THEORETICAL POSSIBILITIES AND CONSEQUENCES OF MAJOR ACCIDENTS IN LARGE NUCLEAR POWER PLANTS

A Study of Possible Consequences if Certain Assumed Accidents, Theoretically Possible but Highly Improbable, Were to Occur in Large Nuclear Power Plants

WASH–740

UNITED STATES ATOMIC ENERGY COMMISSION

March 1957

GUIDES ON: 10¼ X 7½

Foreword

This report to the Commission contains an account of a study undertaken by the Division of Civilian Application, at the direction of the General Manager, to gain a more comprehensive understanding of the potential public hazards of nuclear power reactors.

All technical phases of the project were performed by a study team composed of staff members of the Brookhaven National Laboratory, with assistance of consultants and others from elsewhere. Principal contributors were:

Dr. Clifford K. Beck
Dr. Frederick P. Cowan
Mr. Kenneth W. Downes, Project Director
Dr. Joseph A. Fleck, Jr.
Dr. J. B. H. Kuper
Mr. James McLaughlin
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Mr. Maynard Smith

The study was carried out under the guidance of a Steering Committee composed of scientists and engineers of the Atomic Energy Commission staff and the Brookhaven National Laboratory. Members were:

Dr. Clifford K. Beck, AEC, Chairman, Steering Committee
Dr. Walter D. Claus, AEC
Mr. Kenneth W. Downes, BNL
Mr. Merril Eisenbud, NYOO
Dr. Clark Goodman (replaced by Mr. Howard Hembree, AEC)
Mr. Edwin A. Lamke, AEC, Secretary
Dr. Gerald F. Tape, BNL
Dr. Clarke Williams, BNL

Valuable assistance throughout the study was also rendered by Mr. Joshua Z. Holland, AEC, and in some of the technical phases by Mr. Raymond O. Brittan, Argonne National Laboratory, and Dr. Everitt P. Blizard, Oak Ridge National Laboratory.

Many other staff members, consultants and advisors, including members of the Advisory Committee on Reactor Safeguards, also rendered valuable assistance in the study.

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UNITED STATES

ATOMIC ENERGY COMMISSION

WASHINGTON 25, D. C.

March 22, 1957.

DEAR MR. DURHAM: There is transmitted herewith a report of a study of the possible consequences in terms of injury to persons and damage to property, if certain hypothetical major accidents should occur in a typical large nuclear power reactor.

More than two score leading experts in the sciences and engineering specialties participated in this study.

We are happy to report that the experts all agree that the chances that major accidents might occur are exceedingly small.

This study constitutes a part of the Commission's continuing effort on a broad front to understand and resolve this problem of possible reactor hazards so that we may proceed with an expanding atomic energy industry with full confidence that there will be few reactor accidents and that such as do occur will have only minor consequences. This effort and the work of translating the results into affirmative, concrete safeguards for protection of the public will, of course, be continued and expanded.

Since the beginning of the reactor program the experts and the Congress and the public and the Commission have all been concerned with the causes of and the possible magnitude of damage from reactor accidents and with means of prevention. The subject was considered important enough to command four of the 60-odd sessions of the International Conference on the Peaceful Uses of Atomic Energy in Geneva eighteen months ago, which, as you will recall, we initiated. One conference paper in particular gave estimates of the theoretical magnitude of damage. In May of last year, Dr. Libby presented to your Committee some estimations of the possible extent of harm and damage should a major accident occur.

This study has taken the form in which it is now presented to you as a means of responding to the Committee's specific request of last July 6. To produce such a study, it was necessary to stretch possibility far out toward its extreme limits. Some of the worst possible combinations of circumstances that might conceivably occur were included in the hypotheses in order that we might assess their consequences. The study must be regarded only as a rough estimation of the consequences of unlikely though conceivable combinations of failure and error and weather conditions; it is not in any sense a prediction of any future condition.

This has been a difficult study to make. There has fortunately been little reactor accident experience upon which to base estimates. Nuclear reactors have been operated since December 2, 1942, with a safety record far better than that of even the safest industry. More than 100 reactor years of regular operating experience have been accumulated, including experience with reactors of high power and large inventories of fission products, without a single personal injury and no significant deposition of radioactivity outside of the plant area. There have been a few accidents with *experimental* reactor installations as contrasted with the perfect record of safety of the regularly operating reactors. But even these accidents did not affect the public.

This record which shows that safe operation can be achieved is due to skillful design, careful construction, and competent operation.

Looking to the future, the principle on which we have based our criteria for licensing nuclear power reactors is that we will require multiple lines of defense against accidents which might release fission products from the facility. Only by means of highly unlikely combinations of mechanical and human failures could such releases occur. Furthermore, the

Government and industry are investing heavily in studies to learn more about the principles of safe reactor design and operation.

Framing even hypothetical circumstances under which harm and damage could occur and arriving at estimations of the theoretical extent of the consequences proved a complex task.

To make the study we enlisted the services of a group of scientists and engineers of the Brookhaven National Laboratory and of another group of experts to serve as a steering committee. Through recent months these men have met with many additional expert advisors to test out judgments on the estimates arrived at.

We are not aware of such a study having been undertaken for any other industry. We venture to say that if a similar study were to be made for certain other industries, with the same free rein to the imagination, we might be startled to learn what the consequences of conceivable major catastrophic accidents in those other industries could be in contrast with the actual experience in those industries.

Remembering that this study analyzes theoretical possibilities and consequences of reactor accidents, we might note here the judgments presented on (1) possible consequences of major accidents and (2) the likelihood of occurrence of such major reactor accidents.

The portion of the study dealing with consequences of theoretical accidents started with the assumption of a typical power reactor, of 500,000 kilowatts thermal power, in a characteristic power reactor location. Accidents were postulated to occur after 180 days of operation, when essentially full fission product inventories had been built up.

Three types of accidents which could cause serious public damages were assumed. Pessimistic (higher hazard) values were chosen for numerical estimates of many of the uncertain factors influencing the final magnitude of the estimated damages. It is believed that these theoretical estimates are greater than the damage which would actually occur even in the unlikely event of such accidents.

For the three types of assumed accidents, the theoretical estimates indicated that personal damage might range from a lower limit of none injured or killed to an upper limit, in the worst case, of about 3400 killed and about 43,000 injured.

