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C-84 Aircraft Reactors
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SOME HAZARD CONSIDERATIONS FOR A 100 MEGAWATT FUSED FLUORIDE

MARINE REACTOR

PREPARED BY:

Fred S. Dunning

John C. LeDoux

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DATE

For The Atomic Energy Commission

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PREFACE

In September, 1956, a group of men experienced in various scientific and engineering fields embarked on the twelve months of study which culminated in this report. For nine of those months, formal classroom and student laboratory work occupied their time. At the end of that period, these two students were presented with a problem in reactor design. They studied it for ten weeks, the final period of the school term.

This is a summary report of their effort. It must be realized that, in so short a time, a study of this scope can not be guaranteed complete or free of error. This "thesis" is not offered as a polished engineering report, but rather as a record of the work done by the group under the leadership of the group leader. It is issued for use by those persons competent to assess the uncertainties inherent in the results obtained in terms of the preciseness of the technical data and analytical methods employed in the study. In the opinion of the students and faculty of ORSORT, the problem has served the pedagogical purpose for which it was intended.

The faculty joins the authors in an expression of appreciation for the generous assistance which various members of the Oak Ridge National Laboratory gave. In particular, the guidance of the group consultants, W. B. Cottrell, F. L. Parker, and A. P. Fraas, is gratefully acknowledged.

Lewis Nelson

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The authors wish to express appreciation for the painstaking efforts of Mr. W. B. Cottrell who guided us to the completion of this study, to Dr. F. L. Parker who enlightened us on diffusion theory as applied to turbulent water, and to Mr. A. P. Fraas who provided the encouragement and driving force to make this report possible.

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ABSTRACT

This report is an analysis of the hazards associated with fuel and coolant leakage from a fused-fluoride marine reactor, of the Aircraft Reactor Experiment type. The consequences of contained and uncontained leaks and spills are analyzed and recommendations to minimize or eliminate the hazards are made.

Emphasis has been placed on the problem as it pertains to a moving ship in formation with other ships and the effect of depositing large quantities of radioactive fuel in a harbor or at sea. The doses to be expected and the shielding required are outlined. Working curves are provided from which Sutton's diffusion equations for an instantaneous point source and continuous point sources can be solved. Diffusion theory as applied to turbulent dispersal of dissolved radioactivity in water is presented.

The analysis made tends to indicate that sound engineering design will result in a safe reactor but the probability of a major marine accident must be considered.

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PART I

INTRODUCTION

Before a reactor can be constructed, an analysis of the associated hazards is required to evaluate the hazards associated with the operations of the reactor. A 100 Mw fused-fluoride reactor has been proposed as a propulsion unit for a ship of destroyer size. This is a new application for fused-fluoride reactors and therefore will require a more detailed study than is shown in this report.

The design proposal was made by an ORSORT study headed by K. H. Dufrane during the summer months of 1957.⁽¹⁾ This hazard analysis had to be made concurrently with the development of the design because of the limited time available. Since the design did not firm up until late in the summer, this hazards analysis does not always follow the design in detail. Therefore this report is limited in scope. It is mainly concerned with the accidental release of radioactivity. Special work was done on diffusion of activity in the atmosphere and in water. The reader will note that the report covers, in the main, rather extreme accidents. This fact must be borne in mind in order that the conclusions not be erroneously interpreted.

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PART II

FUEL AND COOLANT LEAKAGE

1. Introduction

One of the greatest possible hazards that might occur during the operation of a fluid fuel reactor is a fuel spill. Leakage at faulty joints, corrosion leakage, or rupture of the shell from thermal or shock stresses are possible, and hence this problem is of prime importance. The problem of gaseous leakage also must be considered. These gases will, of course, be freed in the event of any type of a liquid spill, but they may escape from the containment vessel without a liquid spill and be undetected for some time. The leakage of the secondary coolant which becomes activated during its course through the reactor must also be considered. The problem can be divided into two areas of consideration:

First, what is the dose rate received by personnel outside of the reactor compartment from the various leakage possibilities when the compartment remains intact?

Second, what is the dosage to the surrounding area should the reactor compartment be ruptured and these radioactive substances be released beyond the confines of the ship?

2. Gaseous Fission Product Leak-Contained

2.1 Introduction: Gas leakage is the most likely hazard which might occur in this type of reactor. The stable and radioactive gases are being produced continuously while the reactor is operating and some are produced as daughters of decay fission products. These gases can escape

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through faults or cracks in the containment vessel even though no liquid fuel escapes. If the gases are not continuously removed, the pressure in the system will continue to build up due to the production of the stable isotopes of Xe and Kr and it is this pressure which will force the gases out should a fault exist in the vessel.

2.2 Fission Product Decay Chains: In order to determine the dose rate due to the fission product gases, a study was made of all the decay chains which could possibly be present in the gaseous state. Over 40 chains were studied and the dominant ones were plotted (Figs. B.1 and B.2, Appendix B). For these calculations it was assumed that the elements that would be gaseous under the operating conditions of the reactor (1250°F , 100 psi) would be Br, Kr, I, and Xe, even though experience with the Aircraft Reactor Experiment⁽²⁾ indicated that only Xe and Kr were present in the off-gas. Further, a very thorough study was made of all the daughter products of these gases which could build up and become significant in time. Table B.1, Appendix B, is a list of the isotopes which were considered. Fig. B.1 is a plot of the significant products considering that Br, Kr, I, and Xe remain gaseous upon escape from the reactor. Fig. B.2 is a plot of those products which are significant when only the Kr and Xe remain gaseous as expected from previous experience.⁽²⁾

It is apparent from the first figure (B.1) that only I^{131} and Xe^{133} are important after a few days. The only product with significant build-up is La^{140} and its maximum buildup is well below the I^{131} . If only Kr and Xe escape, which is the more reasonable case, then the only significant long-term product is La^{140} , since Xe^{133} with its 0.081 mev gamma can be neglected. La^{140} has a 3.0 mev gamma.

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2.3 External Dose Rates: Since the relaxation length of gammas in air is much longer than the width of the compartment, the volume source was converted to a surface by multiplying the volume source density by the width of the compartment;⁽³⁾ i.e., 1000 cm. Although this is an approximation, it is justified since only order-of-magnitude results are desired. Other conservative approximations have been taken in order to simulate the worst possible case. Based on the above assumptions the dose rate to personnel on the outside of the reactor compartment would be:

2.6×10^6 rads/hr (t=0) for volatile gases;
i.e., Br, Kr, I, and Xe

9.2×10^5 rads/hr (t=0) for noble gases;
i.e., Kr and Xe

It is proposed by the design group⁽¹⁾ that the reactor compartment be shielded with 6 in. of lead for protection against the radiation from the secondary coolant. If this is done, the dose rate will be reduced as follows:

2.1×10^3 rads/hr (t=0) for volatile gases

7.9×10^2 rads/hr (t=0) for noble gases

The volatile gases will decay by a factor of 10 in one day and thereafter decay with a half-life of eight days. If Xe¹³³ is neglected, since it only has a 0.081 mev gamma, the noble gases will decay by a factor of 300 in one day and then will remain fairly constant until the fifth day due to Ia¹⁴⁰ buildup. Thereafter, they will decay with a half-life of 40.2 hr.

2.4 Shielding: It is of interest to note that the shielding required if these gases do escape into the reactor compartment would be

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30 cm of lead. This is impractical since it would require an additional 500 tons of weight. The high probability that such leaks will occur makes it mandatory that positive means be taken to expel these gases from the compartment. This can be done by specifying a double shelled compartment with an excess pressure in the annulus. Any leaks that occur would then be from the annulus into the inner compartment. The inner compartment could then be exhausted beyond the ship.

2.5 Disposal of Fission Product Gases: The gases that are generated in the reactor can not be exhausted without holdup. They could be discharged into disposable containers which could be dumped at sea. It is not recommended that they be held up and then exhausted to the atmosphere unless the activity discharged is less than 1.0 curie/sec. (See Appendix C.) Furthermore, weapons which "home" on radioactivity might be easily constructed.

3. Liquid Fuel Spill-Contained

3.1 Introduction: For the purpose of analyzing the radiation hazard due to the escape of liquid fuel from the reactor containment vessel, it was assumed that the fuel solidified within a short period of time and the reactor compartment remained intact. For this problem the doses received will be in addition to those due to fission product gases. In order to define the problem further, calculations are based on a reactor that has been operating at constant full power of 100 Mw. The activity is due then to the fission product decay gammas, since any spill reduces the problem to the case of the shut-down reactor.

3.2 Fission Product Decay Gammas: First a study was made of the decay gammas of U^{235} from the data in NDA-27-39.⁽⁴⁾ The information was then compiled and plotted (Fig. A.1, Appendix A). It can be noted from this figure that the time of operation of the reactor has little effect on the initial energy flux. The decay is faster for the shorter periods of operation. To be conservative, it is assumed that the reactor has been operating sufficiently long so that the fission products have reached their equilibrium values at the time of the accident. As a means of comparison with other similar data the Wigner-Way formula⁽⁵⁾ was also plotted on Fig. A.1. The data are limited by the following factors:

- (1) No gamma photons less than 0.1 mev were considered.
- (2) Only known gammas that contribute significantly between 30 min and 1000 hr were included.

The total energy of all decay gammas from the plotted curve for infinite operating time yields a value of 2.17×10^{10} mev/watt-sec at $t=60$ min. Since the data are good only for times greater than 30 min, the value at zero time was calculated.⁽⁶⁾ This yielded a value of 2.2×10^{11} mev/watt-sec. It is felt that this value is reasonable and accounts for those short-lived products which decay out within 30 min. Whenever zero time values were required, this value of 2.2×10^{11} mev/watt-sec was used.

3.3 External Dose Rate: In order to pose a practical problem, it was postulated that the reactor compartment would be the fire room space of a class 930 destroyer. This space is about 40 ft x 40 ft x 30 ft or 10^9 cm³ in volume. The reactor would probably be placed in the center of this space. The distance to the nearest bulkhead would be approximately 500 cm. This is the attenuation distance that is used when calculating doses due

to a fuel spill. The bulkheads were assumed to be 1/4-in. steel plate.

With the above criteria, the dose rate to personnel immediately adjacent to an unshielded reactor compartment would be:

$$1.04 \times 10^6 \text{ rads/hr (t=60 min)}$$

It is proposed⁽¹⁾ that this compartment be shielded with 6 in. of lead.

In this case the dose rate would be:

$$390 \text{ rads/hr (t=60 min)}$$

3.4 Shielding: Associated with the dose problem is the shielding that would be required to reduce the dose to allowable limits. If a maximum emergency dose rate of 1 rad/hr is assumed, the thickness of lead required to protect against a complete fuel spill would be:

$$x(100\% \text{ spill}) = 30 \text{ cm (Appendix A)}$$

If an adjacent compartment at least 5 ft wide were flooded, the shielding due to this water and the proposed 6 in. of lead would reduce the dose rate to 2 rads/hr. In the first case, the additional weight required over that resulting from the 6 in. lead shield would be about 200 tons. The flooding of the 5-ft compartment would add a temporary weight of 300 tons. It would not be feasible to flood the reactor compartment in case of a fuel spill because sufficient fuel would go into solution to provide a dose rate higher than that resulting from the flooding of the adjacent compartment. Assuming only 1% of the fuel went into solution and were uniformly dispersed, the dose rate through the 6-in. lead would be 7 rads/hr. The 1% assumption is conservative since experience with this type of fuel⁽⁷⁾ indicates that when it is very hot, it breaks up into fine particles upon contacting water. This case would allow good contact with the water and allow much of the fuel and fission products

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to go into solution. In addition, the fine powder would tend to be suspended in the water.

3.5 Dump Tank: For operational reasons, this type of reactor⁽²⁾ usually requires a tank into which the fuel may be dumped to prevent damage to the reactor. Assuming rectangular dimensions and an allowed dose rate of 0.025 rads/hr, this tank would require about 40 cm of lead for a shield. This would weigh about 20 tons. This tank would be useful when performing service or maintenance on the system since the fuel could be dumped and the repair effected. Remote handling equipment might be required for some such work.

3.6 Containment of Spill: Should an accident occur which allowed the bulk of the fuel to escape into the reactor compartment, it would be desirable to contain the spill in as small an area as possible. A grid network could be provided on the deck of this compartment which would contain the fuel spill. This network should also have heat transfer characteristics which would convey the afterheat to the sea and surrounding metal so that damage to the ship's hull would not occur.

4. Gaseous Cloud Leak

4.1 Introduction: A cloud of radioactive material released instantaneously into the atmosphere could irradiate personnel downwind in the following ways:

- (1) Externally during passage of the air-borne cloud.
- (2) Internally by inhalation of air-borne material.

Alpha, beta, or gamma radiation might be involved in each case. However, most accidentally released fission products would be primarily beta and

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gamma emitters. The range of the alpha emitters is such that their overall contribution can safely be neglected.⁽⁸⁾

External beta radiation is received only from emitters within a few meters of the receiver owing to the short range of beta particles in air. Once the cloud has achieved sizable proportions the dose from beta radiation would be due to the local concentration and not the entire cloud. Gamma radiation, on the other hand, has a mean free path of roughly 100-200 m in air.^{(9),(3)} The gamma dose then must be the integrated dose from the entire cloud. In both cases the dose is integrated with respect to time.

Radiation exposure from an accidental release would be influenced by a number of factors such as:

- (1) The composition and history of the radioactive isotopes in the cloud.
- (2) The initial height of the cloud.
- (3) Meteorological parameters wind speed, diffusion coefficients, stability, etc.

4.2 Composition of Cloud: The composition of the cloud is a function of the radioactive isotopes of the reactor fuel which are vaporized. For the purpose of considering an extreme accident, it is assumed that all of the fuel is vaporized and the cloud is then a homogeneous mixture of all the fission products. The overall decay of these products depends on the operating history of the reactor prior to the accident. Except for a power excursion, the most conservative assumption is that the reactor had been operating at 100 Mw for "infinite" time prior to the accident.

4.3 Effect of Power Excursion: A comparison of the power excursion to a release at normal power reveals that both types of disaster yield

initial results of the same order of magnitude. The fission product activity produced during this excursion decays with time according to $t^{-1.2}$ (10) where t is in seconds. On the other hand, the activity from normal power operation decays according to $t^{-0.2}$ (8). The power excursion activity dies out quickly and within 10 sec it is only about 10% of the total activity. Since most practical problems are concerned with times much greater than 10 sec, only the activity from normal power operation has been considered hereafter.

4.4 Height of Cloud: In order to analyze the instantaneous cloud case and compare the results of the cold (low) and hot (high) clouds, the height that a hot cloud could be expected to rise was calculated. It was assumed that the reactor had been operating at 100 Mw and 1,250°F when a total spill occurred. The event which caused the rupture of the reactor vessel also ruptured the ship's hull allowing the gases to escape. This spill would make available 3×10^6 Btu from the latent heat and 2×10^6 Btu/hr from the afterheat. The heat would be released slowly to the air and then only a fraction of the total would actually be effective in heating the compartment air and radioactive gases before they escaped. Most of it would go into heating the ship's hull and the reactor metal. Assuming that 5% of the total heat available does go into heating the gases while they are still in the compartment, the temperature rise will be 134°C and the height of the hot cloud will be 100 m.

4.5 Meteorological Parameters: The accuracy with which theoretical analysis of atmospheric diffusion simulates real diffusion rests entirely on the selection of the proper mean values of the meteorological parameters selected for a particular case. Sutton's diffusion formulas⁽¹¹⁾ have

been successful largely due to the introduction of a stability parameter and an effective diffusion coefficient which are based in part on experimental data. Even so, an assumption that parameters selected for a particular location will prevail for a position 10,000 or 1,000 or even 100 m downwind may be grossly in error. It is this uncertainty which makes an answer that can be considered correct within an order of magnitude acceptable.

For the purpose of this report, conservative results are desired. Therefore, parameters have been selected that will yield higher doses than those that would normally result. Table C.1, Appendix C, is a list of these parameters for both day and night conditions used throughout this report.

4.6 External Dose: The external dose was calculated using a method proposed by Hurwitz.⁽⁹⁾ This method yields a dose in rads which was converted to concentration units, i.e., curies-sec/m³ by dividing by 0.25⁽²⁹⁾ so that curves similar to the internal dose curves could be placed on the same figures. (See Figs. C.1 and C.2, Appendix C.) The Hurwitz method is based on Sutton's formula and assumes a finite cloud with an effective radius which is a function of distance from the initial origin. The formulas postulated give the upper limit of the dose which a person may receive at a given distance from the accident. Allowance is made for the different effect of gamma and beta rays as sources of external radiation. Using these curves (C.1, C.2, Appendix C) the external dose is calculated by:

$$TID = Q/\bar{u} \cdot 10^{10} \text{ curies-sec/m}^3$$

where TID = total integrated dose

Q = curies released

$\bar{u}$ = the mean wind speed

n = a non-dimensional exponent

This may be converted to rads by multiplying by $0.25^{(29)}$

To indicate the values that these curves yield, the following table is included in this section. The wind speed is 5 m/sec. The activity released is 8.2×10^7 curies.

TABLE 4.1

EXTERNAL DOSE-RADS (No Decay)

<u>Distance Miles</u>	<u>Night Hot Cloud</u>	<u>Cold Cloud</u>	<u>Day Hot Cloud</u>	<u>Cold Cloud</u>
0.5	2600	8200	320	500
1.0	1600	4100	130	200
5.0	320	500	6	9
10.0	160	160	3.2	4
20.0	65	65	1.0	0.8
50.0	12	12	0.2	0.3

The above table and the curves in Appendix C-I and C-II do not make any allowance for decay, fallout or washout. A separate section in Appendix C with appropriate curves is included to allow correction for these factors.

4.7 Internal Dose: Using the parameters listed in Table C.1, Appendix C, the internal dose for a hot cloud was calculated using Sutton's instantaneous point source formula.⁽¹¹⁾ A height of 100 m was assumed. For the cold cloud, a height of 10 m was used. The result of these calculations was the formulation of working curves from which the TID can easily be obtained. These curves, Fig. C.1, C.2, Appendix C, plot

distance against "m", the exponent of 10 such that:

$$TID = \frac{Q}{\bar{u} 10^m} \quad \frac{\text{curies-sec}}{m^3}$$

Q = curies of activity released

$\bar{u}$ = wind speed

To illustrate the use of the curves, various situations are postulated as problems and the solutions to these problems are worked out in detail in section IV of Appendix C.

