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HAZARDS OF WASTE STORAGE AT HANFORD WORKS

PART I

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by: H.M. Parker, Manager
Health Instrument Divisions

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HAZARDS OF WASTE STORAGE AT HANFORD WORKS

PART I

INTRODUCTION

Speculations on the hazards involved in the accidental dissemination of waste materials at Hanford Works are required for all foreseeable circumstances including enemy attack or sabotage. Due to delay in obtaining data on the potential effects of bombing on waste storage tanks, the report has been held up beyond the anticipated date. It is therefore being prepared in two parts of which this first part is concerned only with potential disaster to the nuclear reactors. From the nature of the process, these are major waste storage units.

Separations process waste stored in buried tanks or otherwise will be considered later. Preliminary speculations on this topic have been given already (1), and it is not anticipated that much improvement in this phase will be effected.

In all cases, it is not expected that numerical conclusions will be valid to a factor of two, but they should be reliable within a factor of 10. This is the estimated accuracy of the excellent British reports of the Plant Location Panel, which have been extensively used in this compilation.

This report is a joint effort of the staff of the Health Instrument Divisions. In particular, F. G. Tabb is responsible for the calculations of fission yield, and Dr. H. A. Kornberg and Dr. R. F. Foster for the principal general biological and aquatic biological data, respectively.

1. Storage of Radioactive Wastes in a Hanford Nuclear Reactor

In an assumed average operation of 200 days at 275 MW, a Hanford reactor will contain

Waste { 584 megacuries of fission products
220 metric tons of uranium

Products { 200 megacuries of neptunium
2.7×10^4 grams of plutonium

By logarithmic classes of half lives, the fission products are divided thus:-

$T_{\frac{1}{2}}$	0 - 1 day	1 - 10 days	10 -100 days	>100 days
Megacuries f.p.	443	70	70	1
Mass of f.ps. (gms)	46	274	1408	2442

[redacted]

1082173 [redacted]

The total mass of fission products approximates 9 lbs; fission product release from an atomic bomb is said to be 2 lbs., with a presumed activity of 10,000 megacuries.

The decay of the total fission products is specified by

Time (hrs)	0	1	2	5	10	24	48	72	120	240	480	720
Megacuries	584	398	339	277	230	176	143	124	105	80	56	43

This is compatible with decay laws

$$\text{Activity} = \frac{\text{constant}}{(\text{time})^{0.2}} \quad \text{for the first 5 hours}$$

$$\text{Activity} = \frac{\text{constant}}{(\text{time})^{0.3}} \quad \text{thereafter.}$$

The decay of atomic bomb fission products follows

$$\text{Activity} = \frac{\text{constant}}{(\text{time})^{1.2}}$$

After a few hours, the release of all the activity from the nuclear reactor would exceed that from an atomic bomb at the equivalent time. The hazard is at all times greater in the present case, because of the higher relative content of long-lived fission products.

The initial activity of certain key fission products is

Isotope	Megacuries
Sr^{89}	6.85
Sr^{90}	0.09
Ru^{103}	6.9
Ru^{106}	1.49
$Te^{131} (\rightarrow I^{131})$	6.45
I^{131}	6.45
I^{133}	10.35
I^{135}	13.6
Cs^{135}	0.0001
Cs^{137}	0.0008
Ce^{141}	11.9
Ce^{144}	0.0008

1082174

[redacted]

2. Circumstances Producing Uncontrolled Release

These have been discussed in the A.E.C. Reactor Safeguard Committee report "Review of Certain Hanford Operations"(2). The reactivity of the Hanford reactors is adequately controlled under all foreseeable conditions except the following:

1. Planned shutdown without addition of poison

After the decay of the natural poison Xe^{135}, the unit could become reactive. It will be assumed that such an operating error is inconceivable.

2. Loss of water in one tube *

If accompanied by failure of the safety devices, the metal in the affected tube would melt and be ejected with an accompanying minor steam explosion. The management of the ejected 0.45 megacuries of fission products would be a serious local problem. If the reactor were then shut down, access for addition of poison might be denied, if the final disposition of the activity prohibited the rapid dumping of shielding material upon it. An explosive run-away is not visualized in such a case.

3. Total loss of water

The loss of cooling water increases the reactivity of the unit by about 850 in-hours, which can be held by the vertical safety rods (1700 in-hours) or in emergency by the third safety device (1800 in-hours). An uncontrolled condition requires the concurrent failure of both safety mechanisms. This is visualized to be possible under three circumstances:-

(a) Earthquake
There is no history of earthquakes in this region of sufficient intensity to disrupt the water supply to the reactors and to damage the safety mechanisms. Nevertheless, there are records both in the western slopes of the Cascade Mountains and in Montana, of earth movements not significantly below that required to produce such damage. The relatively short recorded history of the Pacific Northwest casts legitimate doubt on the permanent stability of the units against earthquake. This is the one plausible case in which all the reactors could be affected simultaneously. This extreme case has not been developed in this report.

(b) Enemy bombing
The Division of Biology and Medicine reports information from the National Military Establishment to the effect that although the reactors are considered relatively invulnerable to bombing attack, the slab construction of the main shield leaves some possibility of disruption of the shield. Evidently an enemy attack could, by chance, demolish the vulnerable safety mechanisms, and damage the water supply. Advance warning of a few seconds only would permit safety to be assured by insertion of all rods. Subsequent bombing, even with disruption of the unit should not lead to a runaway condition.

* The PLP reports adequately discuss the case in which the ejected metal from one tube burns.

Bombing should hold a low priority in the foreseeable hazard pattern.

(c) Sabotage
Sabotage by an enemy agent or by an unbalanced person intrinsically loyal to the United States appears to be the outstanding potential hazard. With two or more persons in collusion, the risk of detection would be negligible. There is no point in elaborating here on the feasible sabotage methods.

The general picture is that of rupture of the water supply, together with lateral motion of the reactor sufficient to close the thimbles to the vertical rods. The fluid of the third safety device would fail to enter the thimbles, or the piping to the thimbles would be broken. Deliberate tampering with the safety mechanisms is an alternate to the lateral motion.

1082176 [redacted]

3. The Uncontrolled Nuclear Reactor

The approximately 6 cubic meters of water in the pile can be raised to the boiling point in about 7 seconds at normal operating power. The water in central tubes would boil in about 3-4 seconds. The power level of the reactor increases rapidly; the excess reactivity above critical is said to be $K_e = 0.025$ without water. On elementary reactor theory, the power increase after loss of water is

$$\frac{\text{Power after t secs}}{\text{Steady power}} = e^{20K_e t}$$

The 250 tons of uranium in the structure is boiled by about 10^{11}cals. By integration, this will occur in 13 secs. The actual course of events is the boiling of the central uranium in a fraction of this time, with possibly the termination of the reaction. In any case, the sequence of events is so rapid that there can be no substitute control. The real rate may be affected by the unknown temperature coefficient, release of stored energy from the graphite, release of Xe^{135} as the uranium melts.

To determine the environmental hazard, we take two simplified pictures.

(a) the 2×10^{11}cal. explosion

basis: all the uranium just boils = 1.16×10^{11}cal.
an equal amount of heat goes into the graphite, aluminum and other parts.

or: some of the stored energy of graphite (calculated as 2.6×10^{11}cal. at the present time) is released, thus terminating the nuclear reaction at a lower integrated flux.

(b) the 2×10^{10} cal. explosion

basis: the Reactor Safeguard Committee states that "it does not seem possible for the metal temperature much to exceed 10,000° C at the time when the course of the accident itself disrupts the chain reaction. This temperature will be reached in a power burst of about 7.5×10^7 KW seconds".

This is equivalent to 1.8×10^{10} cal., which is insufficient to boil the uranium. Presumably the given figure refers to the power burst required to raise the central temperature of an unflattened pile to about 10,000° C. Alternatively, very different physical constants have been used for the metal. This report uses:-

Specific heat of uranium	= 0.028 cal/gm at any temp.
Melting point	= 1150° C
Heat of fusion	= 13 cal/gm
Boiling point	= 3900° C
Heat of vaporization	= 391 cal/gm

1082177 [redacted]

Analysis of the 2×10^{11} calorie explosion

Primary Effect

All the uranium boils and approximately 1.5×10^{11} cal. goes into the hot gas bubble. This is equivalent energetically to an explosion of 150 tons of high explosive. The nuclear reactor will be explosively shattered, although this is probably minimized by the heavy shielding. More probably the hot gases will be ejected violently from each of the reactor tubes. In either case we shall abandon the physical model and proceed to calculate the behavior of the gas cloud as if it were a regular high explosive detonation, following O.G. Sutton's method[3].

Behavior of the gas cloud

The instantaneously generated heat in the cloud is about 1.5×10^{11} cal. The initial temperature is probably 4000° to 8000° K.*

From $PV = RT$

the volume V after the initial rapid expansion to atmospheric pressure is

$$V = \frac{8.3 \times 10^7 \times 150 \times 10^6 \times (4 \text{ or } 8) \times 10^3 \text{ cm}^3}{25 \times 10^6} = 2 \text{ or } 4 \times 10^{12} \text{ cm.}$$

The initial radius = 80 to 100 meters

Note that the mean molecular weight of the explosion gases is taken as 25 for the normal products of explosion, and bears no relation to much higher value in the real model.

The velocity of ascent from the original position after expansion is given by

$$V^2 = \frac{1.5\, g\, Q}{T_a\, C_p\, \rho\, \pi^{3/2}\, C^2\, Z^m}$$

where
- V = velocity of ascent
- g = acceleration due to gravity = 9.8 meters/sec^2
- T_a = temperature of surrounding air = $\sim 300^\circ$ K
- C_p = specific heat of gases produced = $\sim 1/3$
- ρ = mean density of air over the range = ~ 1000 gm/meter^3
- C = generalized diffusion coefficient = ~ 0.2 (meter)$^{1/8}$ or less.
- m = index of turbulence = 1.75
- Z = height in meters above original expansion location

$$\therefore V^2 = \sim \frac{2 \times 10^7}{Z^{1.75}}$$

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* Sutton's formal calculation will always give 3000° C as the temperature. We take a higher value because 3000° C would not start a cloud of uranium gas.

1082178 [redacted]

Z meters	Height above ground (meters)	Vel. of ascent meter/sec
200	~ 300	90
1000	~ 1100	23
2000	~ 2100	12
4000	~ 4100	6

The average wind speed in the Hanford region is

Height (meters)	Wind speed (meters/sec)
1000	5
2000	7
3000	9
4000	11

The cloud is pictured to rise until the velocity of ascent is comparable with the horizontal wind velocity (perhaps one half of it).The subject cloud rises to 3000 to 4000 meters, say conservatively 3000 meters. The main uncertainty in the calculation is the appropriate value of C, which is a function of Z.

$$C = (0.17 - 0.042 \log_{10} Z)\ (\text{meter})^{1/8}$$

Perhaps an average value of C between Z = 0 and Z = 4000 is applicable. This would send the cloud higher, and we take the conservative low value.

Activity in the cloud

The cloud contains M = 584 megacuries of fission products. It moves horizontally with velocity 9 meters/sec. Under average conditions of turbulence, the maximum concentration at the ground is

$$\frac{0.073M}{r_0^3}$$ curie/meter^3, where r_0 meters is the distance from the cloud center to ground.

Over level terrain,	max.conc.	f.p.	=	1.6 μc/liter
similarly	max.conc.	Pu	=	7×10^{-5} μg/liter
	max.conc.	N_p	=	0.5 μc/liter
	max.conc.	U	=	0.6 μg/liter

These concentrations occur at a time, t secs. after the explosion (strictly after the ascent) given by

$$t = \frac{1}{U}\left(\frac{2\,r_0^2}{3\,C^2}\right)^{1/m}$$

where U = horizontal wind velocity (meter/sec)

If C = 0.2 (ground value), t = 5200 sec. = ~ $1\frac{1}{2}$ hrs.

If C = 0.02 (at 3000 meters), t = 73,000 sec. = ~ 20 hrs.

The probable value is about 5 hrs.

[redacted]

[redacted]

1082179

The corresponding distance from the reactor is ~ 100 miles.
Additionally, the activity after 5 hrs. has decayed to approximately one half the initial value.
As a man stands at a point 100 miles from the reactor, the cloud substantially contributes its activity to him in 11 minutes.* The time variation of concentration at the ground is shown in Figure 1.

If the average energy of the fission products is 1.7 MEV, the integrated dose (neglecting scatter) is:

$$\frac{310\ (\mu c/\text{liter})\ \text{sec.} \times 1.7\ \text{MEV}}{2 \times 3600\ \text{sec.}}\ \text{rep} = 0.075\ \text{rep}$$

The variation of activity outwards from the center of the moving cloud at this time is

Radius (meters)	0	1000	2000	3000	4000
Concentration (μc/liter)	2.9	2.5	1.3	0.6	0.2

The gamma-ray component comes from a range of ~ 300 meters which includes zones of higher concentration than at the ground. This is a small factor, and we can write

Dose = 0.1 rep

The width of the cloud in Sutton's arbitrary definition is terminated at points where the activity is one-tenth of the central activity. The subject cloud has a width of 7500 meters at 100 miles from the reactor. It will be noted that significant concentrations can occur at points well beyond the conventional boundaries of a radioactive cloud. Also, in a real case, the effective width at 100 miles will be greatly affected by wind shear. We shall elaborate the effect of meteorological variables for a much more dangerous cloud later.