Theoretical property damages ranged from a lower limit of about one half million dollars to an upper limit in the worst case of about seven billion dollars. This latter figure is largely due to assumed contamination of land with fission products.

Under adverse combinations of the conditions considered, it was estimated that people could be killed at distances up to 15 miles, and injured at distances of about 45 miles. Land contamination could extend for greater distances.

In the large majority of theoretical reactor accidents considered, the total assumed losses would not exceed a few hundred million dollars.

As to the probabilities of major reactor accidents, some experts held that numerical estimates of a quantity so vague and uncertain as the likelihood of occurrence of major reactor accidents have no meaning. They declined to express their feeling about this probability in numbers. Others, though admitting similar uncertainty, nevertheless ventured to express their opinions in numerical terms. Estimations so expressed of the probability of reactor accidents having major effects on the public ranged from a chance of one in 100,000 to one in a billion per year for each large reactor. However, whether numerically expressed or not, there was no disagreement in the opinion that the probability of major reactor accidents is exceedingly low.

Some of the reasons for this belief follow:

First, industry and government are determined to maintain safety and protect the health and property of the public from nuclear hazards. The Congress has authorized and we in the Commission are carrying out a program of close and careful regulation and inspection. Thus the potential hazard of this new industry has been recognized in advance of its development and brought under a strict system of safety control before the occurrence of the incidents which in other fields have marked the birth of new industry and have subsequently led to control.

Secondly, the challenge of this new and important venture in man's application of the forces of nature has attracted able and energetic men into the work of assuring safe design and operation.

In the third place, multimillion dollar efforts in research and development, both public and private, are directed toward identifying and solving safety problems. We know of no other industry where so much effort has been and is being spent on the definition and solution of safety problems.

Fourthly, the cost to the industry and government of reactor accidents, even of a minor nature, would be very high—much higher than for accidents in other industry. Self-interest, therefore, as well as public interest dictates avoidance of accidents.

To sum up, the report affirms that a major reactor accident is extremely unlikely. To reduce the matter of assumed hazards to comparative numbers, let us take the most pessimistic assumptions used and apply them to a case of 100 power reactors in operation in the United States.

Under these assumptions, the chances of a person being killed in any year by a reactor accident would be less than one in 50 million. By contrast the present odds of being killed in any year by an automobile accident in the United States stand at about one in 5,000.

We are not surprised by the contents of the report, nor are we made complacent. The report serves to identify areas where continued research and development are needed, and areas where emphasis is needed in the further development of our regulatory program. It gives renewed emphasis to our belief that our research and development program and our regulatory program in the nuclear power field must continue with vigor to the end that the "conceivable" catastrophe shall never happen.

We would appreciate your regarding the attachment as an "advance" report. It is being reviewed for editorial and mechanical errors and omissions. Copies of the report as corrected will be furnished to you at an early date.*

Sincerely yours,
(Signed) HAROLD S. VANCE,
Acting Chairman.

Enclosure: "Theoretical Possibilities and Consequences of Major Accidents in Large Nuclear Power Plants"

HON. CARL T. DURHAM,
Chairman, Joint Committee on
Atomic Energy,
Congress of the United States.

**Editors Note:* In the attached report, this review has been made and the errors which were all relatively minor, have been corrected.

Introduction

It might be supposed, because the essential fuel in a nuclear power reactor is the same as that in atomic bombs, that gross malfunctioning in power reactors could possibly lead to a devastating explosion similar to those produced by A–bombs. Such is not the case. Under no conceivable circumstances can accidental nuclear explosions in power reactors cause significant direct public damage beyond the boundaries of the exclusion areas around such installations.

There could be explosive nuclear energy releases in power reactors, or chemical or physical energy releases from components or auxiliary systems, sufficient in magnitude to destroy the reactor, possibly break the various containment structures within which it is housed and wreck the auxiliary machinery. Such an accident would constitute a real threat to the life of personnel within the facility and could result in complete loss of the expensive installation. Nevertheless, little hazard to the general public would ensue from the explosion itself.

There is, however, another hazard to the general public which could cause extensive loss of life and damage to property. This is the possibility of radiation exposure and contamination, if the fission products stored up in the reactor should be released. It is possible to conceive of accidents which would release the accumulated fission products from a large nuclear reactor in a finely divided state so that a significant portion of them would become airborne and subject to atmospheric dispersal over wide areas. Injury or death could result to people from exposure to the direct radiation from these materials, or from ingestion of portions into the body. Settling out of these materials could cause both further hazard to health and costly contamination damage to property. Death at distances of many miles and injury and property damage for hundreds of miles could conceivably occur.

Fortunately, radiation intensity from most fission products released from a reactor decreases rapidly. The possibility of total release is exceedingly remote, and among those products most likely to be released are those which decay most rapidly. In no conceivable way could fission products from a reactor be distributed rapidly and uniformly over large areas. The major threat to the safety of people remote from the site of release would not be instantaneous; periods up to hours and even days after release would be available within which to avoid the full effects of radioactivity from the fission products.

It must be clearly recognized, however, that major releases of fission products from a nuclear power reactor conceivably could occur and that a serious threat to the health and safety of people over large areas could ensue.

An overall appraisal of the actual magnitude of hazard to the public arising from operation of a nuclear power reactor revolves around the best possible answers to four essential and difficult questions:

1. What is the likelihood that fission products might be released?
2. What are the factors and conditions which would affect the distribution of released materials over public areas?
3. What are the levels of exposure or contamination which cause injury to people or damage to property?
4. If releases of fission products should occur, what deaths or injuries to people and costs in damaged property could ensue?

Succeeding sections of this report are devoted to consideration of these questions.

It is important to recognize that the magnitudes of many of the crucial factors in this study are not quantitatively established, either by theoretical and experimental data or adequate experience. Appraisal must rest on the judgment and considered opinions of the most knowledgeable persons in the field. At various places in the report note will be made where important components are particularly uncertain, but it must be remembered continuously that this entire study hardly constitutes more than an identification of the factors which are important, the best appraisal of these factors currently possible, and a rough approximation of the magnitudes of the composite results.