To illustrate the values that these curves yield, the following table is included in this section. A wind speed of 5 m/sec was used and a Q of 8.2×10^7 curies was assumed. This is the total activity of a 100-Mw reactor at one day after shutdown. (29)

TABLE 4.2

INTERNAL DOSE-RADS* (No Decay)

<u>Distance Miles</u>	<u>Hot Cloud</u>	<u>Night</u>	<u>Hot Cloud</u>	<u>Day</u>
		<u>Cold Cloud</u>		<u>Cold Cloud</u>
0.5	neg	[5,100]	32.5	420
1.0	neg	[3,200]	41.0	102
5.0	32	[260]	6.5	6.5
10.0	41	[102]	1.7	2.1
20.0	20.5	[26]	0.5	0.7
50.0	5.3	5.3	0.2	0.2

* Rads were obtained by multiplying the dose in curies-sec/m³ by 0.25.

This is an aggregate dose to all organs averaged over 30 isotopes. (29)

5. Release of Fission Product Gases from Stack

5.1 Introduction: One of the attractive features of a fluid fuel reactor is the comparative ease with which fission product gases can be separated from the fuel and ejected to the atmosphere. The decrease in Xe^{135} reduces the required fuel concentration and therefore aids reactor safety. The release of these fission product gases, however, entails a radioactive hazard due to their disposition outside the ship.

For a land type of reactor such as the Homogeneous Reactor Test⁽¹²⁾ or the Aircraft Reactor Experiment,⁽²⁾ it has been found necessary to provide for holdup of these gases until sufficient decay has taken place to reduce the dose to tolerable levels. Aboard ship, however, it is possible that holdup may not be required due to distance between ships in formation and their maneuverability.

5.2 Continuous Release from Moving Stack: To investigate this problem, it was assumed that the gases would be exhausted continuously from the stack of the ship by dilution with air. Table C.1, Appendix C, is a list of the various meteorological parameters that were used in the calculations.

Sutton's equation for a continuous point source⁽¹¹⁾ was modified to allow for the relative wind created by the ship's movement. It is this relative wind which determines the effective stack height of the plume and also the relative direction of the plume travel. The modified formula is:

$$X = \frac{q}{\pi C^2 \bar{w} d^{2-n}} \exp \left[\frac{-b^2}{C^2 d^{2-n}} \right]$$

X = the concentration in curies/ m^3 at a fixed distance "d" from the stack

h = effective stack height

C = Sutton's effective diffusion coefficient

q = the release rate in curies/sec

$\bar{w}$ = the relative wind speed, m/sec

n = Sutton's stability parameter

Using this equation for various wind speeds and fixed distances, Figs. C.6 and C.7 were plotted for day and night conditions, respectively. It is apparent from these curves and the typical problems worked out in Appendix C-IV that only when reactor-equipped ships are widely spaced and positioned correctly could fission product gases be discharged continuously without holdup. Problem 4, Appendix C-IV, indicates that a maximum dose rate of 1 rad/hr will be received at approximately 30 m from a 100-Mw reactor if the discharge rate is 2.0 curies/sec. It is possible to discharge at a higher rate if accompanying ships are in safe crosswind positions. Each case must be calculated at the time with curves similar to C.6 and C.7 of Appendix C.

5.3 Downwind Dose: To indicate the relative values obtained with the curves in Appendix D for the continuous exhaust problem, the following table is included in this portion of the report. The dose rate is in rads/hr received from a ship directly downwind. An arbitrary rate of 100 curies/sec was selected and the wind speed of 5 m/sec was assumed.

TABLE 5.1

DOWNWIND DOSE rads/hr FROM MOVING STACK
DISCHARGE RATE-100 curies/sec, RELATIVE WIND-5 m/sec

<u>Fixed Distance</u> <u>From Stack-Meters</u>	<u>Night</u>	<u>Day</u>
500	neg	0.45
1,000	neg	0.45
5,000	0.57	0.05
10,000	0.54	0.014
10^5	0.18	$2.3 \cdot 10^{-4}$

The values in this table and Figs. C.6 and C.7, Appendix C, do not allow for decay or deposition. Appendix C-III outlines the method whereby these factors can be included in the calculations.

6. Secondary Coolant Spill

6.1 Introduction: The secondary coolant (NaF , LiF , and BeF_2) is circulated through the primary heat exchanger which is located within the reactor vessel. It then passes outside the reactor vessel to the secondary exchanger. The secondary coolant is irradiated by the neutron flux from the active reactor core and also by the delayed neutrons from the fuel in the exchanger. The maximum thermal neutron flux will be on the order of 10^{15} . The flux in the exchanger area would normally be 10^{11} - 10^{12} but it is planned to shield this area from the direct flux by the use of boron. This will reduce the thermal flux to 10^7 . Preliminary estimates indicate that the delayed neutrons will not contribute significantly to this flux. Based on these estimated flux levels, the activity of the

fluid has been calculated and the dose rates to personnel as a function of distance and fluid volume have been computed.

6.2 Activation of Fluid in Neutron Flux: A complete analysis of the activation of fluid in a neutron flux is given in Reference (6). In this particular case only the Na and F have significant activation. Na has a 2.76-mev gamma with a half-life of 15 hr. F has a 2.2-gamma but only a 15-sec half-life. The initial activity of F and Na are of the same order of magnitude but the F dies out quickly and only the Na offers significant long-time hazard. Since the flux level is only estimated and may be off by a factor of 10, the activity of the F can be neglected. For Na the equation reduces to a simple form since $\phi \sigma \ll \lambda$ and $\lambda T \ll 1$; at equilibrium the activity would be: (6)

$$A = n \sigma \phi \frac{t'}{T}$$

where:

$$A = \frac{\text{photon}}{\text{sec-cm}^3}$$

$$n = \text{No. of atoms/cm}^3$$

$$\sigma = \text{Absorption cross section for thermal neutrons (barns)}$$

$$\phi = \text{Neutron flux}$$

$$t' = \text{Time in flux}$$

$$T = \text{Total circulation time}$$

The total activation is the integrated sum of the activation for each neutron energy group since the absorption cross section is a function of neutron energy. Sodium has a resonance peak in the epithermal range and it was found⁽¹⁾ that the activation was due mostly to these epithermal neutrons.

6.3 Composition of Coolant: The coolant composition by compounds and elements is as follows:

TABLE 6.1

COMPOSITION OF COOLANT BY COMPOUNDS

<u>Compound</u>	<u>Mole %</u>	<u>Wt %</u>
NaF	30	30.52
LiF	20	12.56
BeF ₂	50	56.92

TABLE 6.2

COMPOSITION OF COOLANT BY ELEMENTS

<u>Element</u>	<u>Mole %</u>	<u>g/cm³</u>	<u>Atoms/cm³</u>
Na	12.0	0.329	0.861×10^{22}
Li	8.0	0.066	0.573×10^{22}
Be	20.0	0.215	1.436×10^{22}
F	60.0	1.360	4.320×10^{22}

6.4 Dose Rate from Spill: The machine calculations of this activation⁽¹⁾ indicated that the activity of the secondary coolant would be about 4,000 curies. Since the volume of the coolant is $4 \times 10^6 \text{ cm}^3$, the external dose at 1 m that would be received from a spill of this fluid in the compartment would be:

<u>Volume Spilled-cm³</u>	<u>Dose-rads/hr</u>
10	0.01
100	0.1
1,000	1.0

6.5 Shielding: Since the secondary coolant passes outside the unit shield of the reactor, some means must be taken either to shield the pipes carrying the fluid or shield the compartment. It is estimated⁽¹⁾ that a 6-in. lead shield on the overhead and rear bulkhead would be sufficient. The forward bulkhead joins a ballast tank and therefore no shielding would be required if the ballast tank were flooded. The weight of this 6-in. lead shield would be approximately 200 tons. This is a large amount of weight, and although it may be possible to incorporate this shield in the ship's design, it is recommended that more emphasis be placed on reducing the neutron flux in the primary heat exchanger so that this secondary shield can be reduced in weight or removed altogether.

7. Release of Fission Products in Water

7.1 Introduction: The hazard which has the lowest probability of occurring is the release of a substantial quantity of molten fuel or coolant beyond the confines of the ship. It is difficult even to assume a set of circumstances which would rupture the ship's hull, the primary reactor shield, pressure vessel and finally the containment vessel and then allow the fuel, still in a molten state, to enter the sea. Although the probability is low, the consequences of such an event are investigated.

7.2 Solubility of Fission Product Gases: The initial reactor design provided for gas accumulation above the reactor fuel inside the pressure shell with provision for periodic bleeding to a disposable storage container. For one week's operation at 100 Mw, this accumulation amounts to about 30 moles of gas, of which 80% is Xe.

If the reactor were ruptured, the accumulated fission product gases

would be the first radioactive material to escape. This hazard has been examined.

Assuming pure water at 46°F , Henry's Law constant, $k = 0.555 \times 10^7$,⁽¹⁴⁾ release of the gas at a depth of 36 ft, and neglecting the partial pressure of the water, a requirement of $3,870 \text{ ft}^3$ of water to dissolve 36 moles of Xe was found. At a lesser depth and in sea water this volume requirement will be increased.

For a 36-ft deep channel, a radius of 6 ft is required to approximate this volume. The gas, if released suddenly, will accelerate to the surface by reason of density difference and the opportunity to dissolve will be restricted. Therefore, it is extremely unlikely that this amount of gas will be dissolved and a gaseous cloud is probable at the surface.

The quantity of gas released in a rupture might be lessened by frequent bleeding to the disposable container with provision for one-way flow only.

7.3 Molten Fuel: Molten fuel may be exposed to the waters of the ocean or harbor only as the result of an extreme accident. Analog computer studies show that the reactor is stable.⁽¹⁾ Assuming the control system and operating procedures to be soundly designed, the accident of interest requires rupture of the reactor by some external means. Rupture of the pressure vessel by collision would require penetration of the hull, reactor compartment, pressure shell, shield and reactor pressure vessel. Bomb, torpedo, or sabotage damage might rupture the pressure vessel but would require precise placement.

If the ship were to sink, the reactor pressure vessel or dump tank might be ruptured as a result of the combined afterheating, heat transfer, and related stress problem. This is based on the assumption that all power

machinery and mechanically driven heat transfer systems will cease to operate upon submergence.

A special test to determine the ability to transfer afterheat from a reactor vessel to water was performed at the Oak Ridge National Laboratory. (7) It was concluded that the rate of heat transfer through the center of the bottom of a 1-ft radius spherical test tank (Inconel, 5/8 in. thick) was too small to remove the assumed 3.5 Mw of afterheat.

In order to reduce this possible hazard it is recommended that provision be made for the removal of afterheat in the event of sinking. If incorporated, the probability of releasing reactor fuel might be reduced to one involving only direct damage to the reactor. The design could allow for pressure-actuated dumping into a dump tank designed such that natural convection of water would result in low enough temperatures to insure that the fuel was confined. The attitude; i.e., pitch and roll of the ship, must be considered in the design.

7.4 Pressure Release of Secondary Coolant System: A rupture of the reactor pressure vessel is possible if there is no provision for relieving excessive pressures in the secondary coolant circuit; i.e., the circuit between the reactor and the boiler. Steam at high pressure might enter the secondary system via a failure of a secondary heat exchanger tube. The pressure would be transmitted to the primary heat exchanger in the reactor. The primary heat exchanger might then rupture and an abnormally high pressure would be applied to the reactor pressure vessel which might also rupture. (Design of the reactor pressure vessel is assumed as based on about 100 psi maximum pressure.)

It is recommended that frangible diaphragms or pressure relief valves

of sufficient capacity be incorporated into the primary coolant system, near the boiler, in order to eliminate this potential hazard.

7.5 Molten Fuel in Water: Speculation on what happens if a molten fluoride fuel becomes exposed to water depends to a large extent on assumptions. It is known, however, that the heat transfer is rapid and that the fuel solidifies into small crystals having the texture of fine powder. (7)(15) The same is assumed for the primary coolant which is also a fluoride.

The solubility of the individual compounds is shown in the Table 7.1 below. (17)

TABLE 7.1

SOLUBILITY OF COMPOUNDS USED IN FUEL AND COOLANT (16)

<u>Compound</u>	<u>Solubility, g/100g</u>
BeF_2	∞
LiF	0.27
NaF	4.22
ZrF_4	1.39, decomposes
UF_4	Insoluble

Zirconium fluoride decomposes and forms anhydrous zirconium oxide which is less soluble than the other compounds. Thus it forms a protective coating which restricts solubility of the other constituents.

The fuel and coolant are chemically stable in the presence of water and no appreciable exothermic chemical reactions are expected. (16) Both fuel and primary coolant are classed as insoluble in water.

It is deduced, therefore, that the dumping of the reactor fuel in water will involve only the uncontrolled release of radioactive fission products. Under water, all the fission products are assumed to go into solution where their concentration is governed by diffusion processes. This behavior is believed similar to the following examples of turbulent eddy diffusion.

- (1) Fluorescein Dye: ⁽¹⁸⁾ Several pounds released at 50 ft under water did not become visible at the surface. Fifty gal deposited in 2.5 min at a depth of 17 ft diluted by a factor of 10^5 in 15 min and 10^6 in 60 min.
- (2) Ferrous Sulphate and Sulphuric Acid: ⁽¹⁸⁾ Three thousand tons of ferrous sulphate and sulphuric acid were mixed to a density of 1.25 and discharged in a single operation into New York harbor. A dilution of 10^3 occurred within a few hundred yards to the density of sea water. In 12 hr a dilution of 10^8 was observed. The acid did not diffuse lower than 100 ft where the density was 1.021.
- (3) Latent and Afterheat: Upwelling by one megacurie heat dissipation contributes to dilution by making the water move, ⁽¹⁸⁾
- (4) Harbor Flushing: A dilution of 10^6 was observed in the first two tidal cycles of the Delaware River model. Thereafter, 28 tidal cycles were required to reduce activity by a factor of two. ⁽¹⁹⁾
- (5) Diffusion: ⁽¹⁹⁾⁽²⁰⁾ The diffusion rate varies as the distance downstream. The diffusion pattern is independent of velocity but expands more rapidly as velocity increases.

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7.6 Diffusion Coefficients: It is believed by the authors that turbulent eddy diffusion phenomena, as applied to soluble radioactive materials, may be likened to diffusion of dye marker on the ocean where diffusion coefficients are determined from photographs as a function of radius and time. This consideration fixes the upper limit of the diffusion coefficient at about 500 to 1,000 cm^2/sec for radii less than 200 m. Vertical diffusion coefficients vary from 1 to 300 cm^2/sec by experiment and are aggravated by variation of velocity with depth. In fact, the magnitude of the turbulent eddy coefficient tends to follow the magnitude of the velocity. (21)

The graphs and examples shown in Appendix D, therefore, are believed to be reasonable as tools for estimation of dose rates.

7.7 Currents and Tides: The mechanism of currents and tides in a harbor deserves comment. (22) The water flows from a bay into the ocean because of the continuous water entry into the bay and the slope of the bottom. As tides come in, it is known that salt water, because of its greater density, merely slides in under fresh water, raising its height and effectively holding up available potential energy.

The dispersion of this dissolved radioactive material in a harbor might be likened to a cumulus cloud in the atmosphere. The cloud is well defined and the high turbulence is restricted to the region inside.

As applied to dumping large quantities of molten fuel in water, it is believed that the region of turbulence will also be well defined. Further, dispersion in harbors is of concern because of their low velocity currents and large areas. Therefore, a radioactive "cloud" of dissolved materials is expected to move and disperse slowly.

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If an accident were to occur at low tide, it is expected that the "cloud" of radioactivity in water would merely be moved about the harbor until sufficient tidal currents could sweep it out to sea where mixing would be rapid and attenuation of dose rate on the surface would be great. There is possibility that the "cloud" in water will stagnate in some location in the bay or in the ocean. (23) Also, most harbors do not flush, or change water appreciably.

There will be some mixing by tidal action of the salt and fresh water with a tendency for the fission products to attach to plankton, to dissolved salts, or to stirred-up sediment from the bay bottom; (24)(25) this process will tend to lower the dose rates.

Experiment shows that certain of the radioactive nuclei tend to attach to sediment which is in suspension (24) and some form of artificial mixing of bottom sediment may help to attenuate the dose rates if an accident occurs. Iodine and bromine are expected.

In the Bikini bomb tests, (26) radioactivity after several days was found to be concentrated at a depth of about 100 ft. There is a tendency for dissolved material to seek the lower depth due to density and diffusion effects. (27)

For the diffusion coefficients used, a rough approximation is that it will take about 4 hr to reduce the dose rate from a point source of 1.2×10^{19} mev/sec, 1 mev gamma, to a dose rate of 1 rad/hr and that the radius of this dose rate is about 100 m.

The total maximum integrated dose for crossing over this "cloud" is the dose rate at the center times the time it takes to traverse the contamination area.

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7.8 Thermal Column: An analysis was performed of the extreme accident in which it was assumed that all of the 10,000 lb of reactor fuel at 1300°F was dumped into a channel 36 ft in depth. Of particular concern was the possible formation of a thermal column of radioactively-heated water which could potentially carry the activity to the surface. However, the temperature of an assumed 14-ft diameter thermal column is less than 10°F above the 50°F ambient water. This temperature differential will tend to accelerate the water at 0.033 ft/sec². However, not only do the fuel particles have a settling velocity estimated to be 0.16 ft/sec, but the diffusion of the heat and activity is quite rapid so that the thermal column, if formed at all, would be rapidly dissipated. In an actual situation, all of the fuel could not be released instantaneously and, furthermore, any horizontal motion of the water would cause the heat to dissipate even more rapidly.

Assuming instantaneous release and column formation, the dose rate at the point of release was 2.5×10^5 rads/hr after 100 sec and decreasing as an inverse function of time. This calculation assumed a diffusion coefficient of 2.15 ft²/sec and also that the thermal column retained its structure in spite of the dissipation of the thermal energy and horizontal motion of the water. The dose rate at the surface would be considerably lower than at the point of deposition but the magnitude of the source at the surface, although difficult to estimate, would dissipate rapidly.

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PART III

CONCLUSIONS

1. Assuming sound engineering design and operating procedures, the probability of a major reactor accident is related to the probability of a major marine accident which causes direct damage to the reactor or sinks the ship.

Experiment has shown that special design is required in order that afterheat be removed by free convection of water. If the ship sinks and the afterheat cannot be removed by convection, it is likely that the reactor or dump tank will be ruptured, thereby releasing large quantities of radioactivity. It is recommended that consideration be given to the design of the reactor and dump tank combination such that the latent and afterheat will be removed without rupturing the containment system, should this system be immersed in water. The assumption made is that all mechanically driven heat removal systems will cease to operate if the ship sinks.

2. Under normal operating conditions and known methods of construction, Xe and Kr in sufficient quantities to be dangerous may leak from the primary fuel system or exhaust system into the reactor compartment without being detected. The reactor compartment should be double-shelled with positive pressure in the annulus. This positive pressure will contain the radioactive gases in the inner compartment. The inner compartment should be continuously exhausted and should be monitored to prevent the buildup of excessive activity.