Inhalation Figures

Assume 17 liters/min with 50% retention

Fission products - deposit 45 μc - initial dose-rate 40 mrep/day.
no significant hazard if material is absorbed from lung.

Plutonium - deposit 4×10^{-3} μg - no hazard.

Neptunium - deposit 40 μc - initial dose-rate 20 mrep/day.
formation of Pu insignificant.

Uranium - deposit 40 μg - innocuous.

* Neglected throughout is the normally lower wind speed near the ground; exposure time could be about twice the calculated value.

Mountainous Terrain

If the ground elevation rises away from the reactor, a more significant hazard can be encountered at these intermediate distances. In Hanford terrain this is insignificant for the present high cloud. For reference, the central fission product concentration is given as a function of distance, together with the width of the cloud, from which the concentration at any distance and any elevation above the base line can be estimated.

Distance (miles)	0	10	20	40	60	80	100
Central concentration (μc/liter)	2×10^5	3000	270	45	15	7	3
First order width (meters)	180	1000	1750	3400	4800	6000	7500
Second order width	?	1400	2500	4800	6800		
Third order width		1750	3000	5900			

First order width = width to points of 1/10 central activity.

Second order width = width to points of $1/10^2$ central activity, etc.

Second and third order widths probably have poor physical significance, but their use should lead to overestimates of exposure.

Example: A man on Rattlesnake Mountain is ~ 1000 meters above the base-line of the reactor = 2000 meters below the drift-line of the cloud, and 14 miles away.
The central concentration is 750 μc/liter, and the subject point is beyond the fourth order semi-width (= 1250 meters below drift-line). The concentration is below 0.075 μc/liter.

Fall-out

The fall-out of particles under gravity will be inconsequential with an initial high cloud. For example: a particle of specific gravity 5 and diameter 6 microns will fall only 70 meters in the postulated 100 miles horizontal travel

Rain-out

In the Hanford area, a rain originating above 3000 meters is so exceptional that one can disregard the risk of rain-out of activity within say 40 miles of the Plant. If rain-out did occur, it could be a potential major hazard. Sutton estimates from Leicester data that one-eight of the soot content of a cloud can be washed out by rain. We invoke two additional factors:-

(1) Typical British rain is obviously a more formidable scrubbing agent than the Hanford variety.

(2) The British figure is probably weighted by removal of the heavier particles. Most of the fission product activity will be concentrated on very small particles, for which scrubber efficiency is low.

We shall assume a maximum rain-out of 5%. Initially, a deposition of

$$\frac{0.05 \times 584 \times 10^6}{\pi \ (90)^2} = \sim 1000 \text{ curies/sq.meter}$$

is feasible. At 10 miles, the maximum deposition is ~30 curies/sq.meter; at 40 miles it is ~ 6 curies/sq.meter. Such a deposit gives a radiation dose-rate of the order of 100 r/hr. Also deposited would be 400 μg Pu/sq.meter. We conclude that a rain-out could produce intolerable conditions at sporadic locations up to 100 miles or more from the reactor.

Analysis of the 2×10^{10} calorie explosion

Primary Effect

Computed for a flattened Hanford reactor, and this time assuming all the heat goes into uranium heating, the distribution in arbitrary classes will be:-

5 central tons boil
55 tons at the boiling point
40 tons at ~ 3700° C
40 tons at ~ 2500° C
55 tons just melt
55 tons just fail to melt

Behavior of the cloud

Heat in cloud	=	~ 3×10^9 calories
Estimated temperature	=	~ 4000° C
Expanded radius	=	20 meters
Velocity of ascent	=	13 meter/sec at 200 meters
	=	3.3 meter/sec at 1000 meters

Cloud rises to ~ 800 meters.

Activity in the cloud

The cloud contains ~ 20 megacuries of fission products, 4.5 metric tons of uranium, 6 megacuries of Np, and 800 gms of plutonium. Under average conditions of turbulence, the maximum concentration at the ground is ~ 3 μc f.p./liter or 1.8 μc/liter, corrected for decay. The cloud moves horizontally with velocity ~ 4 meter/sec, and touches the ground at times between 40 minutes and 5 hours, depending on the assumed average value of the diffusion coefficient C. A reasonable value is C = 0.1 $(\text{meter})^{1/8}$. The time of maximum concentration at the ground is then 1½ hours after the ascent, and the distance is 13 miles. Figure 2 shows the time variation of concentration at this point. The integrated exposure is 550 (μc/liter)sec., and the estimated dose = 0.25 rep.

1082182 [redacted]

<u>Inhalation Figures</u>

Fission products	-	deposit 80 μc - initial dose-rate 70 mrep/day no significant hazard anticipated
Plutonium	-	deposit 3×10^{-3} μg
Neptunium	-	deposit 40 μc
Uranium	-	deposit 20 μg.

The ratio of these deposits differs from the previous case for two reasons:

(1) different relative concentration in the <u>central</u> reactor tubes
(2) different decay time of fission products.

For general interest, the structure of an instantaneously generated cloud has been calculated with the following assumptions:

Height of center line = 800 meters
Velocity = 4 meter/sec.
Cx (downwind) = Cy (crosswind) = 0.2 $(\text{meter})^{1/8}$
Cy (vertical) = 0.12 $(\text{meter})^{1/8}$
Total activity, Q = 1 curie
Concentration, X in μc/liter.

time, t in secs.

The curves of equal activity are, of course, true ellipses in the vertic plane and circles in the horizontal plane. (Figure 3).

<u>Mountainous Terrain</u>
In this case, persons on either Rattlesnake Mountain (14 miles) or on Saddle Mountain (9 miles) could intersect the axis of the cloud. A representative time is 4000 sec. $Q = 20 \times 10^6 \times 0.65$ (for decay) $= 13 \times 10^6$ curies,

$$X = 13 \times 10^6 \times 3.7 \times 10^{-7} \ \mu c/\text{liter} = \underline{5 \ \mu c/\text{liter}}.$$

The integrated exposure is $\sim$ 2000 (μc/liter) sec.
Appreciable contamination of the mountain slopes would occur. The peculiar air currents over such ridges distort the polluted air stream, and contamination could occur on the far slopes.

<u>Rain-out</u>
The nominal maximum deposition is $\sim$ 800 curies/sq. meter. The value falls to $\sim$ 1 curie/sq. meter over the upper Wahluke Slope (5 miles).

<u>Release of Activity from residual molten metal</u>
The "junior atom bomb" cloud so far pictured in the 2×10^{10} calorie explosi is the minor hazard component. Left at the site is a mass of molten uranium assumed not to be sucked up as the small hot bubble ascends.

1082183 [redacted]

The boiling points of the fission products are:

Element	B.P. °C	Element	B.P. °C	Element	B. P. °C
As	615 (subl.)	Cb	3300	Xe	gas
Se	688	Mo	3700	Cs	670
Br	58.8	43	> 2500 ?	Ba	1140
Kr	gas	Ru	> 2700 (vol.?)	La	1800
Rb	700	Rh	> 2500	Ce	1400
Sr	1150	Sb	1380	Pr	> 1000
Y	2500	Te	1390	Nd	> 900
Zr	> 2900	I	184	61	> 1000 ?

We now calculate that 440 megacuries of fission products will evaporate from the arbitrary metal classes above. This initiates a cloud whose initial height is comparable with that of smoke from a hot fire. At distances not too close to the reactor, the height will be inconsequential. Consider an average case (4)

where $C = 0.2$, $m = 1.75$, wind velo. $U = 5$ meter/sec

$$X\ (\mu c/\text{liter}) = \frac{2 \times 4.4 \times 10^{11}}{\pi \times 0.008 \times (5t)}\ 2.62 \times e^{-\frac{r^2}{0.04 \times (5t)^{1.75}}}$$

where 2 is a ground reflection factor, and other terms are obvious.

X = 120 μc/liter at 11 miles (= 1 hr)

= 80 μc/liter, corrected for decay

Integrated dose as cloud passes = ~ <u>4 rep</u>

During an inversion (Sutton's bad case) assume $C = 0.1$, $m = 1.5$, and

$U = 3$ meter/sec.

$X = \sim 3 \times 10^4$ μc/liter at 11 miles

Integrated dose = ~ <u>1200 rep</u>

Whereas Sutton's equations are well known to give reliable results for the average or zero-lapse rate case, there is reason to doubt the applicability to the marked inversion or bad case, in which the constants are rather dubiously related to physical reality, and wind shear is neglected. We choose an arbitrary model as alternate.

Assume the initial cloud has the dimensions of the reactor.

Concentration = 2.5×10^8 μc/liter.

1082184 [redacted]

P.E. Church's[5] Hanford meteorological data shows dilution during inversion $= 10^4$ at 1.2 miles.

$\therefore$ Conc. $= 2.5 \times 10^4$ μc/liter

Sutton's data shows dilution = 20 between 1.2 and 11 miles for the bad case.

$\therefore$ X $= 1.25 \times 10^3$ μc/liter at 11 miles.

$=$ 750 μc/liter, corrected for decay.

Integrated dose $= \sim 60$ rep. (cloud size is different now)

Let us weight these two cases, and write

Integrated dose in inversion $= \sim$ 400 rep at 11 miles *

This approximates the human lethal dose, and in view of the uncertainties in such calculations, it fully substantiates the conclusion of the Reactor Safeguard Committee that the whole Wahluke Slope (radius $\sim$10 miles around the reactors) is unsuited for settlement.

This is done on the basis of the external radiation alone. Presumably far worse is the inhalation hazard. The computed deposition is $\sim$100 - 200 millicuries! The corresponding initial lung dose-rate is a few thousand rep per day. The highly speculative integrated dose in one month is a few tens of thousands of rep. Such a cloud is conceivably lethal at distances up to 50 or 100 miles, and almost certainly damaging in this range.

Deposition of active material from an active cloud contiguous with ground

With the limited library facilities at this site, we were unable to develop theoretical data on the feasible deposition on the ground as a cloud of particulate matter sweeps over it.

We resort to three "wild" methods from the Hanford experience, together with industrial pollution data.

(1) Emission of long-lived fission products
For the first three years of operation at Hanford Works, the concentration of fission products (excluding Xe, Kr and I) in the stack of a Separations plant was $\sim 10^{-8}$ to 10^{-7} μc/liter. Feasible average concentration at a point 6 miles away cannot exceed 10^{-13} to 10^{-12} μc/liter at ground level. There is agreement between the data of Church and Sutton on this. It assumes a usually 'bad' case, and the wind in one direction continuously.

Take 10^{-13} μc/liter as the representative concentration. The vegetation contamination at this time and place was $\sim$ 0.01 μc/kg. (excluding I). The vegetative cover approximates 2 kg/sq.meter. The practical deposition rate D

---

* This would agree with a Sutton calculation for initial cloud height $= \sim$ 100 meters and accurate reflection factor

1082185

for cloud concentration

$$1\ \mu c/\text{liter} = \frac{10^{13} \times 0.01 \times 2}{3 \times 365 \times 24}\ \mu c/\text{sq.meter/hr.exposure.}$$

$$\therefore\ D = 7 \times 10^{6}\ \mu c/\text{sq.meter/hr.}$$

This agrees with the calculation at 2 miles.

(2) Emission of I^{131}

By similar methods, $D = \sim 10^4$ μc/sq.meter/hr at 6 miles

and $D = \sim 10^6$ μc/sq.meter/hr at 30 miles.

assuming that the observer who samples the vegetation effectively looks at the average deposition within the last two weeks, as a result of radioactive decay.

(3) Emission of discrete active particles

Here the calculation hinges on a count of the number of radioactive particles per liter of air, and the number deposited per unit area of a horizontal catching frame in the same time, both observations being by radioautography. In a typical case, about 2 miles from the stack $D = \sim 10^4$ particles/sq.meter/hr per unit concentration.

(4) Atmospheric Pollution

In measurements in New York City, the average dust concentration in the air was 1.7 mg/10 c.meter, and the deposition rate was $\sim$50 tons per sq.mile/month.

Hence $D = 1.2 \times 10^5$ μg/sq.meter/hr for 1 μg/liter

The concentration 1.7 mg/10 c.meter is known to correspond with 0.3 million particles per c. feet. The range of concentration in many principal cities is 0.2 to 10 million particles per c. ft. in short time samples. The reported deposition rate (longer term samples) ranges from 25 to 190 tons/sq. mile/month, (Washington, D.C., and St. Louis, Missouri, respectively). These ranges are compatible with the value $D = \sim 10^5$.

We shall assume that $D = \sim 10^5$ μc/sq.meter/hr for cloud concentration of 1 uc/liter. This figure may be in error by a factor as large as 100. On the whole, the agreement between the quoted results for a fine aerosol on vegetation, iodine vapor on vegetation, radioactive particles on prepared surfaces, and for normal industrial pollution are surprisingly consistent.

