speeds considered and the resulting areas. The initial plume rise has also been varied (see note 9a). The upper and lower limits in Fig IV have been taken from the highest and lowest areas given in Table 4.

Note that land contamination depends upon wind speed and deposition velocity parameters only as a ratio of the two so that the upper and lower limits apply to a wider range of parameter space than one corresponding to a fixed deposition velocity and variable wind speed.

In particular, the upper limit in Fig. IV is an upper limit for all values of deposition velocity and wind speed. (See notes 17 and 17b.)

12b. Since the land contamination results depend upon the release quantity, Q, and the threshold level, T, only as a ratio, different values of T are mathematically equivalent to scaling Q. Thus, a 10 fold higher threshold level (100 rem in 30 years) would lead to areas obtainable from fig IV corresponding to release quantities equal to Q/10 .

Decontamination by a factor of 20 would lead to areas obtainable from Fig IV corresponding to Q/20. (See note 4).

The land would not be contaminated forever. Even in the absence of effective decontamination, the level of contamination would die out at first due to leaching of the Cs^{137} into the soil and later due to radioactive decay of the Cs^{137}. The area remaining contaminated after 10 years can be obtained from fig IV by using Q/2 instead of Q. Subsequent 30 year doses fall off with the characteristic cesium 137 half life of 30 years. Thus, to find the land area still contaminated after 40 years, one must use Q/4; after 70 years, Q/8, etc.

17. The wedge model assumes a uniform vertical distribution of airborne contaminents contained in a pie-shaped wedge. (see note 17a). Assuming a constant deposition velocity and wind speed, the airborne concentration falls off with distance, r, as $r^{-1} \exp(-\alpha r)$. Assuming that radioactive decay in flight can be neglected.) The parameter, α, equals the deposition velocity divided by the product of wind speed and mixing layer depth, L. Even during (continuous) rain, the solution has the form $r^{-1} \exp(-\alpha^* r)$, where now the parameter in the exponential, α^*, also depends on the washout rate.

17a. "Report to the American Physical Society by the Study Group on Light Water Reactor Safety," Reviews of Modern Physics, 47, S1.

17b. The wedge model upper limit area is the maximum land contamination obtained by varying the parameter α(or α^*) in note 17 over all values. The upper limit area in this model can be shown to be 1) independent of wedge angle (i.e. stability class) and, 2) approximately 5.4 times lower (actually 2 e times lower) than the physical upper limit which would be obtained by spreading the contamination evenly over the ground so as to just reach the contamination threshold level. The proof is obtained by first showing that the wedge area divided by the physical upper limit area can be written as .5R exp $(-\alpha R)$, where R is the threshold cross-over point, and then maximizing as a function of α.

In land contamination cases discussed in this paper, the value of α corresponding to maximum land contamination does occur for physical, as opposed to mathematical, values of meteorological parameters. For the threshold level used here, which corresponds to an initial concentration of 60 $\mu Ci/m^2$, the wedge model upper limit area (in sq. meters) for a release of Q curies equals $Q/(60 \times 10^{-6} \times 5.4)$. Comparison with the upper limit in Fig. IV (obtained from an inspection of a variety of gaussian plume calculations) shows good agreement.

18 The U. S. Reactor Society study assumed a lung cancer risk coefficient at low doses about a factor or 2 lower than the linear hypothesis number of 20 per 10^6 person-rem. (Ref 4a, Appendix VI Table VI, 9-4 and 9-7). However, as discussed in note 8, the low dose value might be an order of magnitude higher than 20 per 10^6 person-rem. Thus, a range of about 10 to 100 lung cancers per 10^6 person rem must be considered as possible until more accurate information is available.

18a. Since Ruthenium-106 has a relatively short half life (about 1 year), the age of the spent fuel becomes a more important consideration than for Cesium 137 which has a 30 yr. half life. Fresh spent fuel 160 days after discharge has a Ruthenium-106 activity of about 4×10^5 curies per metric ton (Ref 10a). After 3 years the activity has decayed to 0.5×10^5 curies (Ref 10a). Assuming an equal mixture of 1 yr and 2 yr fuel in the 3000 metric ton storage facility, and a 90% release fraction, gives a release activity of about 5×10^8 curies.