3. Stack off-gasing is not possible without holdup. Even with distances between ships of 5 miles, continuous discharge of noble gases (i.e., Xe and Kr) without holdup would produce excessive dose rates at certain

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distances from the stack. It is recommended that these gases be discharged into shielded disposable containers which could be dumped at sea.

4. The secondary cooling system should be provided with some means of pressure release mechanism to prevent boiler steam pressure from entering the reactor primary system should there be a tube failure in the boiler.

5. It is not practical, from weight considerations, to shield the compartment against a complete fuel spill outside the reactor vessel. A grid network should be provided below the reactor vessel, designed to contain the fuel in a small area and able to conduct the afterheat away rapidly enough to prevent damage to the ship's hull. The adjacent compartment should be provided with a water-tight bulkhead which will allow flooding and thereby provide a water shield in case of an extreme accident. This compartment should be at least 5 ft in width. The reactor compartment should not be flooded in the event of a fuel spill since dissolved fission products produce excessive dose rates outside.

6. Assuming 40°F fresh water, it was found that about 4,000 ft³ of water is required to dissolve 30 moles of Xe at a depth of 36 ft. It is estimated that this amount of gas, 80% of which is Xe, accumulates above the reactor fuel inside the pressure vessel in 11 days' operation at 100 Mw. If the reactor were ruptured under water and the fission product gases were released in one short discharge, it was concluded that a gaseous cloud is likely at the surface. It is recommended that these gases be bled to storage containers periodically, using one-way check valves in order that the activity released in such an event be lessened.

7. An analysis of the extreme accident in which the thermally-hot, radioactive fuel was released to the water gave a dose rate at the point

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of release of $< 2.5 \times 10^5$ rads/hr after 100 sec. A diffusion coefficient of $2.15 \text{ ft}^2/\text{sec}$ and gamma energy of 1.2×10^{19} mev/sec were assumed. Although the initial upward acceleration of the hot water due to thermal convection is $\sim 0.033 \text{ ft}/\text{sec}^2$, it is problematical whether or not the thermal column can retain its structure for sufficient time to carry much activity to the surface in view of the settling velocity of the fuel particles, the dissipation of the heat and horizontal motion of the water.

The chart on the following pages outlines certain events, the activity and doses associated with these events and the corrective action to be taken. The pertinent sections of the report which analyze these incidents are also noted.

<u>EVENT</u>	<u>ACTIVITY</u>	<u>DOSE</u>	<u>ACTION TAKEN</u>	<u>REPORT REF</u>
Small leak of Xe and Kr into reactor compartment which is continuously	200 curies for maximum allowed dose rate	0.025 rad/hr at outside of compartment with 6 in. of lead	None-gases are expelled by differential pressure	Section II-2 Appendix B
-----	-----	-----	-----	-----
Complete leak of Xe and Kr into Reactor compartment	6.8×10^6 curies	7.9×10^2 rads/hr to outside of reactor compartment with 6 in. Pb shield	Flood adjacent 5 ft compartment Increase differential pressure to expel gases	Section II-2 Appendix B
-----	-----	-----	-----	-----
Complete leak of Xe and Kr into reactor compartment; adjacent compartment flooded (this assumes 5 ft of water)	6.8×10^6 curies	5.1 rads/hr to outside of shielded compartment	Increase differential pressure to expel gases.	Section II-2 and Appendix B
-----	-----	-----	-----	-----
Discharge of Xe and Kr from stack	2.0 curie/sec for maximum dose rate of 1 rad/hr	1 rad/hr at 6,000 m at night 5 mps wind	None	Section II-5 and Appendix C-II
-----	-----	-----	-----	-----
Discharge of Xe and Kr from stack with 2-day holdup	4×10^6 curies	8.1×10^2 rads at 6,000 m at night 5 mps wind	Downwind ships take avoiding action	Section II-5 and Appendix C-II
-----	-----	-----	-----	-----
Cold Cloud - 100% Noble Gases-Night 5 mps wind	6.8×10^6 curies	5×10^3 rads at 1,000 m ----- 100 rads at 10,000 m	Take position 300 m crosswind ----- Take position 2,000 m crosswind	Section II-4 Appendix C Appendix D
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<u>EVENT</u>	<u>ACTIVITY</u>	<u>DOSE</u>	<u>ACTION TAKEN</u>	<u>REPORT REF</u>
Cold Cloud - 100% Fission Products night 5mp wind	8.6×10^7 curies	6.3×10^4 rads at 1,000 m 13×10^3 rads at 10,000 m	Take position 700 m crosswind; take position 2,500 m crosswind	Section II-4 Appendix C
-----	-----	-----	-----	-----
Fuel spill - 1% into reactor compt. with 6 in. lead shield	8.6×10^5 curies	3.9 rads/m	Fuel can be removed when it solidifies	Section II-3 Appendix -A
-----	-----	-----	-----	-----
Fuel spill - 100% into Reactor compt. with 6 in. lead shield	8.6×10^7 curies	390 rads/hr	Flood adjacent compartment	Section II-3 Appendix A
-----	-----	-----	-----	-----
Fuel spill - 100% into sea outside ship's hull	8.6×10^7 curies	$\ll 2.5 \times 10^5$ rads/ hr at the point of release after 100 sec and de- creasing rapidly with distance & time	Ship has been sunk - survivors take upwind and upstream position	Section II-7 Appendix D
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APPENDIX A

LIQUID FUEL SPILL

A.1 Introduction: The determination of dose rates to personnel outside the reactor compartment requires a knowledge of the behavior of the activity of the fuel after it spills out of the reactor. The fuel will go subcritical and the neutron flux will therefore quickly die out. Beta, gamma, and alpha particles will provide the shutdown activity. The betas and alphas will be effectively shielded by both distance and the compartment wall, and only the gamma photons will be of concern for this problem. An analysis of the plotted data in NDA-39 was made resulting in Tables A.1 through A.6 and Figs. A.1 and A.2. Once the behavior of the fission product gammas was determined, the dose rates to personnel were calculated. Finally, the amount of shielding required to reduce this dose to tolerable levels was calculated for two cases:

- (1) Shield for the entire compartment.
- (2) Shield for a dump tank below the reactor.

A.2 Analysis of Fission Product Gammas

In order to analyze the activity due to fission product gammas, the data graphed in NDA-27-39⁽⁴⁾ were tabulated and plotted. The gamma emitters were broken down into seven energy groups as follows:

<u>Group</u>	<u>Energy Range</u>
I	0.1 - 0.4 mev
II	0.4 - 0.9
III	0.9 - 1.35

<u>Group</u>	<u>Energy Range</u>
IV	1.35 - 1.8
V	1.8 - 2.2
VI	2.2 - 2.6
VII	over 2.6

Since the operating time of the reactor influences the buildup of the various isotopes and hence the final rate of decay, various operating times were selected to determine their overall effect. The times of operation selected were 10 hr, 24 hr, 100 hr, 1,000 hr, and infinite time. Cooling times of 1 hr, 3 hr, 6 hr, 1 day, 10 days, and 100 days were then selected in order to determine the rate of decay for the various times of operation. These data are given in Tables A.1 through A.6 of this appendix.

Fig. A-1 is a plot of the total energy flux for various operating times taken from Tables A.1 through A.6. It is evident that the time of operation does not greatly influence the initial activity but does control the decay rates. The decay is faster for shorter periods of operation. Fig. A-2 is a plot by energy groups of the flux vs cooling time for infinite operation. This figure is useful for shielding calculations. These plots and the data in the above tables are limited by the following facts:

- (1) Only those isotopes which emit gammas with energies of 0.1 mev or greater are included.
- (2) All known gammas that contribute significantly from 30 min to 1,000 hr after shutdown are included. Therefore, for times less than 30 min there may be activity due to gamma emitters of short half-life which are not included.

An initial cooling rate of 1 hr was selected in lieu of 30 min for convenience

since the data in MDA-27-39 actually start at 30 min.

In order to determine the fission product gamma energy at zero time, an empirical formula⁽⁶⁾ was used. This formula is:

$$E_{\gamma} = 7.095 \cdot 3.1 \cdot 10^{10} P/V \quad \dots \dots \dots (1)$$

where

$$E_{\gamma} = (\text{mev/cm}^3\text{-sec})$$

P = the power of core in watts

V = active volume in cm³

By dividing by the reactor power and multiplying by reactor volume, the activity/watts is 2.2×10^{11} mev/watt-sec. This is the initial value of the gamma activity at shutdown. It is on the order of 10 times the value at 1-hr decay.

Also plotted on Fig. A.1 is the Wigner-Way equation:⁽⁵⁾

$$G = 0.0315 P t^{-0.2}$$

t = time in sec

where P = the reactor power in the same units as G

G = the gamma activity

for (t = 10 sec) $G = 1.24 \times 10^{11}$ mev/watt-sec

This shows that the gamma activity decays like $t^{-0.2}$ for infinite operation and up to approximately 200 hr cooling time. After 200 hr the actual decay is faster than that postulated by the Wigner-Way formula.

A.3 Dose Rate Calculation

In order to determine the dose rate to personnel on the outside of the reactor compartment due to liquid fuel spill, the following formula⁽³⁾ was used:

$$D(r) = 5.767 \times 10^{-5} \left(\frac{\mu_a}{\rho} \right) E_0 r^0 \text{ rads/hr} \quad \dots \dots (2)$$

$$\frac{\mu_a}{\rho} = \text{energy-absorption mass attenuation coefficient } \frac{\text{cm}^2}{\text{g}}$$

E_0 = photon energy mev

$$\dot{\Gamma}^0 = \frac{S e^{-\mu x}}{4\pi R^2}$$

S = photons/sec

μ = macroscopic cross section, cm^{-1}

x = attenuation distance in steel, 1/4 in.

R = geometric attenuation distance, 500 cm

The following is a sample calculation for Energy Group II where

$E = 0.8$ mev:

$$E_0 \dot{\Gamma} = \frac{G e^{-\mu x}}{4\pi R^2} \frac{\text{mev}}{\text{cm}^2 \text{-watt-sec}} \dots \dots \dots (3)$$

G = energy flux (mev/watt-sec) taken from Table A.1, Group II, for infinite operating time

$\mu/\rho = 0.0668$ for 0.8 mev gamma

ρ = density of steel (7.6 gm/cm^3)

x = wall thickness, 1/4 in.

R = 500 cm, geometric attenuation distance

$\mu_a/\rho = 0.0311$ for tissue and 0.8 mev gamma

Therefore:

$$E_0 \dot{\Gamma} = 2.55 \times 10^3 \frac{\text{mev}}{\text{cm}^2 \text{-watt-sec}}$$

Putting these values into Eq. (2) the dose rate is:

$$D = 4.6 \times 10^{-3} \text{ rads/watt-hr (t = 60 min)}$$

The same calculation must then be done for the other six groups in Fig. 2 and then the sum taken. It can be seen by the units that the wattage of the spill must be used in order to determine the actual dose since this is assumed to be a linear factor. It was assumed in this problem that a 100% spill of a 100-Mw reactor had taken place. Therefore, for Group II a dose rate of 4.6×10^5 rads/hr would result.

Table A.7 shows the calculation for the entire seven groups. From Table A.7 the total dose rate is:

$$\begin{aligned} \text{Dose (t = 60 min)} &= 1.04 \times 10^6 \\ &= \text{rads/hr} \\ &= 1.04 \times 10^7 \text{ rads/hr at zero time} \end{aligned}$$

A.4 Shielding Required for Fission Product Gammas

There are two problems of interest here. First, what thickness of lead would be required for the reactor compartment to protect personnel if there were an uncontrolled fuel spill? Second, what thickness of lead would be required if the fuel were dumped into a shielded container below the reactor? The second problem assumes that entry into the reactor compartment is desired while the first attempts only to protect personnel on the outside of the compartment. Basic assumptions:

Allowable dose rate: 25 m rad/hr (dump tank); 1 rad/hr (compartment)

Compartment structure: 1/4 in. steel

Dump tank: 1-in. steel then lead

Reactor power: 100 Mw for infinite time

Fuel volume: $1.33 \times 10^6 \text{ cm}^3$

Fuel density: 3g/cm^3

Relaxation length of gammas in fuel: .5 cm (average for all energy groups)

A.4.1 Compartment Shielding

$$\mu t = \ln \left(\frac{D(E) B_r}{D_a} \right) \dots \dots \dots (4)$$

where

$\ln$ = logarithm to the base e .

μ = macroscopic cross section for gamma of energy E

$D(E)$ = dose rate from gammas of energy group E

B_r = buildup factor

D_a = allowable dose rate

Table A.8 is the calculation of the shielding required for the compartment.

It is evident from Table A.8 that a shield of about 30 cm must be used if it is desired to protect ship personnel from a complete fuel spill in the reactor compartment. This would still give a dose of 1 rad/hr. This is not practical since such a shield would weigh about 500 tons and would cover only the overhead and the rear bulkhead. The forward bulkhead is adjacent to a ballast tank and therefore no shielding is required. This type of shielding neglects any scattering effect that might be present from the radiation that streamed out of the sides of the ship.

The proposed design⁽¹⁾ of this installation provides for a secondary shield of 6 in. of lead. Table A.9 is a list of dose rate reduction factors by energy groups which can be applied to correct the "unshielded" case for this 6 in. lead shield. This 6 in. lead shield will reduce the dose rate to 390 rads/hr for a complete fuel spill. This can be further reduced to 2 rads/hr if an adjacent compartment at least 5 ft in width can be flooded. Table A.9 lists the reduction factors for 5 ft of water for each of the energy groups.

The reactor compartment itself could be flooded in the event of a fuel spill. However, a portion of the fuel will probably go into solution and produce a volume source of gamma energy in the flooded compartment. Table A.10 shows the dose rate calculation for a flooded compartment and 1% of the fuel in solution. The dose rate in this case would be:

$$D = 1.5 \times 10^4 \text{ rads/hr unshielded}$$

$$D = 7.2 \text{ rads/hr with 6 in. lead shield}$$

The additional weights that these various proposals would entail are as follows:

6-in. lead shield---200 tons

30-cm lead shield---500 tons

5-ft water---300 tons

Flooded compartment---1000 tons

A.4.2 Dump Tank Shield

If a dump tank is provided, it is assumed that maintenance personnel should be allowed to work in the reactor compartment for an indefinite period of time. Therefore, the allowable dose rate must be reduced to 25 mrad/hr. It is assumed that the shape of the dump tank will be such that the volume source can be converted to a surface source by: ⁽³⁾

$$S = P\lambda(\text{mev/cm}^2\text{-sec})$$

where P = volume source ($\text{mev/cm}^3\text{-sec}$)

λ = relaxation length of gammas in fuel assumed to be 5 cm for all energy groups for simplification.

Table A.11 is a calculation of the shield required to reduce the dose rate to 25 mrad/hr. This shield would have to be 40 cm thick. Assuming nominal dimensions for the tank, 3 ft x 3 ft x 5-1/2 ft, large enough to hold the 48 ft³ of fuel would require an additional 20 tons of weight.

TABLE A-1

GAMMA ENERGY (mev/watt-sec) FOR FISSION DECAY PRODUCTS

1 hr Cooling Time

Operating Times

<u>Energy Group</u>	<u>10</u>	<u>24</u>	<u>100</u>	<u>1,000</u>	<u>Infinite</u>
I	3.2×10^8	4.7×10^8	8.5×10^8	1.5×10^9	1.65×10^9
II	21.0	35.0	59.0	8.3	11.0
III	15.0	17.0	18.5	1.9	1.85
IV	20.0	21.0	25.0	4.8	5.2
V	14.5	16.5	16.5	1.65	1.65
VI	0.85	1.1	1.4	0.33	0.37
VII	0.23	0.24	0.24	0.02	0.02
Total	74.8×10^8	85.5×10^8	129.1×10^8	18.5×10^9	21.7×10^9

TABLE A-2

GAMMA ENERGY (mev/watt-sec) FOR FISSION DECAY PRODUCTS

3 hr Cooling Time

Operating Time-Hours

<u>Energy Group</u>	<u>10</u>	<u>24</u>	<u>100</u>	<u>1,000</u>	<u>Infinite</u>
I	2.4×10^8	3.9×10^8	7.7×10^8	1.45×10^9	1.53×10^9
II	17.0	31.0	53.0	7.5	10.0
III	6.2	7.8	8.7	0.92	0.92
IV	2.5	3.5	7.7	3.1	4.0
V	9.0	10.2	10.2	1.02	1.07
VI	0.57	0.75	1.1	0.30	0.33
VII	0.14	0.14	0.14	0.01	0.01
Total	37.81×10^8	57.3×10^8	88.5×10^8	14.3×10^9	17.9×10^9

TABLE A-3

GAMMA ENERGY (mev/watt-sec) FOR FISSION DECAY PRODUCTS

6 hr Cooling Time

Operating Time-Hours

<u>Energy Group</u>	<u>10</u>	<u>24</u>	<u>100</u>	<u>1,000</u>	<u>Infinite</u>
I	2.3×10^8	3.5×10^8	7.3×10^8	1.4×10^9	1.5×10^9
II	14.0	26.0	45.0	6.8	9.5
III	3.2	4.4	5.3	0.54	0.54
IV	0.9	1.8	6.0	3.0	3.3
V	4.4	5.0	5.3	0.54	0.57
VI	0.35	0.5	0.8	0.27	0.30
VII	0.07	0.07	0.07	Neg	Neg
Total	25.2×10^8	41.3×10^8	69.8×10^8	12.6×10^9	15.7×10^9

TABLE A-4

GAMMA ENERGY (mev/watt-sec) FOR FISSION DECAY PRODUCTS

1-Day Cooling Time

Operating Time-Hours

<u>Energy Group</u>	<u>10</u>	<u>24</u>	<u>100</u>	<u>1,000</u>	<u>Infinite</u>
I	1.45×10^8	2.2×10^8	5.5×10^8	1.17×10^9	1.3×10^9
II	7.1	13.5	27.0	4.8	7.4
III	0.62	0.98	1.1	0.12	0.12
IV	0.57	1.33	5.5	2.7	3.0
V	0.16	0.24	0.44	0.08	0.08
VI	0.07	0.13	0.42	0.22	0.26
VII	Neg	Neg	Neg	Neg	Neg
Total	9.97×10^8	18.37×10^8	40.0×10^8	9.1×10^9	13.2×10^9