There are many essential and significant qualifications and uncertainties in the conclusions contained in this report. If separated from these qualifications and uncertainties, the conclusions would lose their validity. However, we believe that the study, if taken in perspective, gives an order-of-magnitude frame of reference, and defines tentative boundaries for this problem.

More definitive information on estimated factors would probably tend to reduce the estimates of damages, though in a few instances the converse might be true. There are a few less usual weather conditions which occur perhaps 5 percent of the time and which could yield estimated damages outside the range of the figures stated here. Therefore, this study does not set an upper limit for the potential damages; there is no known way at present to do this. It does indicate the range of hazards from highly improbable catastrophic reactor accidents which might occur under all except a small percentage of most unusual combinations of circumstances.

Part I

The Probability of Catastrophic Reactor Accidents

The probability of occurrence of publicly hazardous accidents in nuclear power reactor plants is exceedingly low.

This single statement, re-emphasized, would suffice to report this portion of the study, except for the essential importance of this central fact of "low probability" to comprehension of the overall public hazard of power reactors. The significance of damages consequent to accidents cannot be appraised independently of the probability of the accidents.

One fact must be stated at the outset: no one knows now or will ever know the exact magnitude of this low probability of a publicly hazardous reactor accident. In trying to establish some estimation of this quantity, three possible approaches might be used:

1. Operate enough reactors for sufficient length of time to obtain an indication of the accident probability.
2. Give careful consideration and approximate numerical values to all separate factors which would either prevent or cause such an accident, then try to calculate, or guess, the composite result of these factors and hence the likelihood of occurrence of accidents.
3. Obtain a weighted average of the best judgments and judicious opinions of the most experienced and knowledgeable experts in the field.

None of these approaches is satisfactory. Even when combined, they are at the present time still unsatisfactory.

Indications from Cumulative Experience to Date

Nuclear reactors have been operated since December 2, 1942, with a remarkable safety record. We have accumulated more than 100 reactor years of experience with large routinely operated reactors without any accidents.[1] This record of safety, although highly reassuring, does not afford a dependable statistical basis for estimating the probability of occurrence of serious reactor accidents in the future.

In this initial period of power reactor experience, types of reactors, detailed reactor designs, and operating patterns are all experimental and variable.

There are factors both on the side which would lead toward confidence that our "no accident" experience will continue, and on the converse side. On the one hand, we attempt to provide wide margins of safety because of our limited knowledge of accident potentials of reactors. The new and glamorous field challenges and attracts the most expert and competent people. The Government has had and continues to have a substantial safety research program. Experience almost certainly will lead to safer design. On the other hand, since many reactor types are being developed more varied safety problems may exist than would be the case in fewer types. Accident free experience could lead to complacency. Lengthening reactor life could lead to hazards not otherwise encountered (cumulative radiation damage to components). Competitive pressures could furnish incentives to reduce margins of safety.

[1] All the half-dozen "runaway" incidents (Chalk River, Borax, EBR–1, etc.) experienced thus far, either inadvertent or planned, have occurred in research or experimental test reactors—in contrast to the steadily operating power reactors considered here. No one has been injured, and no fission products have been released "off-area." Hence, the accidents are not in the category of concern in this study.

Factors For and Against a Major Accident

It is very difficult to determine whether a reactor of one type is safer, overall, than one of another type. It is easy to point out superior safety features and inferior ones in any one type compared with those in another type. Safety depends on the combination of many complex and interrelated factors and overall comparison of one reactor type with another depends on value judgments which are difficult to define quantitatively.

To estimate the *absolute* safety of a given reactor, or of reactors in general, or to estimate the quantitative probability that an accident will occur is more difficult, and more uncertain, by several orders of magnitude, than is the relative comparison of reactors.

In principle, it should be possible to identify each factor, positive or negative, involved in the safety of a reactor, assign some measure of the magnitude of its effect and some probability of its functioning (or failing to function), then derive a net weighted composite measure of the margin of safety, or of the probability of catastrophic accident in a given time.

On the positive side would be such factors as:

1. In no reactor, so far as is known, will a single equipment failure or a single operating error lead to a fission product-releasing accident (even within the containment structure). If such condition were recognized, it would be rectified. In the vast majority of cases, multiple separate malfunctioning events are a necessary prerequisite to a serious accident.
2. Most reactors are inherently stable, e. g., most reactors possess prompt negative temperature or power coefficients (any increase in these factors is accompanied by a decrease in reactivity, hence, any excursion tends to reach some limiting value, rather than indefinitely increasing power).
3. In heterogeneous (solid fuel) reactors, the fission product inventory accumulates within the solid fuel matrix from which escape is prevented not only by low mobility of these fission products in the solid fuel but also by the metallic surface cladding. Melting or violent damage must occur before fission products can be released into the reactor vessel. In homogeneous (solution or slurry fuel) reactors, the possibility of continuous removal of the fission products offers some compensation for the lack of confinement provided within the fuel elements of other types.
4. Every power reactor will be provided with an adequate primary containment vessel enclosing the reactor core within which fuel and fission products reside. This, in turn, is surrounded by massive radiation shields for biological protection of workers.
5. All power reactors now considered for construction in populated areas are provided with "vapor shells" designed to contain all fission products that might be released in any credible accident.
6. Seventy-five or eighty percent of the fission product elements are solids at ordinary temperatures and, unless opening of the outer vapor shell is caused or accompanied by an event which vaporizes and violently disassembles the core materials, most of the fission products would be expected to remain attached to fragments of fuel elements or to settle out on nearby structures.
7. Should fission products be released from the containment shell, not only the physical state of the materials, but also a complex variety of environmental meterological and other factors, having various probabilities of occurrence, would govern the subsequent pattern of dispersal. Probabilities of progressively unfavorable combinations of conditions become progressively lower, so that likelihood of highly unfavorable combinations is extremely low.