Typical depositions will be

(a) from the 2×10^{11} calorie explosion cloud $\sim 10^4$ μc/sq.meter at 100 miles

(b) from the 2×10^{10} calorie explosion high cloud $\sim 10^{4}$ μc per sq.meter at 13 miles

(c) from the 2×10^{10} calorie explosion low cloud $\sim$ 50 curies per sq.meter at 11 miles

Fate of the molten metal

The residual 95 tons of uranium now contains 51 megacuries of fission products. Some writers have visualized such material running down to the river, and producing gross contamination. This appears most unlikely. If it is ejected violently it will have large surface area. If it cascades from the reactor most of it will be trapped in the pits around the unit, even if these are filled with discrete pieces of the structure after the explosion. We shall consider the naive model of the molten metal cascading from one face of the reactor at an average temperature of 2800° K. The initial area will be a square of side 12 meters, and we assume a comparable area maintained. By Stefan's Law, the rate of radiative cooling is:

Temperature °K	2800	2500	2000	1500
dT/dt (°C per sec)	27	17	7	2

The estimated cooling time is $\sim$ 3 - 5 minutes, insufficient to permit significant travel of the fluid.* The cooled metal presents a local hazard, but the contained fission products can escape only by surface oxidation and weathering. This can be controlled.

4. Accidents leading to disruption of a reactor accompanied by fire.

In any accident which leads to exposure of molten metal to the atmosphere, it is believed probable that the metal would ignite. Consider the case in which the reactor is laid open by the primary event, and the 250 tons of uranium and 2200 tons of graphite burn. The rate of combustion will be so much a function of the local conditions that the combustion time cannot be computed. If the graphite is initially dispersed into particles of dia. 1 cm, and the initial temperature is 2800°, the combustion time is $\sim$4000 secs. It is reasonable to assume that the postulated fire will burn uniformly for at least two hours. The maximum environmental hazard will then be independent of the actual time of combustion, and can be computed from Sutton's equations for diffusion of smoke from a continuous point source.

* Experimentally, molten metal (mercury) flows toward the river at 30 ft./min. in a layer of comparable thickness.

<u>Environmental hazard of combustion of all reactor material</u>

The relevant equation is (4)

$$\underline{X}\ (\mu c/\text{liter}) = \frac{2\ (\text{for reflection}) \times 1000\ (\text{cc/liter}) \times Q \times e^{\frac{-z^2}{Cz^2\, x^m}}}{\pi\ Cy\ Cz\ U\ x^m}$$

where $\underline{X}$ = ground concentration at distance x meters

Q = emission rate = $\sim 8 \times 10^4$ curies/sec (for 2 hours)

Cy, Cz, m, as used before

U = wind velocity = 4.5 meter/sec.

z = height of source above ground (meters)

The appropriate value of $\underline{z}$ is unknown, probably of the order of 100 meters.

If $z < 50$ meters, $\underline{X}$ will differ from the value for $z = 0$ by less than 10% for $x > 4000$ meters. As we are primarily interested in the hazard at great distances, we shall take $z = 0$.

<u>Atmospheric Stability</u>

		Average case	Bad case
Cy	=	0.2 (meter)$^{1/8}$	0.15 (meter)$^{1/8}$
Cz	=	0.12 (meter)$^{1/8}$	0.10 (meter)$^{1/8}$
m	=	1.75	1.5

<u>Choice of wind speed</u>

Although we calculate formally for $z = 0$, we picture z as $\sim$ 100 meters.

The wind speeds at 7 feet and 200 feet above ground are tabulated

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below for the Hanford meteorological station.

PERCENT FREQUENCY OF WIND SPEEDS

Wind Speed Class Intervals (mph) at 7-ft. Level

	0-3	4-9	10-14	15-19	20-24	25-29	30-39	40 or >
1st Quarter	53	37	6	3	1	L	0	0
2nd Quarter	27	55	13	4	1	L	0	0
3rd Quarter	32	51	13	3	1	L	0	0
4th Quarter	55	33	8	3	1	L	0	0
Annual Mean	42	44	10	3	1	L	0	0

Wind Speed Class Intervals (mph) at 200-ft. Level

	0-3	4-9	10-14	15-19	20-24	25-29	30-39	40 or >
1st Quarter	27	32	21	11	5	2	2	L
2nd Quarter	8	41	23	15	8	3	2	L
3rd Quarter	11	42	21	14	8	3	1	L
4th Quarter	25	36	18	10	6	4	1	L
Annual Mean	18	38	21	13	7	3	2	L

These wind speeds are averaged over periods of one hour, and apply well to the present case. A wind speed of 10 mph (= 4.5 meter/sec) is a reasonable average for the estimated height of the source. $\underline{X}$ is inversely proportional to U, so that the most conservative case (say 2 mph wind) can be computed by multiplying the given values of $\underline{X}$ by 5.

Concentration of fission products (uncorrected for decay)

Distance (miles)		3	6	12	19	30	60
Conc. μc per liter	Average case	160	48	14	7	3	0.8
	Bad case	2080	750	270	144	64	16
	Bad case Z = 100	1	60	80	80	40	16

First order width of cloud (meters)

Distance (miles)	3	6	12	19	30	60
Average case	1070	1970	3600	5150	8000	15,000
Bad case	280	470	800	1080	1600	2,700

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Integrated external dose

Assume an average available energy of 1.7 MEV per disintegration (chosen to agree with the Reactor Safeguard Committee's power calculation of dose). The integrated dose computed for a hemisphere without scatter correction is:-

Integrated Dose in rep

Distance (miles)		3	6	12	19	30	60
No decay	Average case	135	40	12	6	2.5	0.7
	Bad, Z = 0	1780	640	230	125	55	15
	Bad, Z = 100	1	50	70	70	35	15
Decay at U =4.5 m/sec	Average case	110	30	8	3.5	1.4	0.3
	Bad, Z = 0	1470	460	150	75	30	7
	Bad, Z = 100	1	35	45	40	20	7

Values for no decay are included to facilitate recalculation for wind speeds other than 10 mph. For speed x miles per hour,

$$\text{integrated dose} = \frac{10}{x}\ \text{(appropriate value in table)} \times \text{(decay factor)}$$

This cloud gives lethal doses up to ~ 6 miles in the bad case if there is no initial rise, and gives troublesome doses up to about 50 miles.

Inhalation figures

The retained amounts in the lung (50% retention) are:

Distance (miles)		3	6	12	19	30	60
Deposit (mc)	Average	130	36	10	4	1.7	0.4
	Bad, Z = 0	1,760	560	180	90	36	8
	Bad, Z = 100	1	45	50	50	22	8
Initial dose-rate rep/day	Average	6,700	1,850	510	210	90	20
	Bad, Z = 0	90,000	29,000	9,300	4,600	1,800	400
	Bad, Z = 100	45	2,300	2,800	2,500	1,100	400
Total dose first month (rep)	Average	52,000	14,000	4,000	1,600	700	150
	Bad, Z = 0	700,000	220,000	72,000	35,000	14,000	3,000
	Bad, Z = 100	350	18,000	21,000	20,000	9,000	3,000

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The crude total dose calculation assumes a rapid elimination of a further 25% of the inhaled amount, with radioactive decay of the rest. Neglected are such factors as the failure to retain gas (e.g., Xe, Kr), and the rapid transmission of some radioisotopes through the lung wall. For the bad case, plutonium deposition in the lung is 35, 12, 7, 3, 0.7 μg at 6, 12, 19, 30 and 60 miles, respectively. This will ultimately be damaging at $\sim$ 30 miles. Neptunium deposition is approximately one third that for fission products.

Deposition on the ground*

If D = 10^5 μc/sq.meter/hr per unit concentration, the ground contamination (fission products) is:-

Distance (miles)		3	6	12	19	30	60
Ground Contamination curies/sq. meter	Average	30	10	7	1.5	0.5	0.2
	Bad, Z= 0	400	150	55	30	12	3
	Bad, Z= 100	0.2	12	16	16	7	3
Initial Dose-rate roentgens per hour	Average	200	70	50	10	3	1
	Bad, Z= 0	3000	1000	400	200	80	20
	Bad, Z= 100	1.5	80	120	120	50	20

All these numbers are freely rounded off. For the dose rate from ground contamination, we have assumed 1 curie/sq.meter. $\longrightarrow$ 7 r/hr. This is greatly affected by the self-absorption of vegetation. A general conclusion is that the ground would be temporarily dangerous at distances up to $\sim$ 50 miles.

Rain-out

Estimated maximum rain-out is 170, 40, 20, 8, 3 curies/sq.meter at 6, 12, 19, 30, and 60 miles, respectively.

*Calculations ignore weakening of cloud by deposition.

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Mountainous terrain

The foregoing calculations for inversion conditions are extremely sensitive to the assumed initial height of the smoke plume. The actual concentration at ground level on a true horizontal plane is conjectural. However, the initial rise cannot exceed a few hundreds of meters. The local terrain (Figure 4) is such that the plume could intersect the ground at distances $\sim$ 6 miles. The given values for the bad case with $\underline{Z}$ = 0 would apply. Some dilution must occur in the primary ascent, but this will be an incalculable function of the rate of combustion and the geometry of the fire. A factor of 10 can perhaps be applied. Conditions on the Wahluke Slope can then be computed from the above data.

5. Circumstances leading to Columbia River Contamination

So far it has been considered that all the available energy will be used up as heat. Undoubtedly, some will go into physical disruption of the unit, and ejection of all sizes of particles from chunks down to submicron size.

The most naive picture shows all the reactor material spread uniformly in a circle of radius x feet about the reactor P.

Let p (feet) = perp. dist. from P to the far bank of the river

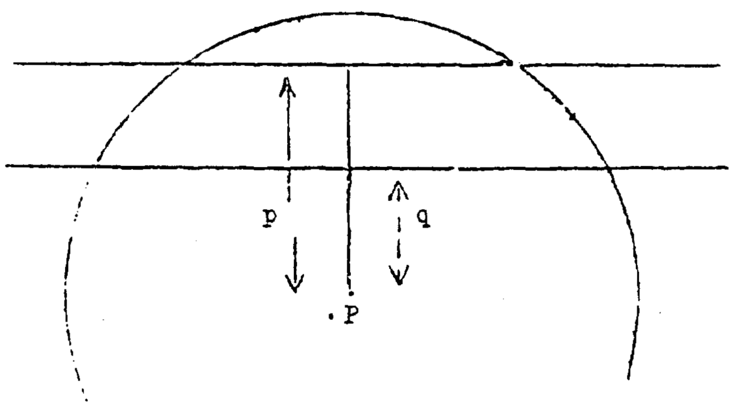

Figure 5

and q (feet) = perp. dist. from P to the near bank of the river.

The area of the circle between the parallel chords is:

$$A = p\sqrt{x^2 - p^2} + x^2 \sin^{-1} p/x - q\sqrt{x^2 - q^2} - x^2 \sin^{-1} q/x$$

The ratio of this to the whole area of the circle is $A/\pi x^2$

This has a maximum value when $\frac{d\left(\frac{A}{\pi x^2}\right)}{dx} = 0.$

i.e.: if $x = \sqrt{p^2 + q^2}$

$$\frac{A}{\pi x^2}\ (\max) = \frac{1}{\pi}\left(\sin^{-1} p/x - \sin^{-1} q/x\right)$$

Representative values for each Hanford reactor are:

$p = 3200$ and $q = 2000$, whence

Maximum fraction falling in river = 0.145

We now elaborate the model to the Jericho Case, in which we picture the reactor shield walls to fall down, and the upper hemisphere of an assumed spherical reactor to be initially projected radially from the center with equal force in all directions. The radial elements are assumed to break up after the initial velocity is established. We further assume that 10% of the maximum possible energy 2×10^{11} calories goes into energy of motion. On this simple model, the maximum range is ~ 1000 meters, comparable with the worst value of x in the previous case. The trajectories of all particles and the ground pattern of contamination can be computed. This pattern can be approximately fitted to a curve of the type

Contamination per unit area at radius r = $A e^{-b r^2}$

in which the constants are related by:-

$$\text{Total activity in half the reactor} = \int_0^\infty A e^{-b^2 r^2} \times 2\pi r\, dr = \frac{\pi A}{b}$$

The fraction of activity thrown into the river can be calculated for various "reasonable" values of b. Such integrations show between 2.5% and 7.0% in the river.

We postulate that in a 2×10^{11} calorie explosion most of the fission products will ascend in the primary hot bubble. Conversely, the 2×10^{10} calorie explosion has insufficient energy to give maximum coverage of the river. * We shall assume that not more than 1% of the total activity is directly thrown into the river. This is ~ 5.8 megacuries of fission products, and proportionate amounts of other activities. The active particles will fall at high

* These calculations are admittedly crude. A firmer opinion is being sought from competent experts in explosives.

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velocity on the simple model. If highly pulverized, much could escape upwards. We shall assume uniform mixing of the full quota throughout the depth of the river in a strip approximately 4000 feet long.*

Width of river	=	1200 feet
Effective length	=	~ 4000 feet
Average flow	=	120,000 c.ft/sec.
Average velocity	=	~ 3 mph = 4.4 ft/sec.

Volume contaminated = 8.2×10^7 c.ft. = 2.3×10^9 liters.

Concentration:-

Fission products	-	~ 1.4 mc/liter
Plutonium	-	~ 0.1 µg/liter
Neptunium	-	~ 0.5 mc/liter
Uranium	-	~ 0.5 mg/liter

<u>Alternate method of contaminating the river</u>

This refers back to the case of burning of all the reactor material. Under inversion conditions, it is feasible for the smoke plume to drift toward the river, and then be caught in the peculiar air stream which flows down ** the Columbia River and is directed over the bend of the river by the White Bluffs on the far side for about 20 miles. Take the simple model in which the plume is centered over the river at a height of 100 meters (reactor is 25 meters above the river). Assume that the deposition in the river is the same as that calculated for the ground.