TABLE A-5

GAMMA ENERGY (mev/watt-sec) FOR FISSION DECAY PRODUCTS

10-Day Cooling Time

<u>Energy Group</u>	<u>10</u>	<u>24</u>	<u>100</u>	<u>1,000</u>	<u>Infinite</u>
I	1.3×10^7	3.1×10^7	1.05×10^8	4.3×10^8	5.1×10^8
II	3.9	9.0	3.4	18.0	41.0
III	Neg	Neg	Neg	Neg	Neg
IV	4.7	10.5	4.1	18.0	24.0
V	0.06	0.14	0.04	0.09	0.23
VI	0.37	0.9	0.34	1.5	1.7
VII	Neg	Neg	Neg	Neg	Neg
Total	10.3×10^7	23.6×10^7	9.9×10^8	41.9×10^8	72.1×10^8

TABLE A-6

GAMMA ENERGY (mev/watt-sec) FOR FISSION DECAY PRODUCTS

100-Day Cooling

Operating Time-Hours

<u>Energy Group</u>	<u>10</u>	<u>24</u>	<u>100</u>	<u>1,000</u>	<u>Infinite</u>
I	2.4×10^5	6.0×10^5	1.9×10^6	1.6×10^7	2.35×10^7
II	58.0	140.0	53.5	48.0	140.0
III	0.02	0.05	0.02	0.02	0.27
IV	3.4	8.2	3.1	1.5	2.0
V	0.14	0.32	0.14	0.13	1.25
VI	0.32	0.82	0.31	0.17	0.80
VII	Neg	Neg	Neg	Neg	Neg
Total	64.3×10^5	155.3×10^5	59.9×10^6	51.4×10^7	146.7×10^7

TABLE A-7

DOSE RATE CALCULATIONS FOR FUEL SPILL-CONTAINED

<u>Energy Group</u>	<u>E</u>	<u>u/p</u>	<u>u</u>	<u>ut</u>	<u>e^{ut}</u>	<u>Q(nev/watt-sec)</u>	<u>D(rads/hr)</u>
I	0.4	0.093	0.71	0.45	1.57	1.65×10^9	9×10^4
II	0.8	0.065	0.49	0.31	1.36	1.1×10^{10}	46×10^4
III	1.3	0.05	0.38	0.24	1.27	1.85×10^9	10×10^4
IV	1.7	0.043	0.33	0.21	1.23	5.2×10^9	28×10^4
V	2.2	0.04	0.30	0.19	1.21	1.65×10^9	9×10^4
VI	2.5	0.038	0.29	0.18	1.20	0.37×10^9	2×10^4
VII	2.8	0.036	0.27	0.18	1.18	0.02×10^9	0.1×10^4
Total							1.04×10^6

TABLE A-8

SHIELDING OF REACTOR COMPARTMENT

<u>Energy Group</u>	<u>D(E)/D_a</u>	<u>E</u>	<u>Br</u>	<u>Br x D (E)/D_a</u>	<u>u</u>	<u>t(cn)</u>
I	9×10^4	0.4	2.7	2.4×10^5	2.8	4.42
II	46×10^4	0.8	4.8	2.2×10^6	1.04	13.00
III	10×10^4	1.3	5.8	5.8×10^5	0.70	21.30
IV	28×10^4	1.7	6.3	1.77×10^6	0.56	25.7
V	9×10^4	2.2	8.0	7.2×10^5	0.50	27.0
VI	2×10^4	2.5	8.9	1.78×10^5	0.49	24.7
VII	1×10^3	2.8	9.6	9.6×10^3	0.49	18.4

TABLE A-9

REDUCTION FACTORS TO DOSE RATE OUTSIDE REACTOR COMPARTMENT
FOR LEAD AND WATER SHIELDS

<u>Group</u>	<u>6 in. Lead</u>	<u>5-ft Water</u>
I	10^{-18}	7.5×10^{-6}
II	4×10^{-7}	1.2×10^{-4}
III	8×10^{-5}	1.3×10^{-3}
IV	7×10^{-4}	3.5×10^{-3}
V	1.6×10^{-3}	5.4×10^{-3}
VI	2×10^{-3}	8×10^{-3}
VII	2×10^{-3}	1.5×10^{-2}

TABLE A-10

DOSE RATE TO EXTERIOR OF REACTOR COMPARTMENT AFTER FUEL
SPILL ASSUMING FLOODED COMPARTMENT AND 1% OF SPILL IN SOLUTION

<u>Group</u>	<u>Energy</u>	<u>P(nev/sec-cm³)</u>	<u>$\mu(\text{H}_2\text{O})$</u>	<u>λ</u>	<u>S(nev/sec-cm²)</u>	<u>$e^{ut}(\text{Fe})$</u>	<u>D</u>
I	0.4	1.65×10^6	0.106	9.5	1.56×10^7	1.57	5.8×10^2
II	0.8	1.1×10^7	0.078	12.7	1.4×10^8	1.36	59.4×10^2
III	1.3	1.85×10^6	0.063	15.9	2.95×10^7	1.27	13.4×10^2
IV	1.7	5.2×10^6	0.050	20.0	1.04×10^8	1.23	48.7×10^2
V	2.2	1.65×10^6	0.047	21.3	3.5×10^7	1.21	16.7×10^2
VI	2.5	0.37×10^6	0.044	22.7	8.4×10^6	1.20	4.0×10^2
VII	2.8	0.02×10^6	0.041	24.4	4.8×10^6	1.18	2.3×10^2

Dose Rate = 1.5×10^4 rads/hr unshielded sides

Dose rate = 7.2 rads/hr with 6 in. lead shield

TABLE A-11

DUMP TANK SHIELD

<u>Energy Group</u>	<u>E</u>	<u>G(mev/sec)</u>	<u>S</u>	<u>e^{ut}(Fe)</u>	<u>Br(Pb)</u>	<u>u(Pb)</u>	<u>ut</u>	<u>t(cm)</u>
I	0.4	1.65×10^{17}	2.3×10^{12}	6.1	2.7	2.8	6.8×10^7	6.45
II	0.8	1.10	15.2	3.5	4.8	1.04	1.41×10^9	20.25
III	1.3	1.85	2.56	2.62	5.8	0.70	3.84×10^8	28.27
IV	1.7	5.2	7.2	2.32	6.3	0.56	1.32×10^9	37.50
V	2.2	1.65	2.28	2.14	8.0	0.50	5.8×10^8	40.40
VI	2.5	0.37	0.51	2.05	8.9	0.49	1.51×10^8	38.40
VII	2.8	0.02	0.03	1.97	9.6	0.49	1.00×10^7	32.84

Fig. A.1. U^{235} Fission Product Decay Activity.

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Fig. A.2 Decay of Fission Products after Infinite Operation.

APPENDIX B

GASEOUS FISSION PRODUCT LEAK-CONTAINED

B.1 Introduction: The behavior of the fission product gases is dependent upon which isotopes of the various fission products are considered to be gaseous upon escape from the reactor. The only elements which could be gaseous in significant quantities at the operating conditions of this reactor (1250°F, 100 psi) are Br, Kr, I, and Xe. Experience with the off-gas from fluoride systems⁽²⁾ indicates that only Kr and Xe will escape as gases in significant amounts and Br and I will remain in solution. Br and I are present in the gases as trace quantities. In addition to the parent gases, consideration must be given to the various daughters which will be formed as the gases decay.

First, an analysis is made of those parents and daughters which have significant activity to be important (Table 3.1). It is shown that the Xe^{140} to La^{140} chain is the only chain which produces an important buildup product. These fission product gases were then plotted to enable an analysis of the overall decay scheme. Fig. B.1 is a plot of the activity assuming that Br, Kr, I, and Xe will escape. Fig. B.2 is a plot of the activity assuming that only Kr and Xe will escape.

The dose rate for personnel from both of these cases is calculated (Table B.2, B.3) and finally the compartment shielding required for the Kr, Xe case is calculated (Table B.4), since this is the logical case to assume in view of previous known experience⁽²⁾. It is assumed that these gases may escape the primary fuel system even though there is no major rupture of the reactor containment vessel.

B.2 Analysis of Fission Product Gammas from Gaseous Products

In order to determine the dose rate from the fission product gases, an analysis of the decay chains of Br, Kr, I, and Xe were made. It is assumed that these are the only products that will be in the gaseous state. Table B.1 is a list of all the isotopes that were considered. Only those that are significant are actually plotted as shown on Figs. B.1 and B.2. Fig. B.1 considers that all the Br, I, Kr, and Xe remain gaseous upon escape to the reactor compartment. It can be seen from Fig. B.1 that after 5 days only I^{131} and Xe^{133} are significant. Since Xe^{133} has only a 0.081 mev gamma it can probably be neglected in comparison to I^{131} . In this scheme the only significant buildup product is La^{140} and in comparison to the I^{131} it, too, can be neglected. The picture is entirely different, however, in Fig. B.2 when only Kr and Xe are considered. Here it can be seen that Kr^{88} is the initially important product and then Xe^{133} is the long-time important product. However, if the 0.081 mev gamma of Xe^{133} is considered too insignificant from a shielding viewpoint, then the buildup of La^{140} which has a 3.0 mev gamma becomes the most important product. This second scheme is the most logical one to expect since I and Br will probably remain in solution and not be present in significant quantities. (2)

Data for the plotting of these curves were obtained by assuming that the gases had reached equilibrium amounts. The following formula was used:

$$A_n = \lambda_2 \lambda_3 \cdots \lambda_{n-1} \lambda_n y_1 P_0 \left\{ \frac{e^{-\lambda_1 t}}{(\lambda_n - \lambda_1)(\lambda_{n-1} - \lambda_1) \cdots (\lambda_3 - \lambda_1)(\lambda_2 - \lambda_1)} \right\}$$

$$\begin{aligned}
& + \frac{e^{-\lambda_2 t}}{(\lambda_n - \lambda_2)(\lambda_{n-1} - \lambda_2) \dots (\lambda_3 - \lambda_2)(\lambda_1 - \lambda_2)} \dots \frac{e^{-\lambda_{n-1} t}}{(\lambda_n - \lambda_{n-1}) \dots (\lambda_3 - \lambda_{n-1})(\lambda_2 - \lambda_{n-1})(\lambda_1 - \lambda_{n-1})} \\
& + \frac{e^{-\lambda_n t}}{(\lambda_1 - \lambda_n)(\lambda_2 - \lambda_n)(\lambda_3 - \lambda_n) \dots (\lambda_{n-1} - \lambda_n)} \left\{ \dots \dots \dots (1) \right.
\end{aligned}$$

where: A_n = activity of n^{th} product in chain

λ_n = decay constant for particular isotope (n^{th})

y_1 = yield of initial gaseous parent

P_0 = reactor power $\times 3.25 \times 10^{10} \frac{\text{fissions}}{\text{watt-sec}}$

t = time of cooling in sec

This reduces to the following formula for the activity due to the gaseous parent:

$$A = y_1 P_0 e^{-\lambda t}$$

Sample calculation:

I^{131}

$$\begin{aligned}
A_0 &= (0.029)(10^8)(3.25 \times 10^{10}) \\
&= 9.43 \times 10^{16} \frac{\text{photons}}{\text{sec}}
\end{aligned}$$

To convert this to $\text{mev/cm}^2\text{-sec}$ we must take each gamma energy present times its yield fraction and then sum up the total. This gives mev/sec .

By dividing by the reactor compartment volume we have a volume source.

This is then converted to a surface source by multiplying by the compartment's width. The volume is 10^9 cm^3 and the width is 10^3 cm . The energies and yields of I^{131} are as follows: (28)

<u>E(mev)</u>	<u>% Yield</u>
0.722	3
0.637	9
0.364	80
00.284	5.3

This summation equals 0.385 mev. Therefore the total energy flux is:

$$I^{131} = 3.65 \times 10^{10} \text{ mev/cm}^2\text{-sec}$$

As an example of the analysis made for significant buildup products, the $\text{Xe}^{140} \longrightarrow \text{La}^{140}$ chain is presented. The other chains investigated are indicated in Table B.1 by **. Values⁽¹³⁾ for the $\text{Xe}^{140} \longrightarrow \text{La}^{140}$ chain are put into Eq. (1). Assuming the reactor had been operating at 100 Mw, $P_0 = 3.25 \times 10^{18}$ fission/sec. Therefore:

$$\begin{aligned} \frac{A_4}{y_1 P_0 \Sigma_i \lambda_i} = & \frac{(1.05 \times 10^{-2})(6.27 \times 10^{-7})(4.79 \times 10^{-6}) e^{-\lambda_1 t}}{(4.79 \times 10^{-6} - 4.33 \times 10^{-2})(6.27 \times 10^{-7} - 4.33 \times 10^{-2})(1.05 \times 10^{-2} - 4.33 \times 10^{-2})} \\ & + \frac{(1.05 \times 10^{-2})(6.27 \times 10^{-7})(4.79 \times 10^{-6}) e^{-\lambda_2 t}}{(4.79 \times 10^{-6} - 1.05 \times 10^{-2})(6.27 \times 10^{-7} - 1.05 \times 10^{-2})(4.33 \times 10^{-2} - 1.05 \times 10^{-2})} \\ & + \frac{(1.05 \times 10^{-2})(6.27 \times 10^{-7})(4.79 \times 10^{-6}) e^{-\lambda_3 t}}{(4.79 \times 10^{-6} - 6.26 \times 10^{-7})(1.05 \times 10^{-2} - 6.27 \times 10^{-7})(4.33 \times 10^{-2} - 6.27 \times 10^{-7})} \\ & + \frac{(1.05 \times 10^{-2})(6.27 \times 10^{-7})(4.79 \times 10^{-6}) e^{-\lambda_4 t}}{(4.33 \times 10^{-2} - 4.79 \times 10^{-6})(1.05 \times 10^{-2} - 4.79 \times 10^{-6})(6.27 \times 10^{-7} - 4.79 \times 10^{-6})} \end{aligned}$$

Finally:

$$A_{La140} = -1.3 \times 10^8 e^{-4.33 \times 10^{-2}t} + 2.2 \times 10^9 e^{-1.05 \times 10^{-2}t} \\ + 4.2 \times 10^{12} e^{-6.27 \times 10^{-7}t} - 4.2 \times 10^{12} e^{-4.69 \times 10^{-6}t} \text{ mev/sec.}$$

This equation is plotted on Figs. B.1 and B.2.

B.3 Calculation of External Dose Rates from Gaseous Fission Products

In order to calculate the dose rate due to the fission product gammas, the gamma photons from the important gaseous products were broken down into the seven energy groups that were used for the problem in Appendix A. Table B.2 is the calculation assuming that Kr, Br, I, and Xe are gaseous. Table B.3 considers that only Kr and Xe are gaseous. These dose rates are the initial rates for an unshielded compartment and they decay differently depending on the long-lived products in each group. Figs. B.1 and B.2 show the decay schemes. The formula⁽³⁾ used to calculate the dose rate is:

$$D = 5.767 \times 10^{-5} G \mu_a / \rho e^{-ut} \quad (2)$$

D = dose rate in rads/m

G = energy flux $\frac{\text{mev}}{\text{cm}^2\text{-sec}}$

μ_a / ρ = energy absorption coefficient for tissue

e^{-ut} = attenuation in steel plating

The dose rate for the unshielded compartment from Tables B.3 and B.4 would be:

$$D = 2.6 \times 10^6 \text{ rads/hr volatile gases (Br, Kr, I and Xe)}$$

$$D = 9.2 \times 10^5 \text{ rads/hr noble gases (Kr and Xe)}$$

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If the compartment is shielded with 6 in. of lead, Table A.9 corrects the above values to:

$$D = 2 \times 10^3 \text{ rads/hr volatile gases}$$

$$D = 7.9 \times 10^2 \text{ rads/hr noble gases}$$

B.4 Shielding Calculations for Gaseous Decay Gammas

For this problem it is assumed that the gaseous products escape the primary reactor shield and diffuse throughout the reactor compartment, which is considered gas "tight." The most probable case is the one where the Kr and the Xe and their daughters are present in the gaseous state. The reactor power is taken as 100 Mw; the reactor compartment volume is 10^9 cm^3 ; the reactor compartment width is 1,000 cm. Using these parameters and assuming an allowable dose rate of 1 rad/hr initially, Table B.5 is a calculation of lead thickness required in order to attenuate the various gamma energy groups to the allowable dose rate.

It is seen from Table B.5 that a shield of 30 cm would be required to reduce the dose rate to 1 rad/hr. This would involve an additional 200 tons over that required for the 6-in. shield. This is impractical. Therefore, other means must be taken to prevent the buildup of these gaseous products. This can be done by expelling the gases from the compartment. It is proposed that the reactor compartment be double-shelled. The annulus would be under a slight positive pressure to insure leakage into but not out of the inner compartment. The inner compartment would then be vented outside the ship. The periodic discharge of fission product gases is designed into the reactor so that gas leakage from the fuel system is not detrimental to the operation of the reactor. The features suggested above would protect personnel without adding excessive weight to the ship.