19. Assuming an average population density of $50/km^2$, there would be 30 million people exposed to 10 rem doses in the .01 m/sec deposition velocity case, and 100 million so exposed in the .003 m/sec deposition velocity case. Assuming (conservatively) that all receive only 10 rem, the incidence of fatal lung cancer would be 10^{-3} to 10^{-4} (note 18). Thus, the number of delayed deaths, in this simplistic calculation, would range between 3000 and 100,000.

20. Ideally, deciding at what distance to stop evacuating should be based on an estimate of the distance at which the risk from inhalation would match the risk from accidents during evacuation and relocation. To avoid the plume at great distances from the site, people would have to travel 100's of kilometers. As a result, the risk of immediate death due to automobile accidents alone might begin to approach a significant fraction of the risk of fatal lung cancer from 10 rem doses. Consequently, it might not make sense to even think about evacuating people much beyond the 100 rem lung dose distance.

21. This can be seen by considering the wedge model. (See note 17 and 17b.) For inhalation, the wedge model upper limit area contains the deposition velocity parameter in the denominator,

$$A_{max} = Q/X\,V_{dep}\;2\,\exp\,[+1]$$

where X is the "exposure" (curie-seconds per M^3) necessary to give the dose threshold, Q is the release in curies, and V_{dep} is the deposition velocity in m/sec. Thus, the maximum area is largest for low deposition velocities.

The situation is actually more complicated than this. For low deposition velocities, unphysically low wind speeds may be needed to allow the parameter, α, of note 17 to obtain the values necessary to produce the upper limit area. For the very highest releases considered in this paper, this does not happen. Nevertheless, this complication implies still further model-dependence for the maximum area in the inhalation case.

22. This value has been taken from the U.S. Reactor Society Study (Ref 4a Fig VI 9-3). The dose/death relationship was developed by the study group, and, to my knowledge, has not received independent review. The numbers are based on extrapolation from doses given to healthy, (non-smoker) dogs and may be optimistic. Use of this value in this report is not meant to imply acceptance of the relationship used in Ref 4a. It has been used here to avoid an argument over a peripheral matter.

23. Thompson in Section 3.5 of the G.I.R. has shown that the cesium land contamination from waste tanks exploded by a one kiloton tactical nuclear weapon would exceed the cesium fallout from the weapon by many orders of magnitude.

24,25. See Thompson, G.I.R. Sections 3,7,3.8.

26. The upper limit risk from nuclear was is obviously much higher than the upper limit from civilian nuclear facilities. The Gorleben plant would certainly not significantly increase the upper limit risk in a full-scale nuclear war. Also, it could be argued that the plant's radioactivity might serve as a deterrent to bombings by the Soviet bloc countries and thus might actually reduce the probability of war. In effect, the Gorleben plant gives the F.R.G. a nuclear deterrent - not just defensively, but offensively as well. The government in time

of war could threaten in desperation to cause an accident to counter a nuclear threat. Of course, these are not very positive arguments in favor of the present Gorleben design.

The possibility of a non-nuclear-weapon country causing meltdowns at its own nuclear facilities has been suggested by Bennett Ramberg, "Destruction of nuclear energy facilities in was: A proposal for legal restraint." Occasional paper #7, Center for International Studies, Princeton University, 1978.

27. I refer here to the long-term nuclear risk only. Reactors contain a great deal of short-lived isotopes (which spent-fuel does not) and are sited closer to cities. As a result, Gorleben as designed would not increase the early death Nuclear Risk upper limit by a factor of 60. However, the early death risk is not, in my opinion, the major nuclear problem, since the probability of large numbers of early deaths is low. Non-common weather and accident conditions as well as the proximity of large populations are required.

28. Some comments on design philosophy: The designer of safety systems should recognize that it is not enough to convince industry and government specialists that a design is "safe". The designer must convince the technical community outside of the reactor industry also. Otherwise, public comment by non-nuclear scientists and engineers (who may have greater credibility with the public) may destroy the possibility for the design's acceptance. Simplicity of design, such as natural cooling, allows the non-specialist scientist or engineer a chance to be satisfied with the concept.

Although a nuclear plant designer may see the various levels of safety systems in a reactor as decoupled, thereby providing great safety, those unfamiliar with the item-by-item design of the plant tend to see the plant as one single system which can fail as a unit. Reduction of the inventory avoids a debate on this subject and should make a facility more likely to receive acceptance from the non-industry, technical community.

29. If the inventory is reduced, natural cooling becomes technically easier and, conversely, natural cooling may force a reduction of inventory. Thus, the two concepts may naturally go "hand-in-hand."