Deposition rate = 12, 16, 16 curies/sq.meter at 6,12, and 19 miles.

The average deposition across the river (360 meters) can be calculated from the known cross river pattern of the cloud.

$$\frac{\text{Average deposition}}{\text{Axial deposition}} = 0.7,\ 0.8,\ 0.9 \text{ at 6, 12, and 19 miles.}$$

Total contamination = ~0.8 (6x14 + 7x16) curie-miles/sq.meter x 5.8×10^5 sq.meter/mile = ~ <u>90 megacuries</u>

---

*Most of the fission product material is expected to be oxidized. These oxides are normally insoluble, but at low concentration the solubility product is exceeded, and the material is postulated to hydrolyse.

**or <u>up</u> the river

Colonel Holzman[6] estimates that oxides in the hot bubble of the atomic bomb cloud agglomerate to particles of diameter 0.1 μ. Assume this happens in the cooler fire considered. Assume that all the particles in the present cloud are normal inactive particles uniformly coated with an active layer 0.1 μ thick.

Fission product oxides have specific gravities between 3.9 and 6.9.

Assume mean coating density = 5 gm/cm^3
mean carrier material density = 2.5 gm/cm^3

For any coated particle of final radius r microns.

$$\frac{\text{Active mass}}{\text{Total mass}} = \frac{0.6\,(r - 0.1)}{r^2 + 0.3\,r - 0.3} \quad \text{to 2nd order}$$

$$= \frac{0.6}{r + 0.3} \quad \text{to 1st order (good if } r > 1\,\mu)$$

The distribution of activity as a function of particle size is now calculated from the Alamagordo data, assuming same distribution applicable here.

Diameter μ	Relative number of Particles	Estimated Relative Mass	Active mass / Total mass	Relative Activity
0. - 3.3	98.3	98	0.75	73
3.3 - 4.7	0.94	60	0.26	15
4.7 - 6.6	0.55	110	0.18	20
6.6 - 9.4	0.10	50	0.14	7
9.4 -13.2	0.07	74	0.11	8
13.2 -18.7	0.04	120	0.08	9
18.7 -26.5	0.008	83	0.05	4
Coarse grains	--	--	v.low	--

The rate of fall of particles in air (Bagnold's data corrected to dens.5)[7] is:-

Diameter μ	Velocity meter/sec.	Fall in 5 hrs. meters	Percent Cloud * content falling
9.4	2×10^{-2}	300	75
6.6	5×10^{-3}	100	50
3.3	8×10^{-4}	16	8
~1.	2×10^{-4}	4	2

*Calculated from vertical thickness of plume, allowing for reflection at the water surface, but not for vertical pattern of concentration. Cloud moves downriver at 4 mph.

Activity in river is:-

Class μ	Percent Total Activity	Percent Class Falling	Percent Activity in River
$>$9.4	15.4	75	11.5
6.6 -9.4	5.1	50	2.5
3.3 -6.6	26	8	2.0
1 -3.3	∼ 40 ?	2	2.0
		Total	18

Eighteen percent for the mean decay time is ∼ 50 megacuries.

In comparison of the two methods, the first should be adjusted to the lower wind speed of the second, giving ∼ 200 megacuries. The agreement is satisfactory. The value 50 megacuries appears more probable, as the higher value is incompatible with the observed rate of disappearance of fine smoke near the ground.

This activity descends in a peculiar pattern distorted by the motion of the river. The initial mixing in the river is probably very low. However, we shall assume 50 megacuries uniformly dispersed in ∼ 15 miles of river. The average concentration is 1.1 mc/liter. This is the same as that calculated for direct dumping in the river, but the potential nuisance is greater by a factor of 20 due to the longer contaminated strip.

6. Speculations on biological effect on man

Permissible exposure -- ingestion toxicity

Known to this writer is no significant improvement on the early calculations of W.Cohn[8] with respect to the real hazard of fission product ingestion. Cohn's methods are adopted, with the current more conservative radiation limits, and occasional use of newer biological constants (Morgan, Brues, etc.) where these seem well-founded.

Fission Products

(a) Lethal dose, LD 50 in 30 days

Single dose of 1000 rep delivered to the gut in 24 hours from a single ingestion is given by ∼ 30 mc, because the radiation at the gut wall will be approximately one-half that at the center of the filled tube.

Lethal concentration in water = ∼ 30 mc/liter (single drink)

= ∼ 10 mc/liter (contamination persists one day)

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If 30 mc fission products are ingested, the bone marrow deposition may be ~ 1.2 mc, and the initial dose-rate ~ 40 rep/day. The integrated dose is ~ 500 rep. While probably not lethal in 30 days, this is presumably damaging. There is a rather close balance between the gut radiation and the skeletal deposition as the principal damaging agent. *

(b) Permissible Emergency Concentration for 1 day

Gut damage - assume 100 rep (comparable with fluoroscopy) is insignificant.

Permissible emergency concentration = ~ 3 mc/liter (single drink)

= ~ 1 mc/liter (for 1 day)

Deposition in bone marrow - as the fission products age, the relative concentration of dangerous long-lived products, especially those prone to deposit in bone increases. Assume 100 rep (integrated dose) to the bone marrow is tolerable. Permissible emergency concentration (30 day material) = ~ 2 mc/liter (single drink)

= ~ 0.7 mc/liter (for 1 day)

(c) Permissible emergency concentration for 1 year

The values according to K.Z. Morgan(9) can be adjusted with the new radiation exposure limit to -

Permissible emergency concentration = 1 uc/liter (for 1 year)

This is higher by a factor ~ 1000 than the planned waste disposal limit of an atomic energy installation.

---

* Appropriate values of LD 50/30 are rather poorly known. In the animal, experimentation has concentrated on other modes of entry, or on the transmission to other organs of orally administered material. One value can be deduced from the ingestion of Y^{91} by rats (14). Animals fed 1 - 6 mc lived until eventually killed by adenocarcinoma of the colon. Take the mass of gut plus contents as 5% body weight (standard 1 year rat = 280 gm.). Estimated dose = 6000 rep.

Flaskamp(15) reports that an X-ray dose of 140% SED (= ~ 850 r) to the colon does not produce irreparable damage. The writer estimates that in man, the LD 50/30 for gut irradiation is 2000 - 3000 rep.

We adhere to the 1000 rep of the tabulations, because the higher figure would probably lead to intolerable depositions in other organs, and while not a true LD 50/30 it may well be a representative lethal dose.

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Plutonium

(a) Lethal dose LD 50 in 30 days

Gut as limiting organ receives 1000 rem (= 50 rep for alpha radiation) from ~ 5 mg Pu.

Lethal concentration = ~ 5 mg Pu/liter (single drink)

Note that concentrations of the order of 1/3 of this may deposit enough plutonium in the skeleton to be <u>ultimately</u> lethal.

(b) Permissible Emergency Concentration for 1 day

The skeletal deposition is of the order of 0.05% of the ingested dose, and the permissible skeletal deposition is ~ 0.1 ug Pu. *

∴ Permissible emergency concentration = ~ 200 μg/liter (single drink)

= ~ 60 μg/liter (for 1 day)

(c) Permissible Emergency Concentration for 1 year

Permissible emergency concentration = ~ 1.5×10^{-2} μg/liter.

Neptunium

Lethal concentration = ~ 100 mc/liter (single drink)
= ~ 35 mc/liter (one day)

Permissible Emergency concentration = ~ 10 mc/liter (single drink)
= ~ 3 mc/liter (one day)
= ~ 1 μc/liter (for one year)

Apparently the neptunium need only be considered separately in a circumstance in which primary plutonium is absorbed out, for example, by seepage through soil, and neptunium is transmitted. The neptunium may then become a carrier of plutonium to the skeleton. No case is currently visualized in which this effect would be significant.

Uranium

Lethal concentration (radiation effect) = ~ 6×10^5 mg U/liter (single drink)

but chemical toxicity probably intervenes at ~ 700 mg U/liter if the material is in soluble form.

---

* Hamilton[16] quotes oral absorption as 0.007% with 65% going to bone. i.e. Skeletal deposition = 0.0045%. Morgan writes skeletal deposition = 0.03%. We consider this critical value to be inadequately known, especially for low concentrations. A definitive experiment on this is in progress at Hanford Works. Meanwhile we use the more conservative value of 0.05%.

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Uranium - continued

Permissible emergency concentration (soluble U compounds)

= ~ 5 mg U/liter (single drink)

= 1.7 mg/liter (one day)

= 250 µg/liter (for one year)*

Inhalation toxicity

The inhalation toxicity depends on

(1) retention of particles - we assume arbitrarily a primary retention of 50%, with rapid removal of one-half of this which then presents an ingestion hazard. The residuum is supposed to be eliminated with a biological half-life of 2 months;
(2) transmission through lung wall - bromine, rubidium, strontium, ruthenium, iodine, cesium and barium, will be assumed rapidly soluble, and all other active materials totally insoluble;
(3) hazard of discrete particles - this will be neglected here, although it is a conceivable limiting hazard.

Fission Products

For simplicity, the composition at 2 hours after the explosion will be used throughout. Of the calculated depositions, the percent distribution is:

Lung insoluble	62%
Lung soluble	
bone-seekers	14%
iodine	12%
others	5%
Gas - escapes	7%

Lethal deposition (LD 50 in 30 days) = ~ 20 mc.
(assumes all deposit stays for one day and gives 1000 rep to the lung tissue - this is conservative).

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* These values for chemical toxicity of uranium are taken from Rochester Reports (Neumann, et al).

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[redacted]

Fission Products - continued

Permissible emergency deposition P.E.D. = 0.3 mc.*

Such a deposit may send 36 uc radioactive iodine to the thyroid gland, where it produces 63 rep/day initially, but a total of ~ 80 rep due to rapid decay of all except I^{131} and I^{133}.

Similarly, the 54 μc bone seekers, if 50% is retained in bone, gives ~ 0.2 rep/day, for a total of ~ 3 rep.

---

* Approximate calculation as follows:

0.3 mc resides in lung for 1 day; dose in 1 day

$$= \frac{62 \times \text{Energy per dis (MEV)} \times \text{deposited amount (mc)}}{\text{Lung mass (kg)}} = \frac{62 \times 1 \times 0.3}{1.2} = \underline{15.5} \text{ rep}$$

Thereafter, 25% of the deposit has been eliminated (ciliary action, etc.) and ~ 60% of the remainder is lung insoluble. The integrated dose in 2 months is

$$\int_1^{60} \frac{\text{initial daily dose}}{t^{0.3}} e^{-\frac{.693t}{60}} dt = \sim 17 \times \text{initial daily dose}$$

$$\therefore \text{additional integrated dose} = \frac{17 \times 62 \times 1 \times 0.5 \times 0.6 \times 0.3}{1.2} = \underline{79} \text{ rep}$$

Total dose = 96.5 rep = ~ 100 rep.

Note that this is conservative on two counts:-

(1) the revised value of 1 rep is 93 ergs/gm (10) instead of the earlier 83 ergs/gm used here.

(2) Following Cohn, the average energy per disintegration is taken as 1 MEV, unless otherwise specified. From Wigner and Way (11) (12) we have

Time After Fission Days	Average beta energy per beta disintegration MEV	Average gamma energy per beta disintegration MEV
10	0.35	0.7
100	0.3	0.45

Our use of curie has the customary questionable meaning of 3.7×10^{10} beta disintegrations per sec.

In body tissues, not all the gamma energy will be absorbed. About 30% will be absorbed in gut or lung. We are concerned with times in the general order of 10 to 200 days on the above time scale.

The average energy is therefore about (0.35 + 0.21) to (0.3 + 15) MEV

= ~ <u>0.5 MEV</u>

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Plutonium

Lethal deposition (LD 50/30) = $\sim$ 2 mg ?

P.E.D. = $\sim$ 5 μg

This is not much higher than the normal permissible deposition $\sim$ 2 μg.

Neptunium

Lethal deposition (LD 50/30) = $\sim$ 50 mc

P.E D. = $\sim$ 1.5 mc

Uranium

Lethal deposition (LD 50/30) = 270 gm.

P.E.D. = 650 mg.

Application of speculative exposure limits

We have drawn a series of pictures of the potential air, ground, and river contamination arising from a reactor explosion. Along with these should be considered the somewhat different pictures of the P.L.P. reports. Enough data has been included so that the reader who prefers other postulates can deduce the corresponding contamination. In applying the equally speculative exposure limits we shall choose the bad cases, but not necessarily the worst cases for elaboration. For example, if the major damage could arise from a particular explosion on a day of minimum wind velocity, with the wind in just the right direction to put the cloud over the river, with a severe rain-out at that time, and the river at minimum flow, it will be considered inconceivable that all these disadvantages should arise simultaneously. An exception will be made for cloud deposition in the river, where incomplete mixing of contaminants with the water is physically probable.