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TABLE B.1

FISSION PRODUCT GASEOUS DECAY CHAINS

<u>Isotope</u>	<u>T_{1/2}</u>	<u>Yield</u>	<u>Daughters</u>	<u>Parent</u>	<u>Daughter</u>
Br ⁸²	35.9h	3.5 x 10 ⁻⁵		2	
Br ⁸³	2.4h	0.48	Kr ^{83m}	1	5 and 1
Br ⁸⁴	30m	1.1		2	
Br ⁸⁵	3m	1.5	Kr ^{85m}	3	4
Br ⁸⁷	55.6s	2.7	Kr ^{87m}	4	4
Br ⁸⁸	15.5s	2.9	Kr ⁸⁸ , Rb ⁸⁸	3	4,2
Br ⁸⁹	4.5s	?		3	
Kr ^{83m}	114m	0.48		5 and 1	
Kr ^{85m}	4.36h	1.5		4	
Kr ⁸⁵	10.27 y	0.3		7	
Kr ^{87m}	78m	2.7	Rb ⁸⁷	4	3 and 7
Kr ⁸⁸	2.77H	3.7	Rb ⁸⁸	4	2
Kr ⁸⁹	3.18m	4.6	Rb ⁸⁹ , Sr ⁸⁹	3	3,3
Kr ⁹⁰	33s	5.2	Rb ⁹⁰ , Sr ⁹⁰ , Y ⁹⁰	3	3,3,2
Kr ⁹¹	9.8s	3.7	Rb ⁹¹ , Sr ⁹¹ , Y ⁹¹	3	2,2,2
Kr ⁹²	3.0s	2.7	Rb ⁹² , Sr ⁹² , Y ⁹²	3	2,2,2
Kr ⁹³	2.0m	1.3	Rb ⁹³ , Sr ⁹³ , Y ⁹³	3	2,2,2
Kr ⁹⁴	1.4	0.6	Rb ⁹⁴ , Sr ⁹⁴ , Y ⁹⁴	3	2,2,2

1-Energy Flux too low ($< 10^7 \frac{\text{mev}}{\text{cm}^2 \cdot \text{sec}}$)

2-Gamma present, yield unknown (Ref. (9) - Disintegration % unknown)

3-Beta emitter only

4-Graphed-B.1, B.2

5-Stable isotope

6-Gamma present, energy too low (less than 0.05 mev)

7-Gamma present, activity too low (long half-life > 10 years)

TABLE B.1 (continued)

<u>Isotope</u>	<u>T_{1/2}</u>	<u>Yield</u>	<u>Daughter</u>	<u>Parent</u>	<u>Daughter</u>
I ¹²⁹	1.7 x 10 ⁷ y	1.0		1	
I ¹³⁰	12.6h	†		3	
I ¹³¹	8.05d	2.9	Xe ^{131m}	4	2
I ¹³²	2.4h	4.4		4	
I ¹³³	20.8h	6.5	Xe ^{133m}	4	1
I ¹³⁴	52.5m	7.6		4	
I ¹³⁵	6.68h	5.9	Xe ^{135m} , Cs ¹³⁵	4	4,3
I ¹³⁶	86s	3.1		2	
I ¹³⁷	22s	4.9	Xe ¹³⁷ , Cs ¹³⁷ , Ba ¹³⁷	3	3,3,3
I ¹³⁸	5.9s	3.4	Xe ¹³⁸ , Cs ¹³⁸	2	2,4
I ¹³⁹	2.7s	1.8	Xe ¹³⁹ , Cs ¹³⁹ , Ba ¹³⁹	2	2,2,2
Xe ¹³¹	12d	0.03		4	
Xe ^{133m}	2.3d	0.16	Xe ¹³³	4	4
Xe ¹³³	5.28d	6.5		4	
Xe ^{135m}	15.6m	1.8	Xe ¹³⁵	4	4
Xe ¹³⁵	9.13m	6.2	Cs ¹³⁵	4	3
Xe ¹³⁷	3.9m	5.9	Cs ¹³⁷ , Ba ¹³⁷	3	3,3
Xe ¹³⁸	17m	5.5	Cs ¹³⁸	2	4
Xe ¹³⁹	41s	4.7	Cs ¹³⁹ , Ba ¹³⁹	2	2,2
Xe ¹⁴⁰	16s	3.7	Cs ¹⁴⁰ , Ba ¹⁴⁰ , La ¹⁴⁰	2	2,2,4
Xe ¹⁴¹	1.7s	1.8	Ba ¹⁴¹ , La ¹⁴¹ , Ce ¹⁴¹	2	2,2,2
Xe ¹⁴³	1.0s	0.2	Ba ¹⁴³ , La ¹⁴³ , Ce ¹⁴³	2	2,2,2

TABLE B.3

DOSE RATE FROM Br, Kr, I, AND Xe AT ZERO TIME

<u>Energy Group</u>	<u>E</u>	<u>G(mev/cm²-sec)</u>	<u>e^{ut}</u>	<u>Dose Rate (rads/hr x 10⁻⁵)</u>
I	0.4	0.58 x 10 ¹¹	1.57	0.64
II	0.8	4.191 x 10 ¹¹	1.36	5.31
III	1.3	6.223 x 10 ¹¹	1.27	8.47
IV	1.7	2.137 x 10 ¹¹	1.23	3.00
V	2.2	1.424 x 10 ¹¹	1.21	2.04
VI	2.5	1.514 x 10 ¹¹	1.20	2.16
VII	2.8	3.040 x 10 ¹¹	1.18	4.47
<u>Total</u>				26.09 x 10 ⁵ rads/hr

TABLE B.4

DOSE RATE FROM Kr AND Xe AT ZERO TIME

<u>Energy Group</u>	<u>E</u>	<u>G(mev/cm²-sec)</u>	<u>e^{ut}</u>	<u>Dose Rate (rads/hr x 10⁻⁵)</u>
I	0.4	0.291 x 10 ¹¹	1.57	0.31
II	0.8	0.811 x 10 ¹¹	1.36	1.03
III	1.3	3.357 x 10 ¹¹	1.27	4.57
IV	1.7	0.263 x 10 ¹¹	1.23	0.37
V	2.2	1.221 x 10 ¹¹	1.21	1.75
VI	2.5	1.505 x 10 ¹¹	1.20	2.17
VII	2.8	None		
<u>Total</u>				9.20 x 10 ⁵ rads/hr

TABLE B.5

COMPARTMENT SHIELD FOR GASEOUS PRODUCTS

<u>Energy Group</u>	<u>E</u>	<u>D(E)/D_a</u>	<u>Br</u>	<u>Br x D(E)/D_a</u>	<u>u</u>	<u>t(cm)</u>
I	0.4	0.31×10^5	2.7	0.837×10^5	2.8	4.07
II	0.8	1.03×10^5	4.8	4.94×10^5	1.04	12.60
III	1.3	4.57×10^5	5.8	26.5×10	0.70	21.70
IV	1.7	0.37×10^5	6.3	2.33×10^5	0.56	22.10
V	2.2	1.75×10^5	8.0	14.00×10^5	0.50	28.30
VI	2.5	2.17×10^5	8.9	19.30×10^5	0.49	29.50

Fig. B.1. Decay of Fission Products.

APPENDIX CESCAPE OF FISSION PRODUCT GASES TO ATMOSPHERE

C.1 Introduction: The controlled escape of radioactive gases from a fluid fuel reactor is normally designed into the operation of a reactor to reduce the neutron poisoning by Xe^{135} . It is possible, however, for an accident to occur which would release a substantial quantity of radioactivity in a short period of time. It is assumed that the accident which ruptures the reactor vessel allows the fission product gases to escape to the atmosphere. It is possible, also, to discharge radioactive gases intentionally; the problem, then, is to determine the dose that might be received by personnel downwind should such an incident occur.

In Section C.2 of this appendix, working curves are plotted so that the internal and external doses due to a radioactive cloud can be computed. The effect of a power excursion is analyzed. The height that a hot cloud is expected to rise is computed and the choice of the meteorological parameters is explained.

In Section C.3 of this appendix, working curves for computing the dose rates to be expected from a controlled continuous release are plotted. Sutton's diffusion equation for a continuous point source has been modified to account for the ship's movement. A crosswind curve has been included to simplify the problem of computing the distance crosswind that a ship must go in order to reduce the received dose to tolerable limits.

Section C.4 is an analysis of the influence of radioactive decay, dry deposition, and rainout on the doses or dose rates received. These factors have been purposely omitted in sections C.2 and C.3 since they

tend to decrease the doses received for distances that are of interest here. Although the theory and equations concerning these phenomena are fairly well understood, the choice of the proper parameter values is difficult. Consequently, any answer that is arrived at must be viewed critically. It seems better, then, to realize that these conditions exist, but to use them only when the proper value of the parameters is known with certainty.

C.2 Gaseous Cloud Release

C.2.1 Power Excursion vs Normal Power Release: A short-lived nuclear reactor power excursion of 1 Mw-sec will release radioactive fission products which will emit approximately $4.8 \times 10^{16} t^{-1.2}$ mev/sec of gamma energy⁽¹⁰⁾. If the release occurs at normal power, there is $2.3 \times 10^{14} P t^{-.2}$ mev/sec of gamma energy released⁽⁶⁾. P is reactor power in kilowatts. A power excursion is usually over within 0.5 sec. Therefore, if it is assumed that the reactor was operating at 100 Mw when it suddenly went on a power excursion of 1500 Mw in 0.5 sec, the initial total radioactivity would be 5.9×10^{19} mev/sec. Of this 3.6×10^{19} mev/sec would be due to the power excursion and 2.3×10^{19} mev/sec to the normal power. In 10 sec the activity would be 1.67×10^{19} mev/sec. Only 13% of this would then be due to the power excursion. For the gaseous cloud problem the doses of interest occur at times much greater than 10 sec and, therefore, the effect of the power excursion will be negligible.

C.2.2 Height of Cloud: In order to determine what cloud height would be reasonable for the 100-Mw reactor under consideration, it was assumed that a complete fuel spill had occurred. The fuel itself is very stable⁽¹⁶⁾ and hence no chemical reaction with water or other substances is expected. Therefore, there will not be an exothermic reaction.

The heat available then is the latent heat in the fuel and the afterheat.

The latent heat is based on the following:

Fuel volume: 48 ft³

Fuel density: 207 lb/ft³

Specific heat: 0.25 Btu/lb-°F

Temperature change: 1200°F

$$H = V C_p d (T_2 - T_1) \dots \dots \dots (1)$$

$$H = 3 \times 10^6 \text{ Btu}$$

The afterheat based on 6% of reactor power is:

$$\begin{aligned} H_a &= 10^8 \times 3.415 \text{ Btu/watt-hr} \times 0.06 \\ &= 2 \times 10^6 \text{ Btu/hr} \end{aligned}$$

Half of this afterheat is gamma heat and will not be available locally.

The gases that are heated are assumed to leave the compartment within 10 min. Therefore, the beta afterheat available during the time the radioactive gases are in the compartment would be:

$$\begin{aligned} H_a &= 2 \times 10^6 \times 1/2 \times 1/6 \\ &= 170,000 \text{ Btu} \end{aligned}$$

With afterheat, the total heat content available during the time the gases are present will be approximately 3.2×10^6 Btu. Only a portion of this will go into heating the air and the fission product gases in the compartment before they escape, since the heat transfer to the air would be poor. Most of the heat will be dissipated in the metal structure into which the fuel has been poured. Assuming that 5% is available to heat the gases, the height of the cloud would be: (8)

$$z_{\max} = \left[\frac{q_h}{2 C_p d \pi^{3/2} C^3 \theta_a} \right]^{0.276} \dots \dots \dots (2)$$

C_p = the specific heat (0.25)

d = the air density

C = the diffusion coefficient (0.3)

θ_a = the temperature gradient (0.02°C/m)

Q_h = the heat available (4×10^7 cal)

Using the above values, a height of 107 m results. In subsequent calculations this is rounded off to 100 m. The rise in temperature of the air and gases would be: (8)

$$T = Q_h / V d C_p \dots\dots\dots (3)$$

$$= 134^\circ\text{C} \text{ (for this case)}$$

For the cold cloud case the height of the cloud was arbitrarily set at 10 m. The other parameters chosen for substitution in Eq. (1) are listed in Table C.1.

C.2.3 Internal Dose: The internal dose is determined by solving Sutton's equation⁽¹¹⁾ for concentration of radioactivity at the desired location downwind. This equation is:

$$TID = \frac{Q}{\bar{u} \pi C^2 x^{2-n}} \exp \left[\frac{-h^2}{C^2 x^{2-n}} \right] \dots\dots\dots (4)$$

TID = the total integrated dose in curies-sec/m³

Q = the curies released

C = Sutton's effective diffusion coefficient

x = the downwind distance in meters

h = the height of cloud

n = Sutton's stability parameter

$\bar{u}$ = the mean wind speed

The coefficient 2 has been dropped as a multiplier since the effect of the sea is to present an infinite medium for diffusion. The internal dose in curies-sec/m³ can be converted to rads by multiplying by 0.25.⁽²⁹⁾

Working curves to aid in the solution of this equation have been plotted. See Figs. C.1 and C.2. The TID can be determined from these figures as follows:

$$TID = Q/\bar{u} 10^m \text{ curies-sec/m}^3 \quad \dots \dots \dots (5)$$

Q = curies released

$\bar{u}$ = wind speed

m = a dimensionless number*

Enter the curve with the desired distance and obtain the exponent of 10.

With the proper Q and $\bar{u}$, the TID follows.

C.2.4 External Dose: The external doses were plotted on Figs. D.1 and D.2. These doses were calculated by a procedure outlined by Hurwitz⁽⁹⁾ and they are the sum of the gamma and beta doses to be expected from the cloud. The gamma dose is given by:

$$D(\text{rads}) = \frac{\alpha C_0}{\bar{u} r_0} F(r_0/\lambda) \quad \dots \dots \dots (6)$$

$$\alpha = 0.57 \frac{\text{E rads/m}^2}{\text{curie-hr}}$$

C_0 = curies released

$\bar{u}$ = wind speed m/hr

r_0 = effective cloud radius

$$F(r_0/\lambda) = \pi^{3/2} - 2 r_0/\lambda \ln 2\lambda/r_0$$

Plotted on page 17 of KAPL-1045, Fig. KH-9A2596.

λ = 200 m, relaxation length of gammas in air

* The use of "m" as a dimensionless number should not be confused with the use of "m" as an abbreviation for meter.

$$r_o = C_d(r_v + x)^{(2-n)/2} \dots \dots \dots (7)$$

C_d = Sutton diffusion parameter (0.187)

r_v = distance to virtual origin from origin of the accident

x = distance downwind

n = Sutton's stability parameter

The beta dose is given by:

$$D_B = \frac{D_\gamma}{2} \frac{\left(\frac{4\lambda}{r_o}\right)}{F(r_o/\lambda)} \dots \dots \dots (8)$$

D_B = beta dose in rads

D_γ = the gamma dose in rads at a distance from the origin where the cloud radius is r_o with an attenuation length λ

F_γ = given by Fig. KH-9A2596, KAPL-1045

The external dose formula assumes that a person is at a point through which the center of the cloud passes. This formula, therefore, gives the upper limit of the dose which a person may receive at a given distance from the accident. The beta dose formula is based on the assumption that the total beta and gamma energies are approximately equal;⁽⁹⁾ hence, the ionization density from the beta and gammas would be equal at the center of an infinite fission-product cloud. The gamma effect is smaller than the beta effect in the ratio:

$$F(r_o/\lambda)(4\lambda/r_o)_\gamma$$

from Eq. (8) above.

This is because of the fall-off in concentration at increasing distances from the cloud center which effectively reduces the gamma dose but not

the beta dose. However, the observer's skin produces a shielding effect and the beta dose is therefore reduced by a factor of 2.

Using the values of C and n as tabulated in Table C.1 of this appendix, working curves for determining the cold and hot cloud external doses were plotted on Figs. C.1 and C.2, respectively. The only difference between the hot and cold cases is the value of the virtual radius, r_v . For the cold cloud, the initial volume was assumed to be the volume of the reactor compartment, 10^9 cm^3 . This volume determines r_0 at $x = 0$ and therefore r_v can be determined from Eq. (7). For the hot cloud, the volume at a height of 100 m was determined by: ⁽⁸⁾

$$V_h = \frac{\Delta\theta_1}{\Delta\theta_2} V_g$$

V_h = volume at height h

V_g = volume at ground (10^9 cm^3)

$\Delta\theta_1$ = temperature above gradient*

$\Delta\theta_2$ = decrease in air temperature for height of 100 m (2 C)

Using these volumes, then, the value of r_v for the cold cloud was found to be 52 m. The hot cloud r_v was 200 m. At night the values are r_v (cold) = 360 m, r_v (hot) = 1800 m.

Fig. C.4 is the solution for various distances of the exponential:

$$\text{EXP} \left[\frac{y^2}{C^2 x^{2-n}} \right]$$

where y = crosswind distance

This is used to determine how far a vessel must go in the crosswind direction in order to reduce the dose by a factor 10^n .

* This value was determined prior to final settlement of fuel volume by design group.

C.3 Release of Fission Product Gases from Stack

The release of fission product gases from a moving stack at sea presents a slightly different problem from that from a stationary land stack. The speed of the ship, in combination with the true wind speed, creates a relative wind which acts on the gases as they leave the stack. For other ships operating in formation with the reactor-equipped vessel, it is also the relative wind with which calculations must be made to determine the deposition rate. The problem in this case is to determine what the steady state concentration of gases will be at a fixed relative distance from the stack and not to a geographically fixed point on the sea. With this in mind, Sutton's formula⁽¹¹⁾ for the concentration at a downwind position from a continuous point source was modified to include the effects of the relative wind as follows:

$$X = \frac{q}{\pi C^2 \bar{w} d^{2-n}} \text{EXP} \left[\frac{-h^2}{C^2 d^{2-n}} \right] \dots \dots \dots (9)$$

X = concentration in curies/ m^3 at fixed distance (d) from the stack

q = release rate, curies/sec

$\bar{w}$ = relative wind speed, mps

The modification is based on the following:

where $\underline{d}$ = fixed distance between ships

$\underline{v}$ = ship velocity

$\underline{u}$ = true wind speed

$$\bar{w} = \bar{v} + \bar{u} \quad \text{relative wind speed}$$

The time it takes for the instantaneous puff to reach the fixed distance d is: $t = d/w$. During this time the puff has actually traveled a distance x equal to ut . Therefore, the distance d equals wt or wx/u . If the ejecting ship and the following ship are traveling at different speeds, the speed of the following ship should be used as it is its relative speed that is important. In this case, a TID would be calculated since the ship will move through the cloud in a finite time. The effective stack height, however, is dependent on the relative wind created by the ejecting vessel. Using this relative wind, the effective stack height was determined from Fig. 5.16, AECU-3066.⁽⁸⁾ The stack diameter was chosen to be 3.16 ft, so that d^2 would be 10 ft^2 . Fig. C.5 is a plot of effective stack height and virtual origin distance, x_0 , vs wind speed. Table C.1 is a tabulation of the various parameters that were used throughout this section. Assuming various values of wind speed and distance, plots were made of distance vs m (the exponent of 10) to aid in the solution of Eq. (9). Figs. C.6 and C.7 are these plots for daytime and nighttime operation, respectively. Enter these curves with the distance and go to the curve with the correct relative wind to obtain the exponent m . The concentration is then

$$x = q/\bar{w} \cdot 10^m \quad \text{exp curies/m}^3$$

$$q = \text{curies/sec released}$$

$$\bar{w} = \text{relative wind speed, mps}$$

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C.4 Decay, Dry Deposition and Rainout

The effect of radioactive decay, dry deposition from natural settling and washout due to rain have been intentionally omitted in the previous sections since all these effects tend to decrease the doses and dose rates from those distances that are of concern to ships operating in formation, namely 2-5 miles. Neglecting these factors presents the most pessimistic picture of the concentrations as a function of distance. This section is included so that these factors can be included in the computations for a particular problem. It should be noted, however, that unless the physical factors which influence decay, deposition, and rainout are precisely known, it is better to neglect them and take action based on the more conservative analysis of the previous sections.

C.4.1 Decay: One of the problems involved in including decay in the analysis of diffusion problems is that decay is a function of time whereas concentration is primarily a function of distance. Another, and perhaps more difficult, problem is to determine which decay scheme would be proper to use. Fig. C.8 is a plot of the most important decay schemes that would be applicable to gaseous fission products. Wigner-Way⁽⁵⁾ suggests that $t^{-0.2}$ is the proper one for a combination of all fission products. This could be used when it is possible to predict that the entire contents or part of the contents of the reactor have been vaporized during the accident. Another source⁽²⁹⁾ suggests that the volatile fission products (I, Xe, and Kr) decay by $t^{-0.8}$ from 1 hr to 500 hr after shutdown. The noble gases present yet a third. This scheme was plotted from the curves of Fig. B.2, Appendix B.