On the negative side, account would have to be taken of such factors as:

1. Many power reactor systems will operate under high pressures. High pressure systems are subject to failure.
2. The cumulative effect of radiation on physical and chemical properties of materials, after long periods of time, is largely unknown. Eventual serious failures may occur.
3. Various metals used in reactors such as uranium, aluminum, zirconium, sodium and beryllium, under certain conditions not at present clearly understood, may react explosively with water, also present in many reactors. During incidents of abnormal operation resulting perhaps in melting of some of the metals in contact with water and under the influence of radiation, chemical reactions of enough violence to rupture the containment vessels, with release of the fission products, could occur.
4. After initial operation, many of the vital components become inaccessible for inspections. In non-nuclear plants, serious accidents are often averted through detection of incipient failure.
5. Much remains to be learned about the characteristics and behavior of nuclear systems.

Listing of such items, in both positive and negative tabulations, could proceed at length. However, it should be clear already that, even if all the significant factors relevant to safety were known, it would be essentially impossible to assign dependable quantitative values to their respective probabilities of functioning and to derive therefrom a reliable indication of the margin of safety under operating conditions likely to exist.

The Best Judgment of the Most Knowledgeable Experts

Many outstanding leaders in reactor technology and associated fields were consulted in the course of this study. It is their unanimous opinion that the likelihood of a major reactor accident is low. There is a general reluctance to make quantitative estimates of how low the probability is. There is a common aversion to attachment of quantitative estimates to a phenomenon so vague and uncertain as the probability of occurrence of catastrophic accidents, particularly since such assignment of numerical estimations conveys an erroneous impression of the confidence or firmness of the knowledge constituting the basis for the estimate. Also, some hold a philosophic view that there is no such thing as a numerical value for the probability of occurrence of a catastrophic accident; that such a thing is unknowable.

Thus, many decline to make even order-of-magnitude guesses of the probability of catastrophic reactor accidents. On the other hand, a few have ventured to express their confidence of the extremely low probabilities of occurrence of such accidents by stating numerical, order-of-magnitude estimations. An indication of the range of these is illuminating.

Should some unfortunate sequence of failures lead to destruction of the reactor core with attendant release of the fission product inventory within the reactor vessel, however expensive this would be to the owners, no hazard to the safety of the public would occur unless two additional lines of defense were also breached: (1) the integrity of the reactor vessel; and, (2) the integrity of the reactor container or vapor shell.

Accidents of sufficient violence to breach these successive lines of defense occurring concurrently with progressively unfavorable combinations of dispersive weather conditions have decreasing probabilities of occurrence.

Thus, the probability of public hazards from reactor accidents may be considered in terms of a sequence of events, each being prerequisite to the situation arising from succeeding events, and each having a lower probability of occurrence than its predecessor. As indicated above, the numerical estimates ventured here represent an attempt to express in numerical terms the degree of feeling held by some of our advisors for the remoteness of the possibilities of occurrence of the various accidents described. It should be emphasized that these numbers have no demonstrable basis in fact and have no validity of application beyond a reflection of the degree of their confidence in the low likelihood of occurrence of such reactor accidents.

Their estimates for the likelihood of destruction or major damage to the reactor core with significant internal release of fission products, but no release outside the reactor vessel, ranged from one chance in 100 to one in 10,000 per year for each reactor.

Their estimates for the likelihood of accidents which would release significant amounts of fission products outside the reactor vessel but not outside the containment building (the contained accident) ranged from one chance in 1,000 to one in 10,000 per year for each reactor.

Finally, their estimates for the likelihood of accidents which would release major amounts of fission products outside the containment (the major release accident) ranged from one chance in 100,000 to one in a billion per year for each reactor.

Taking the most pessimistic of these estimates for the major accident, assuming that 100 reactors are in operation in the United States, and making the unrealistic assumption that each accident of the type defined would kill 3,000 people, there would be one chance in 50 million per year that a person would be killed by reactor accidents. For comparison, the chance of a person in the United States being killed by automobile accidents, assuming that each person has an equal likelihood of being among the 40,000 killed, is about one in 5,000 per year.

Safety Through Safeguards

Detailed evaluation of the safety of a reactor before approval is given for its operation may not lead to any better estimations of accident probabilities than those yielded by other considerations, but it does furnish added confidence that accident probabilities are indeed exceedingly small. In fact, the confidence of many persons in the low probability of accidents is due in large part to the application of these evaluation procedures.

Three aspects of these procedures contributing to minimization of public hazards from reactor accidents are worthy of mention:

1. Knowledge that safety evaluations and reviews are prerequisite to operation approval insures attention to and emphasis on safety aspects of a facility at all stages of the design.
2. The detailed safety analysis and evaluation by experts on the Commission staff, with assistance as necessary from consultants and advisors, including the Advisory Committee on Reactor Safeguards, assures that at least one independent review is given to each reactor facility in addition to that given by the designers.
3. As a part of the pre-evaluation procedure, careful analysis must be given to establishment of the accident of maximum proportions considered to be credible for each reactor facility, and demonstration must be made that adequate safeguards are provided the public against this eventuality.

Thus, since there is protection against "credible" accidents, no damages to the public will occur unless "incredible" accidents take place. It must be recognized, of course, that errors in judgment can be committed, with resulting occurrence of what was believed to be an "incredible" accident. Nevertheless, the consistent and rigorous execution of these procedures for every reactor warrants a considerable degree of confidence that safeguards against serious accidents have been incorporated, and that the probabilities of such occurrences are small.

Part II

Assumptions Used in the Damage Studies

It has been concluded that there is some remote but quantitatively uncertain possibility that a major reactor accident might occur. The immediate question then follows: What could be the extent of consequent damages? The remaining sections of this report devote attention to this question. Consideration is restricted to estimation of the damages to the public. No attempt has been made to appraise the hazard or damage to the facility itself or to its personnel.

To evaluate the hazardous consequences to the public of a reactor accident of major proportions, many features must be further described relating to the size and location of the reactor, its fission product inventory and the portion released, the conditions of release and the features of its delivery to public areas. In this section of the report, brief definitions and descriptions of those situations and features considered pertinent are recorded. Details of the technical foundations for these assumptions and specifications, and mathematical manipulations to arrive at estimates of the consequences thereof, are contained in various appendices as indicated.

Two comments are appropriate at this point. (1) Conditions and specifications described below are chosen to be representative of a "generalized" power reactor situation. Specific reactor situations will vary somewhat from the one described herein; however, use of the generalized reactor and site is adequate to permit a reasonable evaluation of general public liabilities. (2) The assumptions and specifications are chosen to be on the pessimistic side, i.e., result in higher damage estimates. This is due to an attempt to be on the safe side where uncertainties exist in present knowledge but no deliberate safety factors have been introduced.