(1). Immediate Effects of River contamination on man
Table 6-1 exhibits the predicted contamination in drinking water from the Columbia River, subjected to representative water treatment. The following assumptions are involved:

(a) Sand filter beds remove 90% of the plutonium and no other activities.*
(b) Ground filtration (recharge systems) removes 100% Pu and 90%

* This is conservative because sand is said to remove fission products by the following schedule: (13)

Time of Contact	Percent Removal
1 min.	8
15 min.	20
1 hr.	37
6 hrs.	64
24 hrs.	78

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TABLE 6-1

Comparison of Concentrations in Water Systems with damaging concentrations

Material	LD-50 1 drink	LD-50 1 day	P.E.C. 1 drink	P.E.C. 1 day	Concentration in River (Blow-Up)
FP	30 mc/L	10 mc/L	3 mc/L	1 mc/L	1.4 mc/L
Pu	5 mg/L	1.7 mg/L	0.2 mg/L	0.07 mg/L	0.1 µg/L
Np	100 mc/L	35 mc/L	10 mc/L	3 mc/L	0.5 mc/L
U	700 mg/L	230 mg/L	5 mg/L	1.7 mg/L	0.5 mg/L

Concentration in Water Distn.System

Material	Direct (no filtration)	Sand Filter Beds	Ground Filtration
FP	1.4 mc/L	1.4 mc/L	0.14 mc/L
Pu	0.1 µg/L	0.01 µg/L	0.00 µg/L
Np	0.5 mc/L	0.5 mc/L	0.005 mc/L
U	0.5 mg/L	0.5 mg/L	0.05 mg/L

For humans drinking 1 Liter, fraction they will receive of the

Material	Direct LD-50	Direct P.E.C.	Sand Filter LD-50	Sand Filter P.E.C.	Ground Filter LD-50	Ground Filter P.E.C.
FP	0.047	0.47	0.047	0.47	0.0047	0.047
Pu	2×10^{-5}	5×10^{-4}	2×10^{-6}	5×10^{-5}	0	0
Np	5×10^{-3}	5×10^{-2}	5×10^{-3}	5×10^{-2}	5×10^{-5}	5×10^{-4}
U	7×10^{-4}	0.1	7×10^{-4}	0.1	7×10^{-5}	0.01

For humans drinking 3 Liter, fraction they will receive of the

Material	Direct LD-50	Direct P.E.C.	Sand Filter LD-50	Sand Filter P.E.C.	Ground Filter LD-50	Ground Filter P.E.C.
FP	0.14	1.4	0.14	1.4	0.0014	0.14
Pu	6×10^{-5}	1.4×10^{-3}	6×10^{-6}	1.4×10^{-4}	0	0
Np	1.5×10^{-2}	0.15	1.5×10^{-2}	0.15	1.5×10^{-4}	1.5×10^{-3}
U	2.1×10^{-3}	0.3	2.1×10^{-3}	0.3	2.1×10^{-4}	0.03

[redacted]

1082202

fission products, neptunium and uranium.*

The feasible eventual slow leaching of activity from the filter beds is not considered here. The two types of explosion considered give initial strips of contaminated water respectively < 1 mile and 15 miles long. With an adequate warning system, currently under development by the Disaster Control Committee, municipal systems could be by-passed with a generous margin for expansion of the strips by mixing and diffusion.

The tabulation predicts that all exposures will be below the relevant LD 50/30 by a safe margin. Borderline will be the ingestion of fission products and uranium relative to the permissible emergency concentration. This assumes that a storage tank has been refilled during the time of passage of the contaminated strip. Not only is this unlikely, but also the holdup will introduce a useful decay factor for fission products ($\sim$ 3-fold in one day).

If the reactor burns up and the river contamination is acquired from the contacting cloud, the mixing in the river may be far from uniform. At low flow, when the possible dilution is least, water intakes will tend to be near the river surface, and the surface-contaminated layer could be directly drawn into the system. If the water activity is assumed 100 times greater than before, the dose is well into the lethal range. At 10 times greater, the P.E.C. is clearly exceeded, and injury would be anticipated.

Listed in Table 6-2 are communities, populations, sources of sanitary water, and the fractional LD 50's and P.E.C. they will receive if no effort is made to have their pumping stations turned off temporarily. (This table has been abstracted from as complete a listing as could be provided by State officials, of all towns between Hanford Works and the mouth of the Columbia river, using the Columbia River for sanitary water). The concluding figures are based on drinking contaminated water from the various systems for one day. They may be uniformly divided by 3 to find fractions of LD 50's and P.E.C. for people taking but one large drink (1 liter) before being warned. Longer periods are not considered since a supply showing contamination in excess of 1 μc/liter of fission product, 1.5×10^{-2} μc/liter of Pu, 1 μc/liter of neptunium, or 0.25 mg/liter of uranium, a few weeks after the emergency should be decontaminated or abandoned. Table 6-2 includes the decay factor of fission products travelling downstream. Without such a factor, the exposures in all towns except Richland, for the burn-up case (calculated as 10 times the previous concentration) would exceed the LD 50/30. In view of the many uncertainties in computation, we can only conclude that a critical condition may arise in the water supply of any downstream community using the Columbia River.

*This is possibly optimistic. Anions (Br, I) and Group I cations (Rb, Cs) will be poorly retained. Of these, only I^{131}, I^{133}, and Cs^{137}, are present in sufficient yield and long enough half-life to merit examination.

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TABLE 6-2

Community	Population	Source of Sanitary Water	Blow-up, 1 days drinking, receiving fraction of LD-50	P.E.C.	Burn-up, 1 days drinking, receiving fraction of LD-50	P.E.C.
Richland, Wn.	25,000	2-Y W + 1-C W	0.0002	0.002	0.002	0.02
Kennewick Irrigation Proj	400	C	0.06	0.6	0.6	6.
Pasco, Wn.	8,000	CF	0.06	0.6	0.6	6.
McNary, Ore.	1,500	CF	0.04	0.4	0.4	4.
Arlington, Ore.	600	CF	0.02*	0.2*	0.2*	2.

Key:

YW = Yakima River water stored in earth basins to raise table for wells

C = Columbia River water, no filtration.

CF = Columbia River water, sand filtered.

* ½ calculated value due to dilution from tributaries.

(17,18, 19, 20, 21, 22)

(2) Immediate Effects of river contamination on lower forms

River Population

(1) Fish

During the summer run, there are about 300,CCO adult salmon and trout in the Columbia River, based on counts at Bonneville Dam and estimated fishing mortality. With the normal 20% survival of potential spawn of adult salmon, and assuming half the young fish in the Lower Columbia, there will be 85 million young migrant salmon.

Other migratory fish (smelt and shad) are in the Lower Columbia, and sports fish, (bass, whitefish and sturgeon) are found throughout the section below the Hanford Works. Coarse fish are abundant. From test samples, the relative populations can be set at

Adult salmon and trout	300,000
Young salmon and trout	85,000,000
Other fish	1,500,000,000
Total	~ 1,600,000,000

This represents 1000 fish per linear foot of river.

(1-b) Other aquatic vertebrates

There is no important form. Lamprey eels have been included as fish.

(2) Micro-organisms

Near the Hanford Works there is 5 lbs. of algae and associated microscopic forms per 100 sq. ft. of productive bottom. If such bottom averages 500 feet from either bank from Hanford Works to the mouth, there is 40,000 tons of algae in the river. Planktonic organisms are a special case, because they will float downriver with the contaminated water. The mass involved for the "blow-up" case is ~ 1 ton, and for "burn-up" is ~ 17 tons. The mass is approximately 9 parts phytoplankton to one part zooplankton.

(3) Insect larvae and associated forms

At Hanford, larvae, snails, etc., approximate 2.7 lbs. per 100 sq. ft. productive bottom. The estimated total mass is ~ 22,000 tons.

Concentration factors

(1) Fish

From data of Prosser, et al (21), the concentration of fission mixture (disregarding differences in age of mixture, etc.) is estimated as:

Tissue	Concentration Factors: Blow-up ~ ½ hr. exposure	Concentration Factors: Burn-up ~ 10 hrs. exposure
Intestine	10	100
Bone	0.2	1.5
Viscera	1	2
Muscle	1	2

[redacted]

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Hypothetical values for plutonium and uranium are derived as follows:

Some will be ingested with food, and perhaps 0.1% Pu and 10% U absorbed from gut. For an average fish (200 gm), 10 grams of food is estimated to contain < 0.01 μg Pu, which deposits < 10 $\mu\mu$g Pu (= 0.1 $\mu\mu$g/kg). Uranium deposit is ~ 5 ug. These amounts are small compared with those in the water. Ion exchange across gill membranes should equilibrate the specific activity in the fish with that in water (0.1 μg Pu/kg and 0.5 mg U/kg, respectively).

(2) Micro-organisms

The estimated concentration factor for fission products in bottom forms is ~1000 for a 10-hour exposure, and ~100 for one-half hour, based on the fecal activity of Prosser's goldfish, and Hanford data on concentration factors of other radio-elements. Plutonium and uranium concentration factors are arbitrarily taken as 2 in both cases.

Plankton travelling with the contamination is estimated to have a concentration factor (F.P.) of ~ 1000. Arbitrarily, the factor for plutonium or uranium is written as 10.

(3) Insect larvae and associated forms

By generous extrapolation of Hanford data, the average concentration is written as 50 for ½ hour (blow-up) and 500 for 10 hours (burn-up).

The concentration of available contamination is exhibited in Table 6-3, in comparison with crudely estimated damaging doses. The LD50/30 is that estimated to give 3000 rep to the gut in fish.

In the above picture, damage is confined to:

(1) Fish in Case III for fission products
(2) Larvae in Cases II and III for fission products
(3) Borderline chemical toxicity of uranium, possibly of all forms.

(3) Delayed effects on aquatic forms -- food chains

Plankton of the Columbia River consists mainly of diatoms. These and the filamentous algae of the river bottom concentrate radioisotopes from the water and subsequently provide contaminated food for higher forms. The diatoms are probably the most efficient concentrators of activity in the river, other things being equal. Here they are unequal because they float freely in zones of maximum activity, and travel with the contaminated water. Possible intake into unfiltered water systems has to be considered. An important distinction is that, if not captured enroute, they escape in about 5 days from the biological system of the river. All other forms will tend to set up a biological chain of activity transfer in the river.

Bottom forms include the algae, protozoa and insect larvae. All these participate in the food chain. For the customary Hanford

TABLE 6-3

Concentration of Radioactivity in aquatic organisms

Contaminant	Damaging exposures: LD 50 Fish	LD 50 Algae	LD 50 Plankton	LD 50 Larvae	PDC Fish	Conc. in River	Specific Activity (rounded-off): Fish Viscera	Fish Bone	Fish Muscle	Fish Gut	Algae	Plankton	Larvae
Fission Products mc/kg	100	10,000	10,000	500	6 (viscera)	I 1.4	2	0.5	2	15	140	2800	70
						II 1.4	3	2	3	140	1400	2800	700
						III 14	30	20	70	1400	14,000	28,000	7,000
Plutonium mg/kg	15	1,500	1,500	75	1	I 10^{-4}	$< 10^{-3}$	$< 10^{-3}$	$< 10^{-3}$	$< 10^{-3}$	$< 10^{-3}$	$< 10^{-3}$	$< 10^{-3}$
						II 10^{-4}	$< 10^{-3}$	$< 10^{-3}$	$< 10^{-3}$	$< 10^{-2}$	$< 10^{-3}$	$< 10^{-3}$	$< 10^{-3}$
						III 10^{-3}	$< 10^{-2}$	$< 10^{-2}$	$< 10^{-2}$	< 0.1	$< 10^{-2}$	$< 10^{-2}$	$< 10^{-2}$
Neptunium mc/kg	300	30,000	30,000	1500	20	I 0.5	0.5	0.1	0.5	< 5	5	5	3
						II 0.5	1	< 2	1	5	5	5	3
						III 5	10	10?	10	50?	50	50	25
Uranium mg/kg	100	200	200	200	1	I 0.5	Chemical toxicity basis						
						II 0.5	includes concentration factors						
						III 5							

NOTES: All values highly speculative, except for fission products. Uranium calculated as for lead poisoning.
Case I - Blow-up of reactor
Case II - Burn-up
Case III- Burn-up, and non-uniform mixing of deposits in river.

Underlined values are those possibly above a safe limit.

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effluents, aquatic insect larvae, such as of caddis flies, which feed on plankton, or midge larvae that feed on algae and plankton, acquire about the same specific activity as their food. Forms such as the may fly which are partly carnivorous are less active by a factor of two. Carnivors, such as crayfish, acquire one-fifth the activity of plankton feeders. Similarly, the carnivorous game fish are less active than carp or suckers.

In application to the current contamination, it follows that coarse fish, escaping direct injury by ingestion of fission products could easily acquire a lethal dose from contaminated algae. Such forms as adult bass or trout would probably avoid this fate. Young salmon or trout, still feeding on micro-organisms would be likely candidates for extinction.

No attempt has been made to calculate the distribution pattern of activity in the water. Known from experience with reactor-cooling effluents is that mixing from a small source is incomplete 20 miles downriver, but approximately complete at 40 miles. Bottom forms probably have access to the explosion contaminants 10 to 20 miles below the reactor. Their concentrating action will unbalance the concentration. If all the algae in the river were exposed to the active water, all the activity could be removed:-

Mass of algae = 40,000 tons = 36×10^6 kg.