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This decay commences as soon as the products leave the reactor, and this does not necessarily coincide with the time the gases leave the ship. For stack release, holdup is usually employed and, hence, decay may have proceeded for many days prior to release.

In order to use the decay factor intelligently, one must know the composition and history of the escaping gases and also the initial activity as the gases leave the ship. The time can then be computed for the desired location by dividing the distance by the mean wind speed. Using this time, enter Fig. C.8 and from the proper decay scheme, obtain the reduction factor. Divide the value obtained without decay by this factor to obtain the true value.

C.4.2 Deposition: The concentration predicted by Sutton's formulas are based only on the diffusion of the particles with time and distance and do not include any contribution due to settling out. For most practical cases, the reduction due to settling out will be small since the radioactive products which can be reasonably expected to escape are normally gaseous. It is possible for these gases to become attached to small dust particles which are influenced by gravitational forces. Settling velocities can be predicted with accuracy by Stokes' Law. The only problem, then, is one of determining the mean size of the settling particle and the proportion of the radioactive particles which attach themselves to these dust particles. This is an extremely difficult problem to solve and has been done only for the rainout case where the size and the distribution of the particles are known to a fair degree.

If an incident occurs where the fission products themselves are released as finite particles similar to a smoke plume, then the dose or dose rate

downwind due to deposition can be calculated by a modification of Sutton's equation suggested by Chamberlain: ⁽³⁰⁾

$$\Delta = \frac{Q V_g}{\pi \bar{u} C^2 x^{2-n}} \exp \left[\frac{-4 V_g x^{n+2}}{u n C_z \pi^{1/2}} \right] \exp \left[\frac{-(y^2 + h^2)}{C^2 x^{2-n}} \right] \quad (10)$$

V_g = settling velocity

Δ = curies/m² if Q is in curies

Δ = curies/m²-sec if Q is in curies/sec

Assuming a mean disintegration energy of 1 mev, Δ can be converted to rads/hr or rads/hr-sec by multiplying by 16.4 for a distance of 1 m from the contaminated surface. ⁽⁵²⁾ Table C.3 gives a value of V_g for various particle sizes. Figs. C.9 and C.10 are solutions to the exponential:

$$\exp \left[\frac{4 V_g x^{n/2}}{n \bar{u} C_z \pi^{1/2}} \right] \quad (11)$$

These curves are used in conjunction with C.1, C.2, C.6, and C.7 to solve the dose or dose rate for deposited activity. Thus,

$$TID = \frac{Q V_g}{\bar{u} 10^{m+m'}} \quad (\text{curies/m}^3) \quad (12)$$

m = from Figs. C.1 and C.2 (internal dose)

m' = from Figs. C.9 and C.10

$$TID = \frac{Q V_g}{\bar{u} 10^{m+m'}} \quad (\text{curies/m}^2\text{-sec}) \quad (13)$$

m = from Figs. C.6 and C.7

m' = from Figs. C.9 and C.10

Only very stable conditions ($n = 0.4$, $C = 0.5$) and particles larger than 7 microns provide values for Eq. (11) that are significant for distances less than 10^5 m. Experience has indicated that the mean size of fallout particles from radioactive clouds has often been in the neighborhood of 2 microns. (31)(32) In most cases, then, for distances that are of interest in tactical maneuvering, the deposition from dry particles can be neglected. For daytime conditions when the velocity of fall can be estimated, the dose due to deposition can be estimated by letting $m' = 0$ in Eqs. (12) and (13).

C.4.3 Rainout: Rainout is analyzed in the same manner as dry deposition except that all the particles are now raindrops. A given raindrop, however, affects particles throughout the height of the cloud as it falls and, therefore, the height of the cloud is not important. Integration of Sutton's equation with respect to height then gives: (8)

$$R = \frac{\Delta Q}{u x^{1/2} C x^{(2-n)/2}} \exp \left[\frac{-\Delta x}{u} \right] \exp \left[\frac{-v^2}{c^2 x^{2-n}} \right] \quad (14)$$

Δ = fraction of the activity in the cloud removed/sec

R = curies/m² when Q is in curies

R = curies/m²-sec when Q is in curies/sec

The depletion factor (Δ) is related to many other factors besides rainfall characteristics. However, a complete analysis is beyond the scope of this report. Table C.4 is a list of values taken from Chamberlain's work (20) for two rainfall figures; 0.02 in/hr is considered an average figure, and 0.15 in/hr is listed to indicate the effect of a heavy rainfall.

The general solution to Eq. (14) is obtained from the working curves plotted on Fig. C.11. The "b" curves for night and day conditions are

based on the parameters listed in Table C.1. To obtain a solution for a particular distance, the equation:

$$a = \Delta x / u \quad (15)$$

must be solved first. A value of " Δ " is chosen from Table C.4. With the computed value of "a", enter the left ordinate of Fig. C.11 and proceed to the curve e^a . The abscissa, then, is the reduction factor due to the exponential. Enter the right ordinate with the desired distance and proceed to the proper "b" curve to obtain a second factor. Then:

$$R = \Delta Q / u b e^a \quad (16)$$

$$R = \text{curies/m}^2 \text{ for } Q \text{ in curies}$$

$$R = \text{curies/m}^2\text{-sec for } Q \text{ in curies/sec.}$$

To convert to rads/hr or rads/hr-sec, multiply by 16.4.

C.5 Problems Involving the Gaseous Fission Products

Problem 1: A disaster to a reactor-equipped ship occurs allowing a substantial quantity of radioactivity to escape as a gaseous cloud. What doses could be expected by ship personnel on the stricken vessel and on a vessel downwind? What action could the second vessel take in order to reduce the total dose to 25 rads or less?

Conditions:

- (1) Assume that 1.74×10^9 curies is released. This is 100% of the decay activity from a 100-Mw reactor. See Table C.2.
- (2) Wind speed is 4 mps.
- (3) The second vessel is 5,000 m downwind.

Solution:

Since the problem makes no assumption as to whether a cold or hot cloud resulted, the solution for both cases will be presented. A range of 100 m is assumed for the stricken vessel; therefore, from Fig. C.1, the cold cloud case, the following values of "m" are obtained:

External night, 1.9
Internal night, negligible

External day, 2.8
Internal day, 2.9

From Fig. C.2, the hot cloud case, the following values are obtained:

External night, 2.9
Internal night, negligible

External day, 3.4
Internal day, negligible

By simple algebra the internal and external doses are combined by the following formula:

$$TID = \frac{Q}{u} \left(\frac{10^{m_i} + 10^{m_e}}{10^{m_i} + m_e} \right)$$

m_e = external dose exponent

m_i = internal dose exponent

Using this formula for the cold cloud dose during the day:

$$TID = \frac{1.74 \times 10^9}{4} \left(\frac{10^{2.9} + 10^{2.8}}{10^{5.7}} \right)$$

$$TID = 4.4 \times 10^6 \frac{\text{curies-sec}}{m^3}$$

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By a similar process the doses received on the stricken ship for the various cases are:

Cold cloud-night = 1.4×10^6 rads*
 day = 3.1×10^5 rads

Hot cloud-night = 1.4×10^5 rads
 day = 4.3×10^4 rads

Referring again to Figs. C.1 and C.2 for the ship positioned 5,000 m downwind, the following values of "m" are obtained:

Cold cloud   External-night, 3.6
                   Internal-night, 3.8

                  External-day, 4.9
                   Internal-day, 5.4

Hot Cloud   External-night, 3.8
                   Internal-night, 5.6

                  External-day, 5.2
                   Internal-day, 5.5

Using these values of "m" and the above formula gives the following doses for the downwind vessel:

Cold Cloud-night, 45,000 rads
 day, 1,800 rads

Hot Cloud-night, 17,700 rads
 day, 1,000 rads

With a wind of 4 mps it will take the cloud approximately 20 min to reach the downwind vessel. The above doses were calculated without considering decay. Referring to Fig. C.11 the decay of the total fission products in 1,200 sec amounts to a reduction factor of 4. Therefore, the above figures should be reduced by this amount. If the downwind vessel is willing to take a total dose of 25 rads, it has 20 min to take

* curies-sec/m³ converted to rads by multiplying by 0.25.

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evasive action. This can best be done by taking a crosswind position. For the cold cloud-night case with decay considered, a reduction factor of $\frac{45,000}{4 \times 25}$ or 450 will be required. Using Fig. C.4, enter the bottom with an "m" of 3 (this is equivalent to a reduction factor of 1,000) and go up to the 5,000-m curve. This yields a "y" of 900 m. The ship has 20 min to take a position 900 m crosswind to the stricken vessel. The other cases can be handled in a similar fashion.

Problem 2: What is the dose rate to shipboard personnel and to a downwind vessel if a ship operating at 100 Mw wishes to discharge the noble gases immediately and continuously, assuming 1% of the equilibrium quantity of gas is discharged continuously?

Conditions:

- (1) Relative wind is 6 mps.
- (2) The downwind vessel is 2,000 m away.

Solution:

Figs. C.6 and C.7 indicate that the shipboard personnel will not receive appreciable doses.

For daytime operation the ship stationed 2,000 m downwind, $m = 4.9$, therefore:

$$\begin{aligned} D &= 6.8 \times 10^6 / 6 \times 8 \times 10^4 \\ &= 0.14 \times 10^2 = 14 \text{ curies/m}^3 \\ &= 12,700 \text{ rads/hr.} \end{aligned}$$

$$\begin{aligned} q &= 1.36 \cdot 10^6 \text{ curies/sec (Table C.2)} \\ D &= \frac{1.36 \cdot 10^6}{6 \times 8 \times 10^4} \\ &= 2.8 \text{ curie/m}^3 \\ &= 2,550 \text{ rad/hr} \end{aligned}$$

Problem 3: What position crosswind must the second vessel in Problem 3 take in order to reduce the dose rate to 0.025 rad/hr?

Solution:

The reduction in dose must be $2,550/0.025$ or 10^4 . Therefore, on Fig. C.4, enter with 4 and go to the 2,000-m curve to obtain a y of 500 m. The ship must move a distance of 500 m crosswind to reduce the dose rate to 0.025 rad/hr.

Problem 4: What is the maximum emission in curies/sec that would be allowed in order that the maximum dose rate for any position would be 1 rad/hr?

Solution:

From Fig. C.6 it can be seen that the minimum reduction factor is on the order of 10^3 . A concentration of $1/900$ curies/ m^3 will produce this factor.

Therefore:

$$\begin{aligned} q &= X 10^3 \\ &= 1/900 \cdot 10^3 \\ q_{\max} &= 1.1 \text{ curies/sec.} \end{aligned}$$

Problem 5: What is the maximum total dose that a ship would receive if it passed through the plume of a reactor vessel emitting 1,000 curies/sec?

Conditions:

- (1) Reactor Vessel: Speed 10 knots (5 mps): Course $270^\circ T$.
- (2) Passing Vessel: Speed 10 knots (5 mps): Course $043^\circ T$.
- (3) True Wind: 4 mps at $130^\circ T$.
- (4) At time zero, the position of the passing vessel is 4,500 m bearing $220^\circ T$ average.

Solution:

From the maneuvering board solution of the above tactical problem, it can

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Problem 5: Maneuvering Board Solution.

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be seen that the point of closest approach to the center of the plume is about 2,000 m. The relative wind is 6 mps at 183°T. The relative speed of the passing vessel is 18 knots at 067°T. From Fig. C.4, we see that a crosswind distance of 500 m will give a reduction in dose of 10^4 . To arrive at the maximum possible dose, assume that the ship receives the dose rate it receives at the center of the plume (this is the maximum rate) for the period of time it takes to travel 1,000 m, i.e., the 500 m crosswind distance on both sides of the center line. It is known that the actual dose rate varies from that at the center to 10^{-4} that of the center at 500 m, therefore, the dose calculated will be a maximum. To determine the maximum dose rate, go to Fig. C.6, enter the graph for 2,000 m and a $w = 6$ and obtain an m of 4.9. The maximum dose rate will be:

$$\begin{aligned} X_{\max} &= 1,000/6 \times 10^{4.9} \\ &= 0.0021 \text{ curies/m}^3 \\ &= 1.89 \text{ rad/hr} \end{aligned}$$

It takes the vessel 1,000/9 sec or 1.85 min to traverse the crosswind distance involved. Therefore, the maximum dose the passing vessel would receive is:

$$\begin{aligned} D_{\max} &= 1.89 \times 1.85/60 \\ &= 0.058 \text{ rads} \end{aligned}$$

Problem 6 What is dose rate after 20 min due to the deposition of material 10,000 m downwind from a vessel emitting 6.8×10^6 curies/sec?

Conditions:

- (1) Relative wind = 4 mps
- (2) $v_g = 2.0 \times 10^{-2}$ mps
- (3) Nocturnal conditions: $n = 0.4$ $C = 0.05$.

Solution:

Enter Fig. C.10 with $x = 10^4$ and at $\bar{u} = 4$ obtain:

$$m' = 1.6$$

Enter Fig. C.7 with $d = 10^4$ and at $w = 4$ obtain:

$$m = 4.6$$

Enter Fig. C.8 with $t = \frac{10^4}{4} = 2.5 \times 10^3$ sec and obtain for noble gases--
no holdup

$$\text{Decay} \approx 1.0$$

$$D = \frac{6.8 \times 10^6 \times 2 \times 10^{-2} \times 16.4 \times 20 \times 60}{4 \times 10^{6.2}}$$

$$= 418 \text{ rads/hr}$$

Problem 7: What would be the dose rate in problem 6 if the mechanism were rainout rather than dry deposition?

Conditions:

$$(1) \Delta = 2.0 \times 10^{-4}$$

Solution:

$$a = \frac{\Delta x}{u} = \frac{2 \times 10^{-4} \times 10^4}{4} = 0.5$$

$$e^{0.5} = 1.65$$

$$\text{for } X = 10^4 \quad b = 1.4 \times 10^3$$

$$X = \frac{6.8 \times 10^6 \times 2 \times 10^{-4} \times 16.4 \times 20 \times 60}{4 \times 1.4 \times 10^3 \times 1.65}$$

$$= 2,930 \text{ rads/hr}$$

TABLE C.1
PARAMETERS FOR CONCENTRATION CALCULATIONS
Wind Speed (m/hr)

Parameter	1	2	4	10	15
C - virtual diffusion coefficient	$(0.035)^{1/2}$	$(0.035)^{1/2}$	$(0.035)^{1/2}$	$(0.035)^{1/2}$	$(0.035)^{1/2}$
x_0 - meters	110	78	58	41	36
h - meters	425	175	75	31	24
n - non- dimensional stability parameters	0.023	0.023	0.023	0.023	0.023

TABLE C.2
DECAY ACTIVITY FOR 100-Mw REACTOR⁽²⁹⁾ (curies)

Activity	t = 0	t = 1 hr	t = 24 hr
Total	$1.74 \cdot 10^9$	$1.74 \cdot 10^8$	8.2×10^7
Volatile	$8.3 \cdot 10^8$	$8.3 \cdot 10^7$	1.6×10^7
Noble Gases	$1.36 \cdot 10^8$	$1.36 \cdot 10^7$	6.8×10^6

TABLE C.3

SETTLING VELOCITY OF SMALL PARTICLES*

<u>Particle Diameter (microns)</u>	<u>Velocity (mps)</u>
0.5	2.5×10^{-5}
1.5	2.0×10^{-4}
3.5	1.0×10^{-4}
7.0	4.0×10^{-3}
15.0	2.0×10^{-2}

* Computed from Stokes' Law (particle density of 2.5).

TABLE C.4

RAINOUT OF SMALL PARTICLES⁽⁶⁾

<u>Particle Diameter (microns)</u>	<u>Δ - Proportion of Cloud Removed/sec</u>	
	<u>Rainfall 0.02 in./hr</u>	<u>Rainfall 0.15 in./hr</u>
0.5	1.0×10^{-5}	2.0×10^{-5}
1.5	1.5×10^{-5}	3.0×10^{-5}
3.5	6.0×10^{-5}	3.0×10^{-4}
7.0	1.5×10^{-4}	7.0×10^{-4}
15.0	2.0×10^{-4}	1.0×10^{-3}

Fig. C.4. Doses From Cold Cloud.

Fig. C.2. Doses from Hot Cloud.

FIGURE C.3

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CROSSWIND COMPONENTDISTANCE y TO REDUCEDOSE BY 10^m AT RANGE x

FIGURE C.4

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FIGURE C.5

EFFECTIVE STACK HEIGHT h AND VIRTUAL
ORIGIN DISTANCE x_0 VS WIND SPEED

Fig. C.6. Sea Level Concentration Downward from Moving Ship - Daytime.

Fig. C.7. Sea Level Concentration Downwind from Moving Ship - Night.

Fig. C.8. Radioactive Decay of Fissions Products After Shutdown.

Fig. C.9. Deposition Curves for 7μ Particles.

Fig. C.11. Working Curves for Solving the Rainout Equation.

APPENDIX DDISPERSION OF SOLUBLE RADIOACTIVE MATERIAL IN WATER

If a soluble substance is placed in water at a point, the concentration at the instant of deposition will be infinite at that point and zero at all others in the medium. As time increases, the concentration at the initial point becomes finite and decreases, while the concentration at other points in the medium increases to a maximum, then decreases. This behavior is the result of diffusion; and, in turbulent water, the dominant diffusion process is turbulent eddy diffusion, where the size and strength of the eddies effectively transport dissolved materials.

The equation describing molecular diffusion of a soluble material is:⁵⁴

$$\frac{DQ}{Dt} = \nabla A (\nabla Q) - \lambda Q - R \quad (1)$$

where:

Q = concentration, number/centimeter cubed

t = time, seconds

D' = total derivative operator (includes convection)

∇ = Laplacian operator.

A = diffusion coefficient, cm²/sec

λ = decay constant, sec⁻¹

R = removal function, such as for settling out of suspended or dissolved material.

The solution to Eq. (1) for an instantaneous point source, implying that the material introduced is immediately completely soluble and the diffusion coefficient is constant,

$$Q = S_0 \frac{e^{-\frac{(x-vt)^2}{4A_x t}}}{(4\pi A_x t)^{1/2}} \frac{e^{-\frac{y^2}{4A_y t}}}{(4\pi A_y t)^{1/2}} \frac{e^{-\frac{z^2}{4A_z t}}}{(4\pi A_z t)^{1/2}} e^{-\lambda t} \quad (2)$$

where: S_0 = quantity of material introduced

The function describing removal by settling out is omitted, and a velocity in the "x" direction only is assumed.

Difficulties are encountered in the application of the molecular diffusion equation to turbulent eddy diffusion phenomena for two major reasons.