Typical Reactor

The reactor considered is a 500,000-kw thermal (100,000 to 200,000-kw electrical) steadily operating, power producing type, having an average fuel reloading (and fission product eliminating) cycle of 180 days. Accidents assumed in this study, described later, are postulated to have occurred near the end of the 180-day cycle, when fission product inventory would be maximum. Research and test reactors and reactor experiments are excluded from consideration. A leak- and pressure-resistant containment building of the usual type is assumed to surround the reactor.

Fission Product Content of the Reactor

For the 500,000-kw thermal reactor, 180 days of operation, the fission product inventory would be approximately 4×10^8 curies, when measured 24 hours after an accident (or shutdown). Decay of the fission products as well as their composition was taken into consideration for calculation of direct radiation exposures or contamination due to deposition. Special attention was given to the volatile fission products, xenon, krypton, bromine, and iodine and to strontium. The latter two are biologically the most hazardous.

Typical Location

The reactor is assumed to be located near a large body of water, most likely a river, and about 30 miles from a major city. As in many sites proposed to date, a site boundary of 2,000-foot radius is postulated.

Population Distribution

Distributions of populations around reactors would differ considerably in detail from one site to the next. However, many general features would be remarkably similar, especially at large distances. Each reactor site would be in an area of low population density, a large city would be located about 30 miles away and the density of population would increase from the reactor toward the city. If the total population enclosed within a circle of radius R centered at the reactor is calculated for distances to the city, it develops that the total population within given radial distances is remarkably alike for all reactor sites now in use or proposed. This population can be expressed by the equation: $P = 200R^{2.83}$, where R is in miles.

At distances beyond the city, the average population density decreases and a different expression must be used. Average population density over the entire United States is about 55 people per square mile. Reactors, however, are likely to be built in more populated areas, such as in the northeast, where the average runs about 500 per square mile. Therefore, the assumption is made that the population density beyond the city is constant, and averages 500 people per square mile. For most situations these assumed population distributions are on the conservative side, i.e., in hardly any likely place would the population be underestimated, and in most places they overestimate the number of persons in areas which may be affected by a reactor accident.

For some types of accidents, the high population density in the nearby city needs to be calculated independently of the general treatment described above. In these cases, it was assumed that the city located 30 miles from the reactor has a population of about 1,000,000 persons spread uniformly over a region having a diameter of about 10 miles. Where the existence of the city contributes significantly to the calculated damages, city damages are listed separately.

Characteristics of Released Products

Accidents of greatest concern would be those which resulted in release and subsequent atmospheric dispersal of fission products from the reactor. The characteristics of the fission products at the time of release would have a great influence on their subsequent dispersal. Two factors having the greatest impact in determining the effect of distribution due to various meteorological conditions would be the size of the particles contained in the release and the temperature of the radioactive cloud at the time of release. These factors could, of course, vary from one reactor accident to another and undoubtedly would be highly dependent upon the particular accident. For the purpose of this study two choices were made for each factor, each choice being considered as probable and also illustrative of widely different conditions. For temperatures of release, the two *chosen* conditions were characterized by "hot" and "cold," the temperatures being 300° F. (temperature of steam at a pressure sufficient to rupture the containment vessel) and 70° F. (normal atmosphere temperature), respectively. For particle size two distributions were assumed, one centered about one micron and the other seven microns in diameter, these being representative of fumes and industrial dust, respectively. Experience does not permit a better definition of the particle size; it does, however, lend credibility to these two choices.

Mechanism of Distribution

Assuming that a release had occurred, consideration must then be given to the assumed existing weather conditions and to other factors that might influence the rate and pattern of distribution of the released materials. Numerous variables here could combine into an almost infinite variety of situations. It is possible (see appendix I) to obtain an indication of the range of damages from calculations on a reasonably small number of cases by limiting the number of meteorological variables to those having major influences and choosing one or two appropriate values for each.

The meteorological variables selected are: weather—(a) dry and (b) rain (0.02 inches per hour over the whole area affected); atmospheric stability—(a) typical daytime lapse with a wind speed of 5 m/sec (12 mph) and (b) night-time typical inversion with a wind speed of 3 m/sec (7 mph) up to 50 meters height and 15 m/sec (35 mph) above; height of cloud rise—(a) cold release, zero, (b) hot release, 860 meters during lapse, 400 meters during inversion (appendix E). It should be noted that the conditions assumed in any given case existed continuously for the duration of the case and the area affected.

It should be noted here that exceedingly little is known about the details of atmospheric distribution, even if the characteristics of the materials under consideration and the many environmental factors involved could be stated with great confidence. Nevertheless, use of these approximate average values, above, does give reasonably dependable general indications of the results to be expected in a large majority of possible situations.

Tolerance Levels for Personal Injury

Personal injury might result from exposure of personnel to the radioactive cloud released during the postulated accidents. Personal injury might also arise from exposure to deposited fission products. In the latter case, ample time often would be available to permit evacuation from contaminated areas before serious injury would occur. In appraising the hazard to individuals who might be exposed, it would be necessary to define the probable extent of injury caused by various doses of radiation. This is an exceedingly complex matter (appendix D). Using the best advice available and considering various biological effects such as ingestion, external and internal radiation problems, and the special problems arising from particular fission product isotopes having special biological importance, the following ranges, as described in appendix D, were adopted:

	Equivalent whole body gamma radiation	*Concentration of released fission products to give equivalent exposures*	
		Volatile FP's (curie-sec/m³)	*Gross FP's (curie-sec/m³)*
A. Lethal exposure	Over 450r	Over 350	Over 400
B. Injury likely	100 – 450r	80 – 350	90 – 400
C. Injury unlikely, but some expense may be incurred; observation required.	25 – 100r	10 – 80	10 – 90
D. No injury or expense.	Less than 25r [1]	Less than 10.	Less than 10.

[1] 25r in one exposure or 50r in three months.