Activity of water = 1.4 mc/kg

Concentration factor = ~ 1000

Activity of algae = 50 megacuries

A plausible distribution of the initial 50 megacuries from the burn-up case is:-

Consumer	Activity curies	Location
Algae	7,500,000	10-200 miles downriver
Fish	1,000,000	throughout the river
Larvae	2,000,000	10-200 miles downriver
Plankton	45,000	carried to sea
Irrigation	60,000	distributed
Water supplies	30,000	as listed
Animals & birds	500	distributed
Balance ~	40,000,000	carried to sea

Relatively superficial contamination appears feasible in the burn-out case. This materially alters the pattern in the river. Contamination of algae, etc. would be displaced perhaps 50 miles to 100 miles downriver. Mixing would certainly occur in the rapids at the Dalles, if not before. Nearer the Plant, fish prone to rise to the surface for insects would enter the very active water. Scum on the surface would presumably accumulate activity by adsorption. Such scum is a favorite food of carp.

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[redacted]

(4) Effects on farm animals and wildlife of the Columbia River

Assumptions made in this case are:

(1) 1000 rep to gut (single exposure) is a conservative LD-50
(2) the contaminant, on the average, is diluted in the ratio of the daily intake of water to the normal gut volume
(3) only fission products need be considered
(4) only Case III of Table 6-3 is significant
(5) if the permissible emergency concentration is taken as one-tenth the conservative LD 50, the range between P.E.C. and LD50 will be a plausible injury-range.
(6) no corrections for decay are made.

The relevant data is assembled in Table 6-4.

The potential affected population of domestic animals is taken as 20% of that of counties adjoining the Columbia River[23]. Gut retention times are as estimated by Morrison [24]. Other animal physiology data comes from Dukes [25].

See Table 6-4

The tabulation suggests that ~ 300,000 domestic animals, and ~ 900,000 wild animals may receive exposures between the estimated P.E.C. and the LD50, and may be injured. For the more probable Case I or Case II, there is no injury. The general speculation is that injury by drinking will be moderate or non-existent. Reservations with respect to aquatic birds eating contaminated algae have to be made.

(5) Effects of river contamination on irrigated crops

Data on the translocation of fission products, plutonium, and uranium, in plants of various types is scarce in the literature. L.Jacobson and R.Overstreet[26][27] quote 0.1 mc/kg soil as the specific activity causing damage. Such an activity is available for Case II, and is readily exceeded in Case III. Plutonium and uranium hazards appear to be insignificant.

Fission products such as Zr-Cb and the rare earths predominantly go to the roots, while Sr has significant translocation to the leaves. Quantitative transformation of the data to the field case is difficult. The laboratory tests were made with plants grown for 24 hours in suspensions of bentonite clay in water. Initially, the activity is concentrated on the clay, and there is competition for the cations between roots and clay. Presumably then, the picture in irrigation is an initial deposition on soil up to some saturation point, with later

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TABLE 6-4

Damage to Animals drinking contaminated river water

Animal	Population thousands	Daily Water-intake liters	Gut Retention days	Gut Volume liters	LD50 mc/L	P.E.C. mc/L	Fraction received of LD50	Fraction received of P.E.C.
Horses	6	40	2	200	80	8	0.2	2
Cows	60	60	2	350	100	10	0.14	1.4
Swine	11	5	1	35	200	20	0.07	0.7
Sheep	60	5	2	45	140	14	0.1	1.0
Goats	0.5	5	2	45	140	14	0.1	1.0
Turkeys	5	0.3	1	0.8	90	9	0.15	1.5
Hens	160	0.2	1	0.5	80	8	0.2	2.0
Game Animals	10	5	2	40	130	13	0.1	1.0
Beavers	0.2	0.5	1	1.5	100	10	0.14	1.4
Muskrats	5	0.1	1	0.5	170	17	0.08	0.8
Otters	0.05	0.5	1	2	130	13	0.1	1.0
Other fur bearers	10	0.2	1	0.1-5	100	10	0.14	1.4
Canada Geese	5	0.8	1	1	40	4	0.35	3.5
Ducks	20	0.4	1	0.5	50	5	0.3	3.0
Other aquatic birds	50	0.03-0.3	1	0.1-0.8	50	5	0.3	3.0
Pheasants	10	0.1	1	0.4	130	13	0.1	1.0
Quail	100	0.01	1	0.05	170	17	0.08	0.8
Song birds	500	0.01	1	0.04	130	13	0.1	1.0

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translocation to the plants. The laboratory results, converted to specific activity, are:-

Element	Concentration factor				
	A		B		
	Leaves	Roots	Leaves	Roots	
Y	0.5	33	0.2	14	A = 0.1 mg bentonite/ml.
Ce	0.1	33	0.06	14	B = 0.6 mg/ml.
Zr - Cb	1.4	40	0.6	17	
Sr	8	13	3.4	5.5	

In Case III, the specific activity of Sr^{89} in water is 14 x 0.011 mc/liter = 0.15 mc/liter. In the leaves will be found ~ 5 x 0.15 mc/kg = ~ 0.75 mc/kg. A vegetable consumption of 0.3 kg/day gives a daily ingestion of ~ 0.2 mc Sr^{89}/day. Over one year, the average daily intake (allowing for decay) is ~ 10 μc. The daily intake which gives the permissible daily exposure after one year is ~ 2 μc. In the event of disaster, the translocation into irrigated crops may require intensive study. We may consider here irrigation projects, either now in existence or contemplated for the future, which would be made unavailable for the production of crops following the accident if the irrigation water could not be turned off in time to avert contamination by radioactive materials.

The Pasco Irrigation Project covers 7,750 acres, with 5,552 acres to be irrigated in the near future.

Below the confluence of the Snake River in the Columbia River Bottom irrigation territory, approximately 1500 acres are being irrigated in small tracts, the largest of which is 700 acres on Blalock Island, located between Umatilla and Wallula. For much of other irrigation required near the Columbia River, tributaries are used which, in rare instances, may be increased supplementing with Columbia River water.

Between the Dalles and the mouth of the Columbia River, small acreages are located which are not irrigated but are subject to inundation by flood. These farms frequently have dikes which would prevent contamination in some measure and consist of plots varying from 10 to 100 acres.

In the distant future, it is contemplated that possibly 280,000 acres will be irrigated by the Columbia River located below Kennewick and through Umatilla, and will include some of the Horseheaven area. Source of the water will probably come from the McNary Dam with Hidden Valley to be irrigated first.

The crops grown between here and the Dalles are almost entirely pasture for stock with little truck farming. No permanent crops are being anticipated until the irrigation projects presently being installed are

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complete.. It may take several years before crops of this type, including orchards, are extensively planted.

In summary, a total of slightly more than 7,000 acres will shortly be irrigated by water from the Columbia River, and perhaps 290,000 acres in the distant future. Whether ground and crops would be contaminated and rendered useless for a protracted period in the event of a catastrophe is dependent on how quickly irrigation operators could be made aware of the hazard and stop drawing water for perhaps a day or two until the bulk of radioactivity has progressed downstream. This should be possible if the communication system is efficient.

The calculations for reactor burn-up with initial height 100 meters in an atmospheric inversion will be accepted as the worst case reasonably expected. The relevant figures are summarized below:

Distance (miles)	3	6	12	19	30	60	100	200
Cloud dose, external (rep)	1	35	45	40	20	7	--	--
Lung deposit, F.P. + Np. (mc)	1	65	75	80	35	14	6	2
Lung deposit Pu (μg)	--	6	8	8	4	2	1	0.5
Ground Contam. (curie/m^2)	0.2	12	16	16	7	3	1.5	--
Ground dose-rate (r/hr)	1.5	80	120	120	50	20	10	5
Rain-out (curie/m^2)	large	170	40	20	8	3	--	--
Cloud width (meters)	280	470	800	1080	1600	2700	--	--

Uranium effects can be neglected, and the neptunium grouped with fission products. The significant initial hazard is inhalation toxicity.

Values above the estimated LD-50 persist to distances of the order of 50 miles. Values above the P.E.D. extend to about 200 miles. At face value, the burn-up could cause substantial injury to the population of Walla Walla, or borderline injury to a strip of the population in Spokane. Such factors as the improbability of an inversion persisting over the required length of time, the weakening by deposition enroute, and the wind shear effect, mitigate this risk.* Nevertheless potential inhalation hazards exist in a triangular area of base about 1 to 2 miles and length ~ 30 to 80 miles, with apex at the reactor. The unpredictable hazardous area will be determined by the wind direction.

For the State of Washington average population, the triangular area would include only ~ 30 people. For the given location, the average target is ~ 500 people. Worse still is the concentration of population in cities including Yakima valley towns, Richland, Kennewick, and Pasco. The three latter are the prime targets, due to level intervening terrain and prevailing wind direction. The probability of scoring a hit on such a center is ~ 1 in 10.** As many as 10,000 people could then be affected. Fortunately, just these towns are the most likely to have effective evacuation schemes operative in the 3 to 5 hours available.

* On the other hand, an additional factor of 2, due to low wind speed is not unreasonable.

** Weighted according to average wind rose.

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The secondary hazard to man in this triangular zone comes from irradiation from contaminated ground. Accurately enough this can be taken initially as ~ 100 r/hr at distances of 6 to 30 miles from the reactor. The rounded-off integrated doses (assumes no leaching) are:

Time after deposition	1 hr	2 hr.	5 hr.	1 day	3 days	1 week	1 month
Dose-rate (r/hr)	100	80	70	40	30	20	10
Integrated dose (r)	100	200	400	1300	3000	5000	15,000

The inhabitants of this zone have been potentially killed by the inhalation hazard, unless previously evacuated. We are concerned only with subsequent re-entry for rescue, etc. Obviously, re-entry times must initially be kept to the order of one hour. Even at one month, entry for more than a few hours would be undesirable. There is a hidden safety factor of 2 because the figures refer to the axial dose-rate, which is about twice the average across the width of the cloud.

An additional hazard to man is the consumption of vegetation that has received surface contamination. In the most dangerous triangle, the specific activity on plants will be ~ 5 curies/kg, which is perhaps on the order of 50-1000 times the permissible limit for human consumption. Regardless of the atmospheric turbulence, dangerous depositions on vegetation could occur up to at least 60 miles. The hazard is not elaborated because it is avoidable by control. Local water supplies - reservoirs and ponds - will be contaminated to the extent of ~ 1-10 mc/liter. This hazard can be traced from the discussion of the river, except that it could persist longer if the supply is not dumped. Control is feasible with a good monitor service.

The hazard to domestic animals and wildlife will exceed that to man, because of the impracticability of removing any other than perhaps bloodstock. Approximately 13,000 domestic animals, and 80,000 others can be expected to perish. As many more could move into the triangle later and be killed by radiation from the affected ground or by eating contaminated vegetation.

The calculations presented are not sufficiently precise to justify ramifications of the discussion for less concentrated clouds of greater width.

Direct injury to plants is a further sequel to the ground deposition. Much of the target area is waste desert land or very low-grade grazing land. Sporadically located are valuable irrigated orchards. To the east and south are extensive dry-farmed wheat areas. It is presumed that these will be rendered useless for at least one growth season.

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SUMMARY AND CONCLUSIONS

Page Reference

This is a preliminary draft, diffuse and un-edited in order to make the speculations available immediately. Comments and criticisms directed to the principal author will be appreciated, and helpful, in preparation of the final draft.

Part I treats the Hanford nuclear reactor as a waste storage unit, 2
and relates the foreseen circumstances under which these wastes may 4
be disseminated to produce environmental hazards outside the Hanford reservation. Disaster requires simultaneous loss of cooling water, and failure of safety mechanisms by earthquake, bombing or sabotage. Simple physical and meteorological pictures of two explosions of heat release
2×10^{10} calories* and 2×10^{11} calories**, respectively, 6
are drawn. The feasible most dangerous cases are probably in this 7 **
range. 11 *

Considered next is the more probably case in which primary explosion 16
is followed by burning of reactor contents. This is the most hazardous predicted event. The behavior of the resultant radioactive cloud under average and adverse meteorological conditions is defined for

(1) activity in air at ground level up to 60 miles 18
(2) width of cloud 18
(3) integrated external dose 19
(4) lung deposition of presumed aerosols 19
(5) deposition of activity on the ground 20
(6) rain-out of activity 20
(7) effects of elevation (mountainous terrain) 21

#(4) is the critical immediate hazard, whereas #(5) or #(6) leads to persistent environmental hazard.

Two models leading to gross contamination of the Columbia River are developed:

(1) Blow-up, in which the primary explosion ejects active material directly to the river. This model is highly speculative. 21

(2) Burn-up, in which the active cloud deposits activity in the river. 23

The estimated specific activity (fission products) in the river is 1-2 mc/liter in either case. The contaminated strip is ~ 0.8 miles in (1) and ~ 15 miles in (2). 23, 25

Speculations on biological effect in man present quite tentative 25
values for a lethal dose (LD-50) and a permissible emergency concentration or deposition for ingestion and inhalation,* respectively,
for fission products, plutonium, neptunium, and uranium. These * 28

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are adequate to define a general damage range, when the current uncertainty of the physical pictures is considered. (We anticipate criticism and wide divergence in values of LD-50 and P.E.C. or P.E.D. From submitted comments, it is hoped to present weighted values for the final draft).