One, the turbulent eddy diffusion coefficient, A , is not constant, nor isotropic,⁵³ but depends on currents, winds, temperatures and surface irregularities in a very complex manner. In any particular application, a spectrum of eddies exists; thus making the choice of a single coefficient of diffusion difficult if not impossible. Further, density currents can radically change a diffusion pattern.⁵⁴

Second, according to Richardson⁵⁵ as explained by Stommel,⁵⁶ the "distance-neighbor" theory is shown to be the process describing diffusion by turbulent eddies. The "distance-neighbor" theory states that the probability of two particles being ℓ distance apart is a function of their initial separation distance, not on their separate original distance from some other fixed point, i.e., an origin. Diffusion theory uses distance from an origin as a basis for the probability that a particle will be that distance from the origin at a given later time.

Richardson's equation takes the following form:

$$\frac{\delta Q}{\delta t} = \frac{\delta Q}{\delta} K(\ell) \frac{\delta Q}{\delta} \quad (3)$$

where: ℓ = distance between two particles considered

$K(\ell)$ = a diffusion coefficient which is a function of distance between particles.

Experiment shows:

$$K(\ell) = k \ell^{4/3} \quad (4)$$

(where K is an empirical constant),

and that there is some correlation between $K(\ell)$ and $A(x)$.⁵⁶

The solution of Richardson's equation as a function of ℓ , of course, has no direct applicability; but, is of interest since it shows equation (1) may not be applied in the strictest sense.

One approach to the practical problem is to present a solution to the molecular diffusion equation with modifications which tend to fit the equation to experimental data. Sutton⁵⁷ has done this, in atmospheric diffusion theory, with a stability parameter. Sverdrup⁵³ assumes the turbulent eddy diffusion coefficient proportional to the mean radius of the diffusion substance, implying that the diffusion coefficient is a function of the scale of observation. Glover,⁵⁴ in studying diffusion in streams, suggests that the diffusion coefficient is proportional to the stream velocity with a value one tenth as great in the cross stream direction.

In this report it is proposed to use characteristic values of turbulent eddy diffusion coefficients in the molecular diffusion equation in order that estimates of dose rates resulting from fission products in solution may be made. Accordingly, typical values of turbulent eddy diffusion coefficients are presented. Table 1, Turbulent Eddy Diffusion Coefficients, will be found at the end of this text.

These coefficients are used in the diffusion equation to estimate concentration of soluble materials as a function of distance and time. The diffusion of soluble fission products is believed by the authors to

be similar to the diffusion of dye marker, or fluorescein dye. Using typical values of diffusion coefficients derived from experiments with dye marker is extremely pessimistic and should result in overestimating dose rates. However, the AEC used values of the diffusion rate, typical for dye marker, in calculations for the spread of contaminant in Operations Crossroads.⁵⁸ Using small values of diffusion coefficients also implies a relatively stagnant water such as might be found in a large harbor.

1. Gamma Ray Dose Rates Analyses

It is assumed that all the fission products released in water go into solution immediately. The dose rate received is calculated assuming a slowly varying concentration of gamma ray sources in an infinite medium. In such a system the energy absorbed must equal the energy emitted and the dose rate in the medium is determined by the application of a conversion factor.⁶³

$$D^0(\text{Rads/hr}) = Q(\text{Mev/cm}^3\text{-sec}) 5.767 \times 10^{-5} \quad (5)$$

The rad is a unit of dose equivalent to the absorption of 100 ergs per gram of tissue.

At one meter above a water medium, the dose rate may be approximated by taking one-half of Eq. (5).

Concentration distribution may be assumed by one of three processes: one by assuming a fixed geometry and a uniform distribution of sources; then

$$Q = S_0/V \quad \text{where } V = \text{volume assumed; } (6a)$$

next, by point source geometry in an infinite medium such as

$$Q = \frac{e^{-\frac{(x-vt)^2}{4A_x t}}}{(4\pi A_x t)^{1/2}} \frac{e^{-\frac{y^2}{4A_y t}}}{(4\pi A_y t)^{1/2}} \frac{e^{-\frac{z^2}{4A_z t}}}{(4\pi A_z t)^{1/2}} \quad (6b)$$

and lastly, by assuming vertical line source geometry (cylindrical) as

$$A = \frac{S_o}{D} \frac{e^{-\frac{(x-vt)^2}{4A_x t}}}{(4\pi A_x t)^{1/2}} \frac{e^{-\frac{y^2}{4A_y t}}}{(4\pi A_y t)^{1/2}} \quad (6c)$$

where: D = depth of the water (i.e., length of line source).

If isotropic turbulence exists and it is desired to use the relation $A/r = \text{constant}$ (1), then for spherical geometry and velocity equal to zero

$$Q = \frac{S_o}{r^{3/2}} \frac{e^{-\frac{r^2}{4(A/r)t}}}{[4\pi (A/r) t]^{3/2}} \quad (6d)$$

1.1 Isotropic Turbulence

1.1.1 Dose Rate from an Instantaneous Source: The equation describing isotropic diffusion as derived above is,

$$Q = \frac{S_o}{(4\pi A t)^{3/2}} e^{-\frac{r^2}{4A t}} t^{-0.2} \quad (7)$$

where $t^{-0.2}$ is included as the decay factor appropriate to reactor fission products. Equation (7) may be rewritten as

$$\frac{Q}{S_o} = e^{-X} t^{-0.2} \quad (8)$$

where X = function of (r, A, t) .

Figures 1, 2, 3 and 4 show X as a function of time and distance from the point of deposition for diffusion coefficients of 3, 30, 300

and $10^5 \text{ cm}^2/\text{sec}$. The dose rate is

$$\begin{aligned} D^0(r, A, t) &= 5.767 \times 10^{-5} Q \\ &= 5.767 \times 10^{-5} S_0 e^{-X} t^{-0.2} \text{ rads/hr} \end{aligned} \quad (9)$$

As an example, enter Figure 3 for $A = 300 \text{ cm}^2/\text{sec}$ and assume $r = 1000 \text{ cm}$ and $t = 1000 \text{ seconds}$. Assume an initial source of $1.2 \times 10^{19} \text{ Mev per second}$

$$X \approx 25$$

$$\begin{aligned} D^0(1000, 1000) &= (5.767 \times 10^{-5})(1.2 \times 10^{19})e^{-25} 1000^{-0.2} \\ &= 6.9 \times 10^3 \text{ Rads/hr} \end{aligned} \quad (10)$$

If $r = 5000 \text{ cm}$

$$\begin{aligned} D^0(5000, 1000) &= (5.767 \times 10^{-5})(1.2 \times 10^{19})e^{-46} 1000^{-0.2} \\ &= 1.7 \times 10^{-6} \text{ Rads/hr} \end{aligned} \quad (11)$$

The presence of boundaries such as the ocean floor, harbor bottom or water surfaces acts as a bar to the diffusion process. However, Figures 1, 2, 3 and 4 may be used for cases of isotropic turbulence with a source under water for dose rates on a boundary provided the time curves do not continue horizontally past the distance (boundary) in question. (Otherwise see non-isotropic solution following this discussion.)

Since the relaxation length of one Mev gamma ray is about 100 meters in air, the dose to a person one meter above the water surface is essentially one half that of a person in the water. With a point source on a boundary such as the ocean floor or harbor bottom the semi-infinite geometry essentially multiplies the source by two. Therefore, the two previous examples apply, but are multiplied by two in the semi-infinite

case for a person in the water. The dose rate is the same as shown one meter above the water in the semi-infinite geometry.

Figure 5 shows the minimum allowable distance from point of deposition based on one Rad per hour, as a function of time for deposition of 1.2×10^{19} mev per second of fission products.

1.1.2 Dose Rate at the Center of Deposition: The dose rate at the center of deposition of a soluble radioactive material, assuming a buildup factor of unity in an infinite homogeneous water system is,⁶³

$$D^0(r,t) \text{ rad/hr} = 5.767 \times 10^{-5} \left(\frac{\mu_a}{\rho} \right) E_0 \Gamma^0(r,t) \quad (12)$$

where:

E_0 = photon energy

$\frac{\mu_a}{\rho}$ = energy absorption mass attenuation coefficient for the energy and material (tissue) considered

$\Gamma^0(r,t)$ = current density of unscattered photons summed or integrated over all sources

Isotopic decay may be included in Eq. (12) by multiplying by a decay function, such as $t^{-0.2}$ or $e^{-\lambda t}$. Furthermore,⁶³

$$\Gamma^0(r,t) = \int \frac{Q e^{-\mu r}}{4\pi r^2} dV \quad (13)$$

where:

μ = linear absorption coefficient for water

Q = defined by equation (7)

$dV = 2\pi r dr$

Now, let

$$\alpha = \sqrt{2\lambda t}$$

and

$$w = (\mu r / 2\alpha^{1/2})^2 + \mu r + \alpha = (\mu r / 2\alpha^{1/2}) + \alpha^{1/2} \quad ^2$$

Substitute α and w in equation (12) and get,

$$D^0(r,t) = \frac{5.767 \times 10^{-5}}{(4\pi)^{3/2}} S_0 \left(\frac{\mu_a}{\rho}\right) \mu^2 \left\{ \frac{e^\alpha}{\alpha} \int_\alpha^\infty e^{-w} w^{-1/2} dw \right\} \quad (14)$$

Noting that

$$\begin{aligned} \int_\alpha^\infty e^{-w} w^{-1/2} dw &= \int_0^\infty e^{-w} w^{-1/2} dw - \int_0^\alpha e^{-w} w^{-1/2} dw \\ &= \Gamma\left(\frac{1}{2}\right) - \int_0^\alpha e^{-w} w^{-1/2} dw \end{aligned} \quad (15)$$

Then:

$$D^0(r,t) = \frac{5.767 \times 10^{-5}}{(4\pi)^{3/2}} S_0 \left(\frac{\mu_a}{\rho}\right) \mu^2 \frac{e^\alpha}{\alpha} \left\{ \sqrt{\pi} - 2\alpha^{1/2} \left[1 - \frac{\alpha}{3} + \frac{\alpha^2}{5 \cdot 2} - \frac{\alpha^3}{7 \cdot 2} \dots \right] \right\} \quad (16)$$

For evaluation purposes, Figure 6 shows a plot of α versus

$$\frac{e^\alpha}{\alpha} \int_\alpha^\infty e^{-w} w^{-1/2} dw, \text{ for } \alpha = .01 \text{ to } 1000. \quad (17)$$

Further, for $\alpha \gg 2$

$$\int_\alpha^\infty e^{-w} w^{-1/2} dw = \frac{0.78 e^{-\alpha}}{\alpha^{1/2}} \quad (18)$$

Using buildup factors as a function of relaxation length makes the integral extremely difficult to evaluate analytically. A method used at ORNL (original source not known to the authors) is to divide the mass attenuation coefficient by 1.2 as an approximation for the buildup.

As an example, suppose soluble radioactivity is placed instantaneously

on the surface of water with isotropic turbulence. To approximate a dose rate, assume:

$$S_0 = 1.2 \times 10^{19} \text{ mev/sec}$$

$$A = 300 \text{ cm}^2/\text{sec}$$

$$t = 100 \text{ sec}$$

$$\mu = .07 \text{ for one mev gamma rays}$$

$$\therefore \alpha = 147, \text{ or } 122 \text{ if the factor } 1.2 \text{ is used.}$$

Enter Figure 6 at $\alpha = 147$ and get 0.00045 for the function of α .

$$D^0(0,100) = \frac{2(5.767 \times 10^{-5})(1.2 \times 10^{19})(0.03)(0.07)^2(4.5 \times 10^{-4})}{(4\pi)^{3/2}} \\ \approx 2.0 \times 10^6 \text{ Rads/hr} \quad (19)$$

Using $\alpha = 122$,

$$D^0(0,100) = 2.8 \times 10^6 \text{ Rads/hr}$$

Compare this result to that obtained from Figure 3 as follows,

$$D^0(0,100) \approx e^{(34.1 - X)} = e^{34.1 - 20} = e^{14.1} \\ = 3.6 \times 10^6 \text{ Rads/hr}$$

The comparison is good considering the extreme extrapolation and approximations involved.

1.1.3 Dose Rate from a Continuous Source: In the case of continuous isotropic point source in an infinite isotropic medium, the concentration at a point is defined by a modified form of equation (7),

$$Q = \int_0^t \frac{e^{-\frac{r^2}{4A(t-\xi)}}}{[4\pi A(t-\xi)]^{3/2}} S_0 d\xi \quad (20)$$

where: s_o = source emission rate, no./sec

ξ = infinitesimal time at which a particular $s_o d$ is introduced

$$S_o = \int_{\xi=0}^t s_o d\xi$$

Equation (20) is the product of the sum of the material introduced and the distribution function for the material in the dispersing media. To obtain a solution, let

$$B = \frac{r^2}{4A} \text{ and } W = \frac{r^2}{4A(t-\xi)} ; \text{ therefore,}$$

$$\frac{B}{W} = (t - \xi)$$

Substitute into equation (20) and get,

$$Q = \frac{s_o}{(4\pi A)^{3/2}} \int_{B/t}^{\infty} e^{-W} W^{-1/2} dW \quad (21)$$

Now let

$$\frac{B}{t} = \alpha' = \frac{r^2}{4At}$$

substitute in equation (21) and get,

$$Q = \frac{s_o e^{-\alpha'} \alpha'}{(4\pi A)^{3/2}} \left\{ \frac{e^{\alpha'}}{\alpha'} \int_{\alpha'}^{\infty} e^{-W} W^{-1/2} dW \right\} \quad (22)$$

The term in brackets may be evaluated from Figure 6 or the integral may be approximated by $(0.78 e^{-\alpha'^{1/2}})/\alpha'^{1/2}$, giving,

$$Q = \frac{0.78}{(4\pi A)^{3/2}} s_o \frac{e^{-\alpha'}}{\alpha'^{1/2}} \text{ for } \alpha' \gtrsim 2 \quad (23)$$

Dose rates may be calculated as shown in the example following equation (18).

Another method approximation of concentration is:

$$Q = \sum_1 s_0 \frac{\Delta t_1 e^{-\frac{r^2}{4At_1}}}{(4\pi A t_1)} \quad (24)$$

where:

Δt_1 = the 1th increment of time

t_1 = time from start of 1th increment of source

As an example, assume

$$s_0 = 1.2 \times 10^{19} / 1,000 = 1.2 \times 10^{16} \text{ nev/sec}^2$$

$$\Delta t_1 = 100 \text{ sec}$$

What is the dose rate at $r = 1,000$ cm and $t = 1,000$ seconds: for
 $A = 300 \text{ cm}^2\text{-sec}$

<u>t_1</u>	<u>Increment</u>	<u>Q/s_0</u>
1000	1	$.050 \times 10^{-9}$
900	2	.055
800	3	.058
700	4	.061
600	5	.062
500	6	.064
400	7	.0575
300	8	.045
200	9	.029
100	10	.001
	$\sum_1$	$.500 \times 10^{-9}$

$$D^0(1000,1000) \approx (5.767 \times 10^{-5})(1.2 \times 10^{16})(.5 \times 10^{-9}) \\ \approx 3.5 \times 10^2 \text{ Rads/hr}$$

This method may be applied to a varying source.

1.2 Non-Isotropic Turbulence

The equation for non-isotropic diffusion is:

$$Q = \frac{S_0 e^{-\frac{(x-vt)^2}{4A_x t}}}{(4\pi A_x t)^{1/2}} \cdot \frac{e^{-\frac{y^2}{4A_y t}}}{(4\pi A_y t)^{1/2}} \cdot \frac{e^{-\frac{z^2}{4A_z t}}}{(4\pi A_z t)^{1/2}} \quad (25)$$

If the source is at a boundary multiply by two, if at the intersection of two boundaries multiply by four, and if at the intersection of three boundaries (diffusing in only one quadrant) multiply by eight.

Suppose the source lies at the bottom of a channel. (The typical depth assumed in this report is ten meters, 36 feet.) The existence of the water surface acts as a bar to diffusion in the "Z" direction. However, the solution is applicable if,⁵⁴

$$\frac{D^2}{4\pi A t} > 4$$

where D = depth.

Otherwise, solve for t_2 in, $D^2 = 16\pi A t_2$, and substitute t_2 in the following series,⁵⁴

$$\frac{e^{-\frac{z^2}{4A_z t}}}{(4\pi A_z t)^{1/2}} \approx \frac{0.4820}{D} e^{-\frac{A_z \pi^2 (t-t_2)}{D^2}} \cos \frac{\pi z}{D} \quad (26)$$

$$+ 0.0722 e^{-\frac{4 A_z x^2 (t-t_2)}{D^2}} \cos \frac{2xz}{D} + \frac{0.433}{D}$$

In general, the interest is in the maximum dose rate. This occurs at $y = 0$, $x = 0$, $v = 0$, or $y = 0$, $x = vt$ if the velocity is constant with depth. If the velocity is not constant with z , then the maximum concentration is approximately the same but varies with x as shown in the diagram below.

Diagram: The Effect of Variable Velocity on Concentration

Note that both curves have approximately the same maximum.