The first column indicates the equivalent whole-body gamma radiation adopted as the basic criterion to define the several categories. Columns two and three have been calculated for these same criteria in terms of units used to estimate the effect of passage of the radioactive cloud. While these values are believed to be the best obtainable at the present time, many of the factors used in deriving them are highly uncertain. It should be noted that personal injury is considered to have occurred only in the first two categories. Expense might be incurred for exposures in the third category, but only for examination, observation and incidentals, not actual personal injury.

Degrees of Land Contamination

By far the largest dollar cost to the public of a major reactor accident would result from contamination of land areas by deposited fission products. Inhabitants of portions of the areas affected would have to be evacuated to avoid serious exposure. Access to various areas might be denied for different lengths of time, and the subsequent use of land for agricultural purposes might be curtailed, with possible loss of standing crops. The same basic exposure-injury criteria listed above (column 1) were used also for determining the consequences of land contamination. Details of calculations are shown in appendix D. In the case of land contamination, the existence of specific isotopes, especially strontium-90, must be considered very carefully. The severe restrictions that might be imposed on farming arise almost entirely from the existence of this particular isotope.

To estimate the potential loss arising from problems of land contamination both the number of persons and the area affected were calculated. In some instances the costs were evaluated by associating them with an average cost per person. In the particular cases associated with farm restriction an average cost per square mile was used.

The categories chosen, and costs assumed for each are:

Range I. Evacuation of personnel — immediate $5000/person

Range II. Evacuation of personnel — orderly and in a reasonable time $5000/person

Range III. Restrictions on land and outdoor activity .... $ 750/person

Range IV. Crop and farm restriction . . $25,000/sq. mile

The criteria used in establishing these ranges are described in appendix D. It should again be emphasized that they are based on meager data.

Reactor Accidents Assumed

Three types of reactor accidents were considered necessary for this study in order to indicate the range of public hazard which could result and to delineate the influence of the important variables as described above on the magnitude of these hazards. The three "typical" cases selected are:

A. *The Contained Case*

In this accident, it is assumed that all of the fission products from the 500,000-kw (thermal) reactor, after 180 days of operation, are released from the core and distributed uniformly throughout the interior of the containment building. None is assumed to escape. The fission products are assumed to decay at their natural rate, with no attempt at decontamination, etc., after the accident. Hazard to the public would arise from the direct gamma radiation from the fission products dispersed inside the containment building. One inch of steel shielding by the walls of the building is assumed. The site boundaries are 2,000 feet from the reactor.

B. *The Volatile Release Case*

In this case it is assumed that all of the volatile fission products in the reactor (500,000-kw (thermal) after 180 days), i.e., xenon, krypton, iodine, bromine and 1 percent of the strontium are released from the containment building and are subsequently dispersed, with characteristics and meteorological conditions as described and specified above. See appendix A.

C. *The 50 Percent Release Case*

In this case, it is assumed that 50 percent of all fission products in the reactor (500,000-kw (thermal) after 180 days) are released from the containment building and are subsequently dispersed, with characteristics and meteorological conditions as described and specified above. See appendix A.

Each of these arbitrary cases represents a highly pessimistic assumption. Certainly more catastrophic releases of the Contained and the Volatile types are not possible. In the third type, it is conceivable that more than 50 percent of all fission products could be released, but this is considered to be so far in the realm of incredibility as not to merit consideration.

Part III

Estimated Consequences of the Assumed Reactor Accidents

In this part of the report, there is presented a brief summary of the calculated damages obtained from each of the assumed accidents, together with brief observations and pertinent comments on the results obtained in the respective cases. Reference is made to appendices H and I, of part IV, for more complete tabulation of results.

CASE I—THE CONTAINED CASE

The assumption is made that all of the fission products are vaporized and dispersed within the containment shell. There is no release to the atmosphere. Damage to the public would then result from direct exposure to gamma radiation. The following tabular summary shows personal injuries and evacuation costs beyond the 2,000-foot boundary of the reactor site.

Personal Injury

	Assuming evacuation in 2 hours (persons)	*Assuming evacuation in 24 hours (persons)*
Lethal exposure	0	0
Injury likely	0	6
Injury unlikely, but expense likely.	1	15

Evacuation Costs

Number of People	*Area*	*Cost*
67	1.8 sq. mi.	$335,000

Observations and Remarks

1. The above results would be the maximum possible for this type of accident in that all fission products would be involved and no shielding except the container is assumed.
2. Under the best conditions, namely, prompt evacuation of nearby personnel, no personal injury would be likely. The public loss would be due entirely to evacuation costs and payments for denial of use of land. This can be measured in the hundreds of thousands of dollars.
3. Under less favorable conditions, namely, slower evacuation, a small number of personal injuries might be expected.
4. Use of the typical site and population distribution is less satisfactory for this case since nearby population variations from site to site are larger than the numbers of people affected. The method does, however, give an order-of-magnitude.
5. For smaller site boundaries, larger numbers of people would be affected, especially in the injury category. However, with proper combinations of distance and shielding no loss to the public would be involved.

CASE II—THE VOLATILE RELEASE CASE

Here it was assumed that, because of a breach in the container or failure to close all openings, all volatile fission products would be discharged to the atmosphere at the time of the accident. Four different situations of meteorological conditions and two particle size distributions were considered. Furthermore, separate indication is given for releases which include 1 percent of the strontium inventory and for those which do not.

A full summary of the calculated damages is contained in appendix I. The following table contains a brief summary to indicate the magnitude and range of the consequences.

The Volatile Release Case

Personal Injury

A. *Lethal exposure*	*Persons*	*Conditions at release*
Minimum	2	Temperature lapse
Maximum	900	Temperature inversion, 1μ particles

Assuming that (1) the particle size distributions are equally probable, and (2) the distribution of weather conditions is as stated in appendix I, then lethal exposures would be less than five people for those accidents which might occur during about one-half of the time or less than 300 people for those accidents which might occur during about three-fourths of the time.

B. *Injury likely*	*Persons*	*Conditions at release*
Minimum	10	Temperature lapse, 7μ particles
Maximum	13,000	Temperature inversion, 1μ particles

Using the same assumptions as under A, the number of persons injured would be less than 20 people for those accidents which might occur during about one-half of the time or 2,000 people for those accidents which might occur during about three-fourths of the time.