Comparison of the damage range with calculated exposures shows:

(1) effects of river contamination on man - borderline damage for unfiltered water systems; certain damage if active water is unfavorably channelized. — 30

(2) immediate effects of river contamination on lower forms - fish damaged in the worst case by fission products. Insect larvae generally damaged by fission products. Dubious chemical toxicity in the worst case. — 34

(3) delayed effects on aquatic forms - food chains with the activity initially concentrated by algae or planktonic forms enhances the damage to higher forms, for fission products only. — 35

(4) effects on animals watering at the river - widespread damage in the worst case only. Probably damage to aquatic birds in an average case. — 38

(5) effects on irrigated crops - primary damage seems feasible. Residual long-lived activity in food plants would have to be checked. — 38

From the possible radioactive clouds:-

(1) the principal hazard is <u>inhalation</u> of fission products and possibly plutonium, rather than the external radiation from the cloud.* Dangerous doses occur up to about 60 miles from the reactor. — 42

(2) the secondary hazard, from deposition of activity on the ground, denies unrestricted access over a similar range for at least days, and possibly months. — 43

(3) the same secondary hazard is lethal to animals by external radiation.

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* This has generally been inadequately discussed in most earlier discussions. (2) (28) (29). Plutonium inhalation has been considered by Jane Hall[30], and iodine inhalation by C. C. Gamertsfelder[31].

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Page Reference

(4) ingestion of contaminated food aggravates the damage to animals.

(5) growing plants may be injured by the deposits. Where possible, the affected populations are speculatively estimated. 43

The Appendix includes a few notes of interest not included in the appropriate text location.

APPENDIX

1. Note on additional activity generated in the power burst

From the Reactor Safeguard Committee Report.

F.P. activity after disruption $= \dfrac{0.1 \times \text{previous steady power in KW}}{(\text{time(sec) after accident})^{0.2}}$

Additional activity during run-away burst $= \dfrac{0.02 \times (\text{integrated burst in KW sec})}{(\text{time(sec) after accident})^{1.2}}$

Steady power $= 2.75 \times 10^{5}$ KW

For the 2×10^{11} calorie explosion, integrated burst $= 8.3 \times 10^{8}$ KW sec.

$\therefore \dfrac{\text{Additional activity}}{\text{Stored activity}} = \dfrac{600}{\text{time (sec)}}$

Our calculations refer generally to times in excess of one hour, so the additional activity is negligible in approximate calculations.

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[redacted]

APPENDIX (Continued)

2. Note on activity in the graphite moderator

Hanford graphite has specific activity = 0.032 curies/kg
of which 0.02 curies/kg is the gamma-ray activity,
and 0.002 curies/kg is C^{14}.

The total activity in a unit = 6.4×10^4 curies
This is negligible in comparison with stored fission product activity.

Predominant gamma emitters are: Eu^{152}, Sm^{153}, Fe^{54}, Fe^{59}, and unidentified rare earths.

3. Note on iodine deposition on vegetation

For stable iodine, Thomas and Hill (32) report a concentration of 0.8 µg I_2 per liter in air to give a deposit of 67 mg I_2/kg in alfalfa leaves in ~19 hours. In two hours, we can assume the concentration to have been ~7 mg I_2/kg. The same ratio holds for radioiodine, if the early radiation does not damage the plant's transfer mechanism. Therefore, 0.8 µc I^{131} per liter for 2 hours should give ~ 7 mc I^{131}/kg in leaves.

In the triangular danger zone of the "bad" case from burn-up, the predicted 80 µc F.P./liter gives by our empirical deposition rule, 16 curies/sq.meter = ~8 curies/kg of vegetation (assumes all the activity caught in a half-grown field of alfalfa). Of the atmospheric contamination, 1.1% is due to I^{131}. By rule of thumb we predict vegetation contamination of ~90 mc I^{131}/kg, about 12 times the Thomas-Hill value. Take the lower value and assume animals feed on such vegetation. The initial thyroid irradiation will be ~ 4000 rep/day. The I^{131} component alone will be hazardous. It will require 130 days decay time to reach the contamination level considered as the permissible permanent limit at Hanford (0.01 µc I^{131}/kg). The total radioiodine deposit will be 8 times that of I^{131} alone. By crude weighting of half-lives and disintegration energy, the total deposit is worth about twice the I^{131} in hazard.

Note that the agreement between 'D' for iodine and 'D' aerosols or particles is presumably fortuitous, and arises from the concentration factors for iodine reported by Thomas and Hill. The copious Hanford data on iodine deposition on vegetation has not yet been reconciled with the Thomas-Hill data. We would anticipate higher depositions than are quoted above. By scaling up the normal Separations Plant emission of I^{131} and the observed deposition at distances up to 50 miles, Gamertsfelder (31) predicts maximum deposition on the order of 400 mc I^{131}/kg. His assumptions on the time in which observed deposits are laid down leads to values about 4 times higher than those of the writer. This would give 100 mc/kg in agreement with the 90 mc/kg predicted in this report.

There appears to be an error of 1000 between the script and tables of the Thomas-Hill report. The script value has been used above.

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APPENDIX (Continued)

[redacted]

4. Note on leaching of activity from the ground

Wherever contamination is laid down by an active cloud (burn-up) or by the physical ejection of reactor material (blow-up), there exists the possibility of leaching of such activity into potable water sources. In all except the blow-up case, this effect is probably low compared with the primary contamination of water. It can be crudely estimated from the data given for ground filtration water systems. Low-level, long-continued water contamination of this type will be discussed in Part II. The general Hanford operating experience has been that whenever an area is accidentally contaminated, it is virtually impossible to remove the contamination by copious washing (exception: uranium). Conversely, if one wants the activity to remain in place, some fraction of it will be transported by one mechanism or another. This gloomy philosophy should be applied by the reader to the subject case.

5. Note on the acute toxicity of inhaled plutonium

For the rat, Abrams, et al[33] report

Exposure µg Pu/rat	8	24	70	210	500
Median Survival time (days)	203	154	67	24	26
Lung dose (rep)	2600	7200	15,000	29,000	72,000
Ratio Lung dose/bone dose	8	10	26	93	86

Taking the lung as 9% body weight in the rat, and 14% in man, and assuming all other factors equal, the comparable depositions in man would be 380 times greater. The "true" LD-50/30 is of the order of 80 mg, but 3 mg is a lethal dose. This should be compared with our current guess of 2 mg as the lethal deposition.

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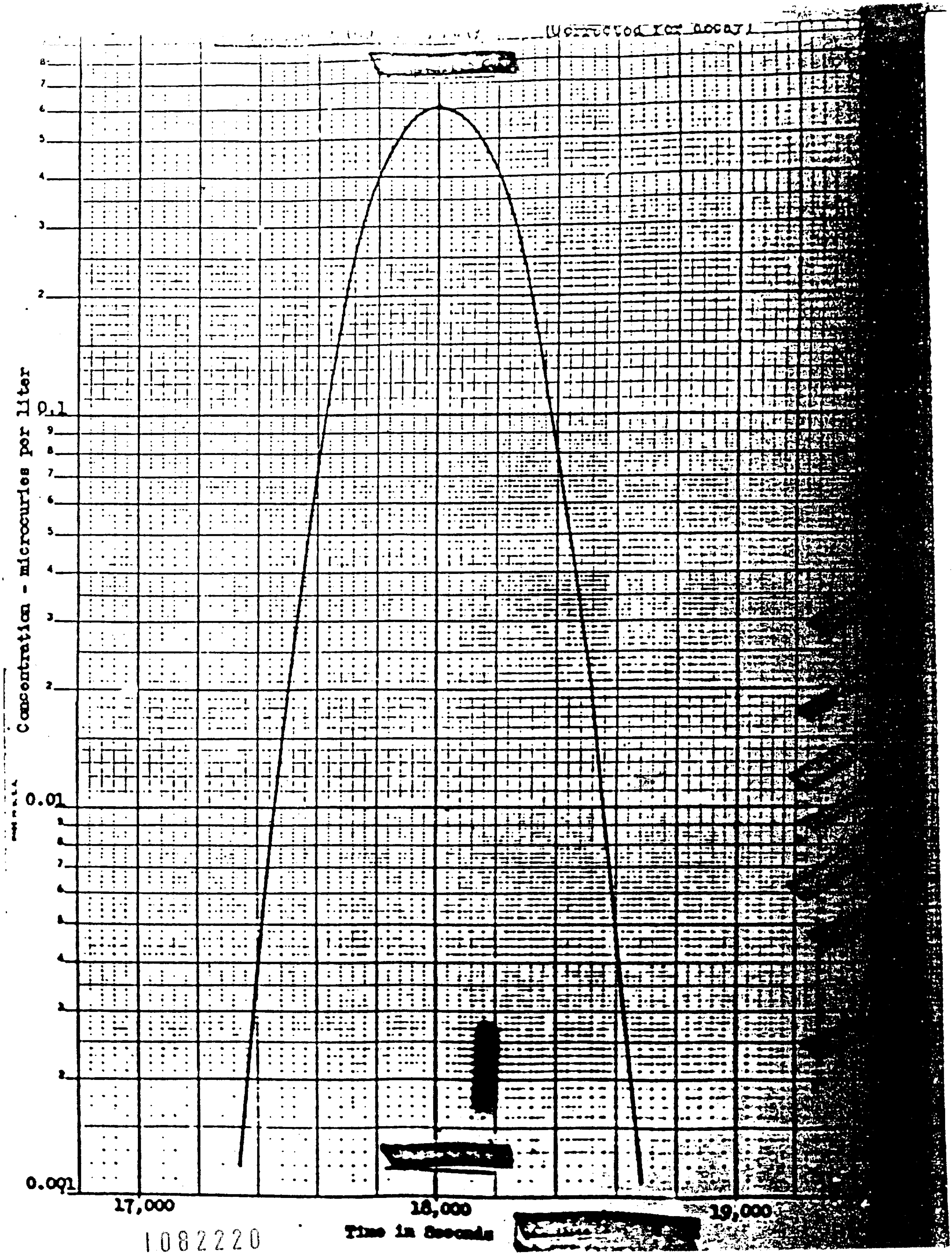
[redacted]