Figures 7 and 8 show X as a function of time, and depth of 1000 centimeters and 1500 centimeters (36 and 45 feet) respectively for three combinations of diffusion coefficients; $A_x = A_y = A_z = 300 \text{ cm}^2/\text{sec}$, $A_x = 300$, $A_y = A_z = 30 \text{ cm}^2/\text{sec}$, and $A_x = A_y = 300$, $A_z = 30 \text{ cm}^2/\text{sec}$. Surface

dose rate be calculated from:

$$D^0(1000,t) = (5.767 \times 10^{-5}) S_0 e^{-X}$$

For example, with 1.2×10^{19} mev/sec source and $A_x = A_y = A_z$
 $= 300 \text{ cm}^2/\text{sec}$.

$$D^0(1000,1000) = (5.767 \times 10^{-5})(1.2 \times 10^{19})(e^{-30}) = 69 \text{ Rads/hr}$$

1.2.1 Instantaneous Point Source at the Surface: Effectively at
 $x = y = 0$, the concentration varies as

$$Q_{\max} = \frac{2 S_0}{(4\pi)^{3/2} A_x^{1/2} A_y^{1/2} A_z^{1/2} t^{3/2}} \quad (28)$$

1.2.2 Vertical Line Sources: The equation applicable to a vertical
line source is:

$$Q = \frac{S_0 e^{-\frac{(x-yt)}{4A_x t}} e^{-\frac{y^2}{4A_y t}}}{D(4\pi A_x t)^{1/2} (4\pi A_y t)^{1/2}} \quad (29)$$

where: D = the depth of the channel

Effectively only the first 100 cm in depth contributes to the dose
rate on the surface. This is diffusion in two dimensions and similar
to the point isotropic source on the surface.

$$Q_{\max} = \frac{S_0}{D 4\pi A_x^{1/2} A_y^{1/2} t} \quad (30)$$

1.2.3 Continuous Point Sources: The case consisting of a continuous
point source under water may be solved in the following manner.

$$Q = \int_0^t \frac{s_0 e^{-\frac{(x-v[t-\xi])^2}{4A_x(t-\xi)}} e^{-\frac{y^2}{4A_y(t-\xi)}} e^{-\frac{z^2}{4A_z(t-\xi)}}}{(4\pi)^{3/2} A_x^{1/2} A_y^{1/2} A_z^{1/2} (t-\xi)^{3/2}} d\xi \quad (31)$$

Neglecting diffusion blocking due to surface boundary and taking the case for the maximum dose rate on the surface; i.e., $x = y = v = 0$, and substituting,

$$W = \frac{z^2}{4A_z(t-\xi)} \quad , \quad \alpha = \frac{z^2}{4A_z t}$$

get:

$$Q = \frac{s_0 e^{-\frac{z^2}{4A_z t}} e^{\frac{z^2}{4A_z t}} \left(\frac{z^2}{4A_z t}\right)^{1/2}}{(4\pi)^{3/2} A_x^{1/2} A_y^{1/2} A_z^{1/2} t^{1/2} \left(\frac{z^2}{4A_z t}\right)^{1/2}} \int_{\frac{z^2}{4A_z t}}^{\infty} e^{-W} W^{-1/2} dW \quad (32)$$

which is put into the form:

$$Q = \frac{s_0 e^{-\alpha} \alpha^{1/2}}{(4\pi)^{3/2} A_x^{1/2} A_y^{1/2} A_z^{1/2}} \left\{ \frac{e^{\alpha}}{\alpha} \int_{\alpha}^{\infty} e^{-W} W^{-1/2} dW \right\} \quad (33)$$

The term in brackets has been plotted in Figure 6 as a function of α . The graph may be used to calculate dose rates. For large α , ($\alpha \geq 2$), the integral term behaves approximately like $0.78 e^{-\alpha/\alpha^{1/2}}$ and:

$$Q = \frac{s_0 (0.78) e^{-\alpha}}{(4\pi)^{3/2} A_x^{1/2} A_y^{1/2} A_z^{1/2} \alpha} \quad (34)$$

1.2.4 Alternate Method for Continuous Point Source: The continuous source problem is approximated in a manner similar to the point isotropic case.

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$$Q = \frac{s_0 \Delta \xi e^{-\frac{(x-vt_1)^2}{4A_x t_1}} e^{-\frac{y^2}{4A_y t_1}} e^{-\frac{z^2}{4A_z t_1}}}{(4\pi A_x t_1)^{1/2} (4\pi A_y t_1) (4\pi A_z t_1)^{1/2}} \quad (35)$$

It is believed that if diffusion coefficients in the 30 to 300 cm²/sec range are chosen that reasonable values of dose rate will be determined if the scale of observation is less than 100 meters (100 yards).

The formulas may be modified to include A/r for larger scales of diffusion phenomena. Then the concentration varies as r^{-1/2}, r⁻¹ or r^{-3/2}, depending on the number of degrees of freedom.

Since the time element enters in as the product (At), it is instructive to compare the different methods of assuming the distribution of fission products.

Suppose a source of $(\frac{1.2 \times 10^{19}}{50})$ mev/sec of which 10% were fission products which were soluble or small enough to be suspended. Postulate that this activity is released below the surface of the water. Some time later assume the soluble fission products occupy a space 10 x 100 x 100 meters. The dose rate above the surface would be:

$$D^0 = \frac{s_0 (\% \text{ dissolved})(5.767 \times 10^{-5})}{2(\text{volume of water})} \quad (36)$$

$$D^0 = \frac{(5.767 \times 10^{-5})(1.2 \times 10^{19})(0.1)}{(2)(50)(1 \times 10^{11})} \quad (37)$$

This may be compared to a calculation using line source diffusion theory and substituting the following assumptions into a modification of equation (6c) times the conversion factor.

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$$D = 1,000 \text{ cm}$$

$$S_0 = 1.2 \times 10^{19} \text{ nev/sec}$$

$$A = 1,000 \text{ cm}^2/\text{sec}$$

$$D_0 = \frac{1}{2} \left(\frac{5.767 \times 10^{-5}}{(4\pi t A)} \right) \left(\frac{1.2 \times 10^{19}}{D} \right) \left(\frac{0.1}{50} \right) e^{-\frac{r^2}{4(1000t)}} \quad (38)$$

$$D_0 = \frac{5.6 \times 10^4}{t} e^{-\frac{r^2}{4000t}} \approx \frac{5.6 \times 10^4}{t} \quad (39)$$

for $r^2 < 4000 t$, and in about five hours, this drops to about 6 rads/hr.

In the ocean taking $A_H = 10^5 \text{ cm}^2/\text{sec}$,

$$D_0 = \frac{5.6 \times 10^2}{t} e^{-\frac{r^2}{4 \times 10^5 t}} \quad (40)$$

and in 100 seconds this activity would be attenuated to 6 rads/hr. Note the dose rate drops off rapidly beyond 60 meters from the source.

2. The Thermal Column Problem

It is assumed that fission products from a reactor which had been operated at 100 Mw are dumped into water. Furthermore it is assumed that all fission products are dissolved in the water and that they have associated with them from the preceding reactor operation a latent heat, H_L , of 3.4×10^6 Btu. These latter assumptions are both pessimistic and in any real situation could be less by orders of magnitude. The resulting calculated doses from the release would then be proportionally lower than those calculated as shown here. In particular if the fuel is in canned elements of one kind or another only a small fraction of the total fission products would be released, whereas with a liquid fuel

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all but a small fraction would be released.

The initial afterheat (fission product decay heat) is estimated at 6% of reactor power. Since reactor power is assumed to be 100 Mw, the initial decay heat is,

$$H_a = (0.6) P \text{ (C.F.)} = \frac{(0.6)(100 \times 10^6)(3.4)}{3.6 \times 10^3} \quad (41)$$

$$= 5670 \text{ Btu/sec}$$

Approximately 50% of H_a is gamma ray energy and 50% beta particle energy, therefore,

$$H_{a\gamma} = 3000 \text{ Btu/sec}$$

$$H_{a\beta} = 3000 \text{ Btu/sec}$$

It is seen that the afterheat is small compared to the latent heat and is subsequently neglected. (Various authorities agree that afterheat contributes to dilution and dissipates quickly.)⁵⁹ It is then assumed that the entire latent heat is transferred to water while the fuel descends to the bottom of a 36-ft channel.

The fuel, then, upon exposure to the water, will transfer its heat as it sinks and will leave a stream of fuel particles behind. (If introduced under water near the bottom, will form a "cloud" of fuel particles near the point of introduction.) In both cases, instantaneous sources of radioactive fission products are available.

For a certain period of time the turbulent eddy diffusion coefficients would be large and localized; estimated greater than $2000 \text{ cm}^2/\text{sec}$.⁶⁰ Also, vertical currents generated, if sufficient in magnitude, may carry particles

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and dissolved radioactive fission products to the surface in a thermal column.

A preliminary estimate of the thermal column possibility may be made by considering the temperature change possible in water, assuming cylindrical geometry, a nominal channel depth of 36 ft and a latent heat (H_L) equal to 3.4×10^6 Btu.

The volume of the water heated would be

$$V = \pi R^2 D = \frac{H_L}{C_p \Delta T \rho_{H_2O}} \quad (42)$$

and the associated temperature rise would be

$$\Delta T = \frac{H_L}{C_p \rho \pi D R^2} = \frac{3.4 \times 10^6}{(1)(62.4)(\pi)(36)R^2}$$

The table below shows assumed radii and the corresponding temperature rise for this equation.

Temperature Rise in a Column of Water
 $(H_L = 3.4 \times 10^6 \text{ Btu}), (\text{Channel Depth} = 36 \text{ ft})$

<u>R(feet)</u>	<u>T (degrees F)</u>
1	482
2	120
3	53.3
4	30.0
5	19.3
6	13.4
7	9.8
8	7.5
9	6.0
10	4.8

It is seen that a realistic temperature rise might be on the order of 10° .

The vertical acceleration of a column of water would be due to the difference in density of the water in the column and the ambient water, the density being a function of temperature.

Representative water densities are:⁶¹

<u>Temperature, °F</u>	<u>Density, slugs/ft³</u>
30	1.940
40	1.940
50	1.940
60	1.938
70	1.936
80	1.934
90	1.931
100	1.927
110	1.923
120	1.918
130	1.913

If the assumed maximum ΔT were to be as high as 50°F and a nominal ambient water temperature of 50°F is assumed, then the acceleration is determined from

$$a = \frac{\Delta \rho}{\rho} g$$

$$= \left(\frac{1.940 - 1.927}{1.927} \right) g = 0.218 \text{ ft/sec}^2 \quad (43)$$

The velocity of this column at the end of one second would be, from

$$v = at$$

$$= (0.218)(1) = 0.218 \text{ ft/sec} \quad (44)$$

Assuming a more probable or reasonable ΔT of 10°F in 50°F ambient water, the acceleration would be

$$a = \left(\frac{1.940 - 1.938}{1.938} \right) g = 0.033 \text{ ft/sec}^2$$

and, at the end of one second,

$$v = 0.033 \text{ ft/sec}$$

The authors estimate the settling velocities of the fuel particles at about 0.16 ft/sec.⁵³ Comparing this to the results of the above analysis, it is seen that a significant ΔT is required before the fuel particles will be convected to the surface. It must be kept in mind that the ΔT will continually and rapidly drop as a result of the turbulent eddy diffusion. On the other hand, some of the fission products will actually dissolve; xenon, for instance, and that the comparison of settling velocities to rising velocities in this case will have no meaning.

If the diffusion of heat energy has the same behavior as the diffusion of dissolved particles, then equation (6c) is applicable except for the substitution of the heat source in place of the radiation source.

$$h = \frac{H_L e^{-\left(\frac{x-vt}{4A_x t}\right)^2} e^{-\frac{y^2}{4A_y t}}}{D 4\pi A_x^{1/2} A_y^{1/2} t} \quad (45)$$

where $h = \text{Btu/ft}^3$

Recalling that

$$h = \rho C_p \Delta T \quad (46)$$

then, for the column case with stream velocity equal to zero and for cylindrical geometry,

$$\Delta T = \frac{H_L e^{-\frac{r^2}{4At}}}{D \rho C_p 4\pi A t} \quad (47)$$

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Assume the nominal channel depth of 36 ft and $A = 2.15 \text{ ft}^2/\text{sec}$,⁶⁰

$$\Delta T = \frac{3.4 \times 10^6}{(36)(62.4)(1)(4\pi)(2.15)t} e^{-\frac{r^2}{8.6t}}$$

$$= \frac{56}{t} e^{-\frac{r^2}{8.6t}}$$

The table below shows the calculated temperature rise for different radii and times.

Temperature Rise in Thermal Column for Various Radii and Times

<u>Time (seconds)</u>	<u>Radius (feet)</u>				
	0	2	5	10	20
1	56.0°F	35.0°F	3°F	- °F	- °F
2	28.0	22.0	6.5	-	-
3	18.7	16.0	7.3	-	-
4	14.0	12.5	6.8	0.8	-
5	11.2	10.2	6.2	1.1	-
10	5.6	5.4	4.2	1.8	-
25	2.2	2.2	2.0	1.8	1.1
50	1.1	-	-	-	-
75	0.8	-	-	-	-
100	0.6	-	-	-	-

The above table shows that the diffusion of the heat energy is quite rapid and should be complete in a maximum time of 100 seconds. A thermal column, if formed, would, therefore, be dissipated within 100 seconds.

Some vertical thermal motion is expected but not long-lasting nor to any significant magnitude. Further, if a current is flowing, the inherent character of the velocity distribution (profile) and the associated shear stresses will tend to dissipate the effective thermal convection,

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since rising columns of warmer water would be required to push colder water aside rather than follow an accelerating column.

If 1.2×10^{19} mev/sec of fission product activity were to be completely dissolved, the dose rate at the assumed deposition line with the previously assumed column geometry and depth and a diffusion coefficient of $2.15 \text{ ft}^2/\text{sec}$ would be from equation (9),

$$D^0(0,100) = (Q)(5.767 \times 10^{-5})$$

Obtain "Q" from equation (6c) and get

$$D^0(0,100) = \frac{(5.767 \times 10^{-5})(1.2 \times 10^{19}) e^{-\frac{0}{8.6 t}}}{(28,500 \text{ cm}^3/\text{ft}^3)(4\pi)(36)(2.15)(100)} \quad (48)$$

$$= 2.5 \times 10^5 \text{ rads/hr}$$

The dose at various distances from the source may be obtained by substituting the desired value of "r" in the above equation. The dose at the surface will persist if thermal convection brings the warmer water to the surface where it will remain and spread horizontally with time.

It is probable that the actual dose rates from an accident of the type under consideration would be much lower if the fission products were deposited at least 10 ft below the water surface, and hence, the radiation will be attenuated. Further, the fission products, except for iodine and bromine, tend to attach to sediment and settle out.

3. Solubility of the Fission Product Gases

The question arises as to whether the gaseous fission products will dissolve in the water or escape as a cloud.

For one week's operation at 100 Mw with holdup of all the fission product gases, about 30 gram-moles of gas will be present, about 80% of which is xenon.

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Assume water at 10°C (46°F); Henry's Law constant,⁹ $c = 0.555 \times 10^7$
and 30 gram-moles gas released at a depth of 36 ft,

$$c = \frac{p}{n} \quad (54)$$

where:

p = partial pressure of the xenon

n = mole fraction in solution

$$n = \frac{p}{c} = \frac{14.7 + \left(\frac{62.4}{144} \times 36\right)}{0.555 \times 10^7} = 5.0 \times 10^{-6} \frac{\text{moles Xe}}{\text{moles H}_2\text{O}} \quad (55)$$

$$\begin{aligned} 1 \text{ ft}^3 \text{ H}_2\text{O} &= 62.4 \left(\frac{\text{lb}}{\text{ft}^3}\right) \left(\frac{1000 \text{ gm}}{2.2 \text{ lb}}\right) \left(\frac{\text{mole}}{18 \text{ gm}}\right) \\ &= 1,550 \text{ moles H}_2\text{O/ft}^3 \end{aligned} \quad (56)$$

$$\begin{aligned} 30 \text{ gm moles Xe requires } &\frac{30}{(1550)(5.0 \times 10^{-6})} \\ &= 3,870 \text{ ft}^3 \text{ of H}_2\text{O} \end{aligned} \quad (57)$$

Assuming 10 meters (36 ft^3) depth,

$$V = 36 \pi R^2 \quad (58)$$

$$R = \left(\frac{3870}{36 \pi}\right)^{1/2} = (34)^{1/2} = 6 \text{ ft}$$

With this required volume and in view of the low column velocities, it is quite possible that this amount of gas will dissolve before reaching the surface. Furthermore, if extremely high diffusion coefficients can be applied or the gas is spread over a large area during release, assuming all the gas was released, it will almost certainly be dissolved.

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TABLE 1. TURBULENT EDDY DIFFUSION COEFFICIENTS

Horizontal

<u>A_h, cm²/sec</u>	<u>Source</u>
1.2 - 1.8 x 10 ⁵	Measurement, Bikini area ⁶⁰
20-1000	Measurement, dye marker ⁶²
3.23 x 10 ⁵	Measurement, Mohawk River ⁵⁴
10 ⁵	Calculated, ideal reservoir ⁵⁸

Vertical

<u>A_v, cm²/sec</u>	<u>Source</u>
300-360	Measurement, Bikini area ⁶⁰
2000	Measurement, Bikini area (special case of diurnal heating and advection over a reef)
1-300	Measurement, oceans ⁵³ (a function of stability and currents)

Ratio A/r

<u>A/r, cm/sec</u>	<u>Source</u>
0.5	Measurement, Bikini area ⁶⁰
0.3 - 0.5	Suggested range, oceans ⁵³
0.2	Measurement, Framingham Reservoir ⁵⁸

List of Symbols

A	diffusion coefficient, cm^2/sec or ft^2/sec
a	acceleration, ft/sec^2
α	$\mu^2 At$
α'	$r^2/4At$
B	$r^2/4A$
c	Henry's Law Constant, $\text{psi}/\text{mole fraction dissolved}$
C_p	specific heat at constant pressure, $\text{Btu}/\text{lb-}^\circ\text{F}$
D'	total derivative operator
D^0	dose rate, rad/hr
D	depth of water, ft or cm
∇	Laplacian operator
g	acceleration of gravity, $32.2 \text{ ft}/\text{sec}^2$
h	volume heat, Btu/ft^3
H_a'	heat rate, Btu/sec
H_0	initial heat, Btu
H_L	latent heat, Btu
k	experimental constant
$K(l)$	diffusion coefficient based on distance-neighbor theory
l	distance between two particles
λ	decay constant, sec^{-1}
μ	linear absorption coefficient, cm^{-1}
μ_a/ρ	mass absorption coefficient, cm^2/g
n	mole fraction in solution
p	partial pressure, psi
Q	concentration, $\text{no.}/\text{cm}^3$ or $\text{no.}/\text{ft}^3$

R	removal function, n/cm^3 -sec
r	radial distance from source, cylindrical or spherical geometry
ρ	density, g/cm^3 or lb/ft^3
S_0	quantity of material
s_0	quantity of material/sec
s	distance
T	temperature
T_0	initial temperature
t	time, sec
V	volume
v	velocity, cm/sec
w	$(\mu r/2\alpha^{1/2})^2 + \mu r + \alpha$
W	$r^2/4A (t - \xi)$
ξ	time, sec
β	beta particles
γ	gamma rays
X	$F(r,A,t)$, see section 1.1.1
x	distance in x direction, cm or ft
y	distance in y direction, cm or ft
z	distance in z direction, cm or ft

REF ID: A66581

FIGURE 1 CONCENTRATION FOR $A = 3 \text{ cm}^2/\text{sec}$

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FIGURE 2. CONCENTRATION FOR $A = 30 \text{ CM}^2/\text{SEC}$

FIG.3 CONCENTRATION FOR A = 300 cm²/sec

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R - CENTIMETERS
FIGURE 4 - CONCENTRATION FOR $\lambda = 10^5$ CM²/SEC

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1000

DISTANCE FROM POINT OF DEPOSITION
METERS

100

10

METERS

1

10

100

1000

10000

10

TIME - SECONDS

FIGURE 2. DISTANCE AT TIME AFTER RELEASE OF 1.2×10^{19} MEV/SEC
FISSION PRODUCTS IN WATER

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FIGURE 6, - CONCENTRATION IN A CHANNEL

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FIGURE 7 - CONCENTRATION IN A CHANNEL

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FIGURE 8 - CONCENTRATION IN A CHANNEL

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