Property Damage

II. *Evacuation*	*Persons*	*Area (sq. mi.)*	*\$ Millions*	*Conditions*
Minimum	0	—	—	Temperature lapse, dry
Maximum	41,000	28	205	Temperature inversion, rain

Under the same assumptions as under A, the number of persons requiring evacuation would be less than 1,000 for accidents which might occur during about two-thirds of the time or 6,000 for those accidents which might occur during about nine-tenths of the time.

III. *General restrictions (due to Sr)*	*Persons*	*Area (sq. mi.)*	*\$ Millions*	*Conditions*
Minimum	20	1	0.01	Temperature lapse, dry, 1μ
Maximum	235,000	350	177	Temperature lapse, rain, 1μ

Under the same assumptions as under A, the area placed under general restrictions would be less than 50 sq. mi. for those accidents which might occur during about three-fourths of the time.

IV. *Agricultural Restrictions (due to Sr)*	*Area (sq. mi.)*	*\$ Millions*	*Conditions*
Minimum	3	0.1	Temperature lapse, dry, 1μ
Maximum	3,500	90.	Temperature lapse, rain, 1μ

Under the same assumptions as under A, the area placed under agricultural restrictions would be less than 500 sq. mi. for those accidents which might occur during about nine-tenths of the time.

Observations and Remarks

1. The number of personal injuries is highly dependent upon existing weather conditions at the time of the accident. Few lethal exposures would occur during daytime conditions. Exposures of large numbers of persons would occur during temperature inversions, typical of night-time conditions.
2. Except when strontium accompanies the release, property damage would range from essentially none to approximately two hundred million dollars. Without strontium, there would be no restrictions on agriculture.
3. The presence of strontium would add severe restrictions on land use both for general activity and for agricultural purposes. Decontamination would also be required within certain city areas. The net effect would be to increase the property damage and personal dislocation costs to a maximum of about 400 million dollars.

CASE III—THE 50 PERCENT RELEASE CASE

In this case it is assumed that 50 percent of all fission products would be released into the atmosphere and subsequently dispersed according to assumptions described earlier. Appendix I contains a summary of the personal injuries and property damages calculated for the variety of conditions considered. The following table contains a brief summary to indicate the magnitude and range of the consequences.

Personal Damage

A. *Lethal exposure*	*Persons*	*Conditions at release*
Minimum	0	Hot release at any time
Maximum	3400	Cold release, 1μ particle size, temperature inversion

Assuming that (1) hot and cold releases are equally probable, (2) particle size distributions are also equally probable, and (3) the distribution of weather conditions is as stated in appendix I, then lethal personal exposures would be less than 10 for accidents which might occur during about three-fourths of the time.

B. *Injury likely*	*Persons*	*Conditions at release*
Minimum	0	Hot release at any time
Maximum	43,000	Cold release, 1μ particle size temperature inversion, dry

Using the same assumptions as under A, the number of persons injured would be less than 100 for accidents which might occur during about three-fourths of the time.

Property Damage

II. *Evacuation*	*Persons*	*Area (sq. mi.)*	*$ Millions*	*Conditions*
Minimum	0	0	0	Hot, temperature inversion
Maximum	460,000	760	2300	Cold, 1μ, temperature inversion, rain

Using the same assumptions as under A, the number of persons to be evacuated would be less than 50,000 for accidents which might occur during about three-fourths of the time.

III. *General restrictions*	*Persons*	*Area (sq. mi.)*	*$ Millions*	*Conditions*
Minimum	0	0	0	Hot, 1μ, dry
Maximum	3,800,000	8200	2800	1μ, rain

Using the same assumptions as under A, the area placed under general restrictions would be less than 1,200 sq. miles for accidents which might occur during about three-fourths of the time.

IV. *Agricultural restrictions*	*Area (sq. mi.)*	*$ Millions*	
Minimum	18	0.5	Hot, 1μ, day, dry
Maximum	150,000	4,000.	Hot, 1μ, day, rain

Using the same assumptions as under A, the area placed under agricultural restrictions would be less than 10,000 sq. miles for accidents which might occur during about 93 percent of the time.

(The numbers above are from different cases and hence are not additive.)

Observations and Remarks

The numbers shown in the previous summary are calculated on the basis of what we believe to be the best available assumptions, data and mathematical methods. As has been stressed elsewhere, there is considerable uncertainty about many of the factors, techniques and data, so that these numbers are only rough approximations. Where information is sufficiently complete we have chosen values to represent the most probable situation but where high degrees of uncertainty exist we have chosen values believed to be on the pessimistic (high hazard) side. The results shown would be quite sensitive to variations in some of the factors which were used. As an example, the amount of fission products actually retained in people's lungs might be quite different from the amount assumed and this difference would change all the personal injury numbers greatly.

In addition, there could be weather conditions which, when combined with other imaginable extremely adverse conditions, could result in damages greater than the maximum considered in this study.

The damages calculated for the assumed 50 percent fission product release would vary widely depending upon weather conditions and assumed temperatures of the released materials.

The lethal exposures could range from none to a calculated maximum of 3,400. This maximum could only occur under the adverse combination of several conditions which would exist for not more than 10 percent of the time and probably much less.

Under the assumed accident conditions, the number of persons that could be injured could range from none to a maximum of 43,000. This high number of injuries could only occur under an adverse combination of conditions which would exist for not more than 10 percent of the time and probably much less.

Depending upon the weather conditions and temperature of the released fission products for the assumed accident, the property damage could be as low as about one-half million and as high as about $7 billion. For the assumed conditions under which there might be some moderate restrictions on the use of land or crops (Range IV), the areas affected could range from about 18 square miles to about 150,000 square miles.

Part IV

APPENDICES

Appendix A

The Nature and Extent of a Fission Product Release from a Power Reactor

Introduction

The principal danger associated with the operation of nuclear reactors of any type is the possible release of the radioactive fission products which they contain. Power reactors are hazardous in this respect because, for economic reasons, they must be operated for long irradiation times and at high power levels. These circumstances lead to large accumulations of fission products. The danger associated with an explosive nuclear energy release in a reactor is quite mild in comparison to the potential hazards from these materials if they should be dispersed. Even in the worst imaginable cases of nuclear runaway the energy release would be comparable only to a mild chemical explosion. Chemical reactions occurring in the wake of a nuclear runaway might in fact contribute more energy than the runaway itself. If power reactors are located at sites similar to those now being proposed, the release of energy accompanying a reactor accident would constitute a negligible hazard to the public. The energy release is important only because it contributes to the possible extent of the fission product release.