(Corrected for Decay)
[redacted]
Concentration - microcuries per liter
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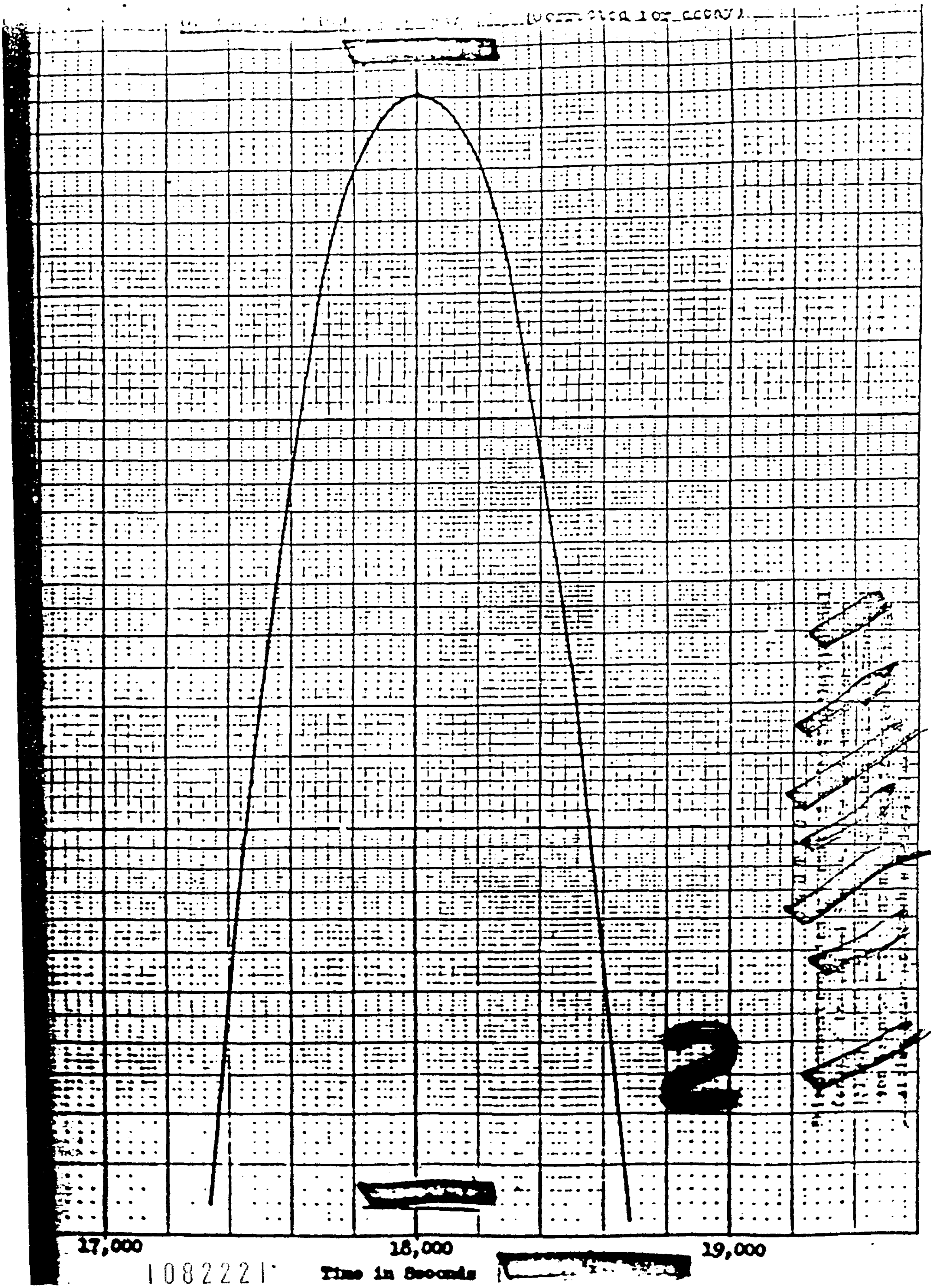
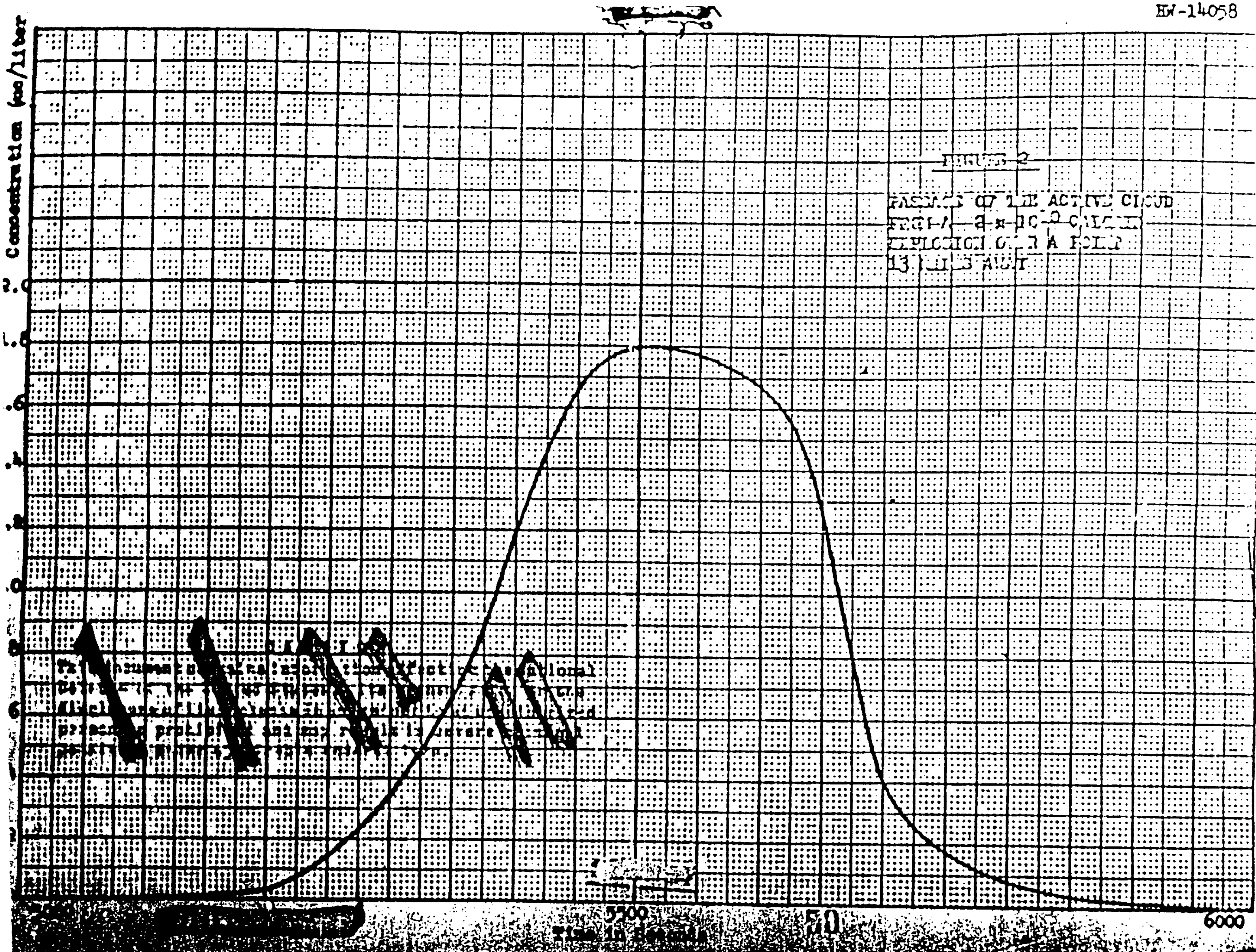
0.01
0.001
17,000
18,000
19,000
[redacted]
Time in Seconds
[redacted]

1082220



108222



1082222

[redacted]

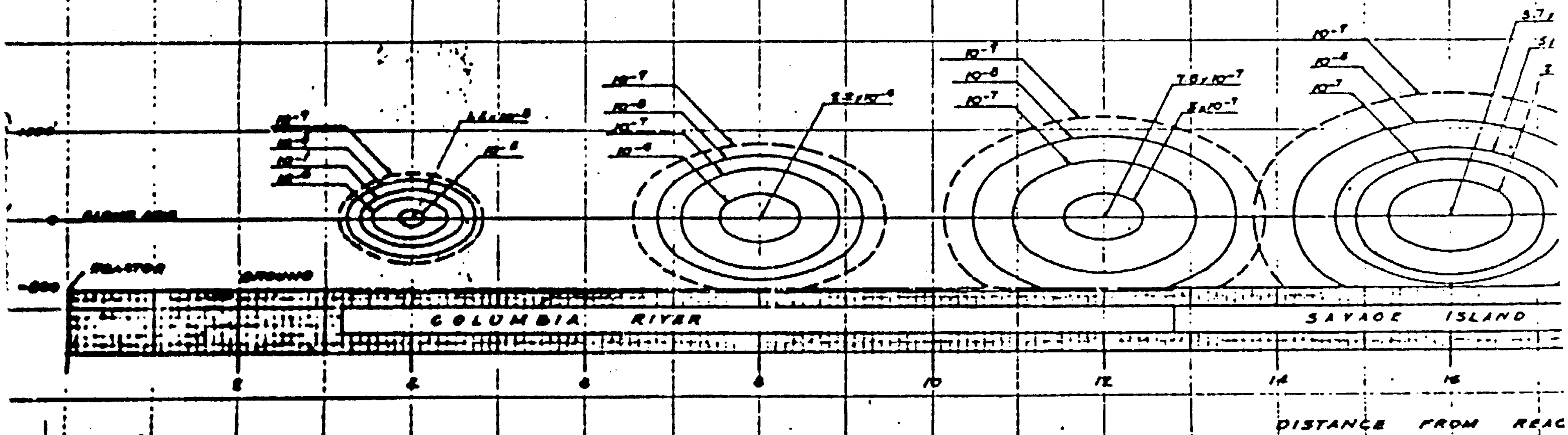
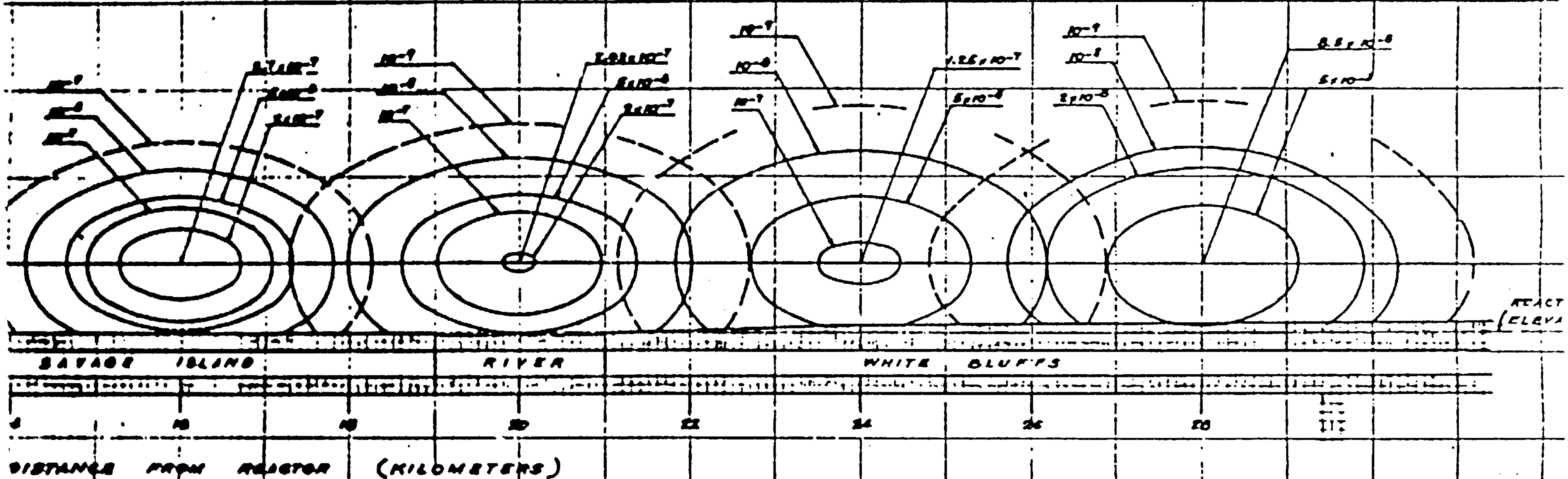


FIGURE 1

[illegible] OF A RADIOACTIVE CLOUD EMANATING FROM AN INSTANTANEOUS POINT SOURCE AND TRAVELLING AT 4 METERS/SEC.
INITIAL ACTIVITY IS 1 CURIE.
CONCENTRATION IN MICROCURIES PER LITER.

[redacted]

1082223



Topography in the direction of the prevailing wind shown for comparison.

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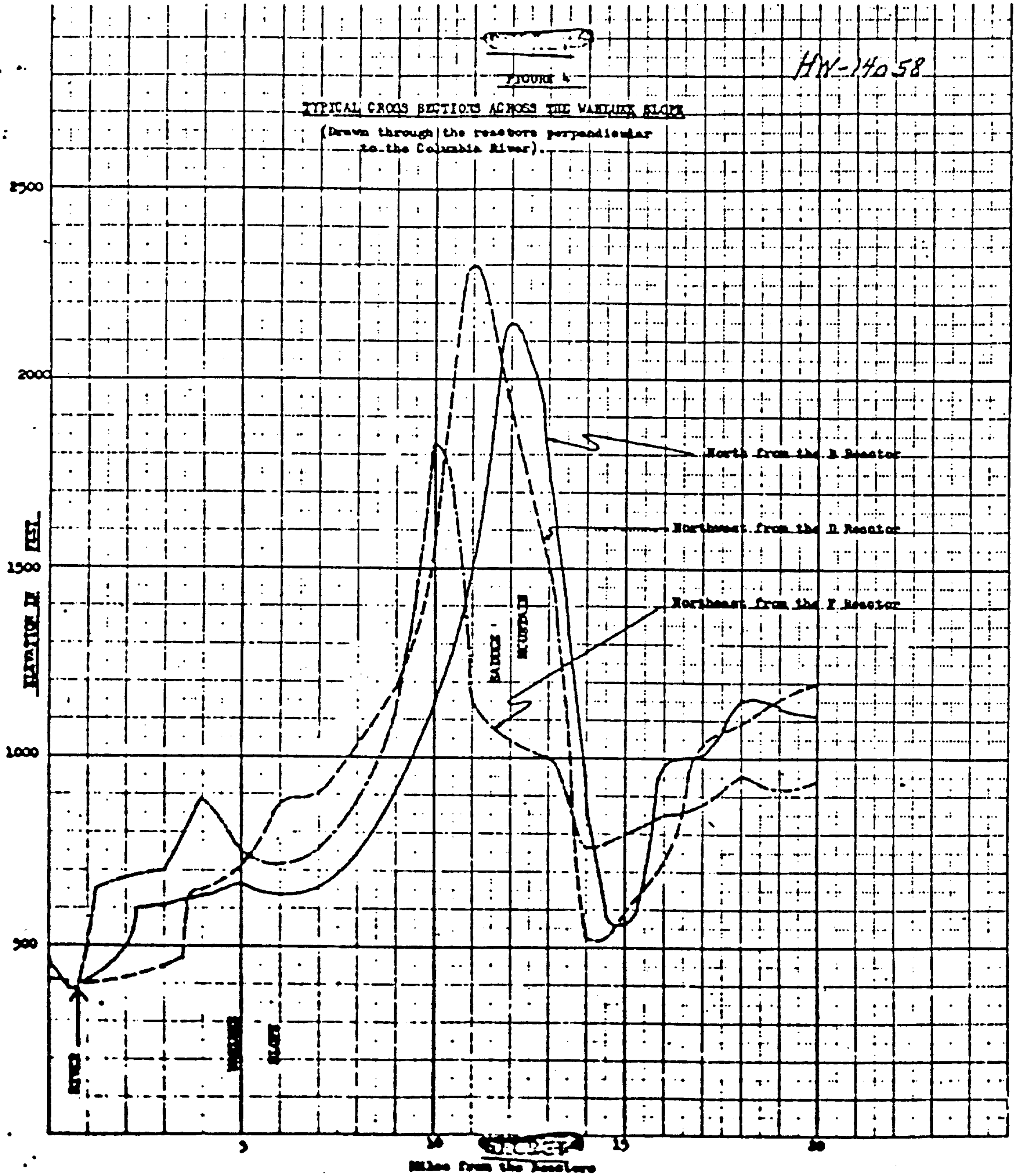
HW-14058

FIGURE 4

TYPICAL CROSS SECTIONS ACROSS THE WAHLUKE SLOPE

(Drawn through the reactors perpendicular to the Columbia River).



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