Basic Power Reactor Types

Power reactors may be classified according to three basic constituents: moderator, fuel, and coolant. A few pertinent comments about the principal types may serve to suggest some of the complexities, differences and similarities relevant to basic problems of safety. Fast reactors are designed in such a way that fissions are caused primarily by the absorption of fast neutrons by the fissionable material. Consequently, these reactors contain only weakly moderating materials. Thermal reactors contain strongly moderating substances such as graphite and water which greatly reduce the energy of the neutrons before they are absorbed. The fissionable fuel may be distributed throughout the reactor in the form of solid rods or plates, in which case the reactor is called heterogeneous, or it may be dispersed in the coolant fluid, in which case the reactor is called homogeneous. Most of the power reactors proposed to date are of the heterogeneous type. Water or liquid metals are among the chief materials now used to extract heat from a power reactor. When water is the moderator it serves also as the coolant. Examples are the pressurized water, the boiling water, and the aqueous homogeneous designs. Fast reactors and graphite-moderated thermal reactors generally utilize liquid metal coolants.

The reactor types differ markedly in engineering design, and each type poses its own peculiar safety problems. Some designs might be more prone to certain types of accidents than others, but it would be exceedingly difficult to compare the various power reactor types with regard to safety. It can be expected that before any reactor is approved for construction and operation all known problems relating to safety will have been resolved. In particular, such reactors would be expected to be inherently stable and would be operated according to certain prescribed procedures. They would be equipped with certain customary safety devices, as well as such special ones as their peculiarities dictate. All power reactors would contain substantially the same fission product inventory when operated under similar conditions. While the hazards posed by various reactor types may not be identical, they are at least similar in a number of respects.

Types of Reactor Accidents

Reactors can malfunction in many ways, and in this respect they are no different from other machines. Among other things, such malfunctioning could result from human errors, equipment failures, design errors, and acts of God. Accidents resulting from such malfunctionings could result in power plant "outage" and damage to the reactor. Only a few types of accidents could plausibly lead to a release of fission products to the atmosphere. Two such accidents, a nuclear runaway and a loss of sufficient coolant to uncover the reactor core, are considered below to illustrate some of the complexities involved.

The Nuclear Runaway

A nuclear runaway would result if the reactor were made supercritical and all safety instrumentation failed to function. As a consequence, the reactor power and temperature would increase until the runaway were terminated either by the inherent self-stabilizing influence of the reactor or by actual mutilation of the reactor core. A possible consequence of an unchecked runway could be the meltdown or vaporization of fuel elements and the release of fission products. Another possible consequence could be the initiation of exothermic chemical reactions between certain metals and liquids in the system. Such reactions would assist in the release and dispersal of fission products. However, it is highly improbable that the nuclear and the chemical energy release could cause much mechanical violence beyond the reactor shield. It is therefore feasible to build a gas-tight container around the reactor which would greatly reduce the chances of a fission product release to the atmosphere, if rupture of the reactor itself should occur.

The possibility of a serious nuclear runaway cannot be completely ruled out, but its occurrence can be made extremely unlikely by careful operating procedure, by adequate design, and by a multiplicity of control devices.

If a nuclear runaway were to occur, its effects would be minimized if the reactor had been designed to be inherently stable. The property of inherent stability implies that the production of heat causes physical changes within the reactor which reduce the reactivity. An inherently stable reactor will be self-regulating as soon as, or very shortly after, its temperature begins to rise. Water-moderated reactors generally possess this self-regulating property to a marked degree, and it seems likely that the property can be designed into all types of reactors to at least some degree.

An inherently stable reactor is not completely immune to destructive runaways, however. In the 1954 Borax experiment it was possible substantially to wreck a stable boiling water reactor by deliberate introduction of a large amount of reactivity at a rapid rate. The self-stabilizing features in reactors may not always operate concurrently with the release of heat by the fission process but may be delayed. If a substantial reactivity were to be introduced into the reactor during this "delay," the reactor would behave essentially as though it were non-self-stabilizing and destruction could be the consequence.

Such large, rapid additions of reactivity are not easily achieved, and in a normally operating reactor could only occur if a series of unlikely misoperations or failures took place. No feature in the design of a reactor receives more attention than those which are incorporated to prevent such inadvertent reactivity additions. Design features and mechanical safeguards, in addition to the inherent self-stabilizing characteristics, are always incorporated to prevent such addition, and these must fail before a potentially hazardous situation would exist.

The Loss of Coolant Accident

A second major type of accident is the loss of coolant. Such an accident could result from a break in the primary coolant circulating system of from a rupture of the reactor vessel itself. Loss of coolant would permit the radioactive decay heat to melt the uncooled fuel, even though the nuclear reaction had stopped, and thereby permit release of volatile fission products. Calculation indicates that, at least for certain reactor core configurations, further heating of the fuel to the boiling point is precluded by radiation losses [3]. There is the additional possibility that the overheated fuel would react chemically with air entering the reactor, or, in the case of water-moderated reactors, with such water as remains. Such a reaction, if violent, would help disperse the fission products and might furnish enough energy to break the external reactor container.

Even in the event of a major loop break it is possible to prevent a fuel meltdown by providing for emergency cooling of the core. This may be accomplished by maintaining a large tank of coolant. In any case, the principal line of defense against loss of coolant accidents would be adequate design and care in construction.

The consequences of a loss of coolant could be serious. But the event is highly improbable since it requires the occurrence of an unlikely material failure in the primary loop coupled with the unlikely failure of emergency cooling schemes, or else the unlikely failure of the reactor vessel itself.

Chemical Reactions

It has already been mentioned that excessive heating of the reactor through either nuclear runaway or loss of coolant could result in potentially violent chemical reactions. Three principal reactions are: sodium reacting with air, fuel metal reacting with air, and water reacting with fuel metal. The additional possibility exists that hydrogen evolved in the last reaction could react with oxygen.

The first reaction would occur if, as a result of an accident with a sodium cooled reactor, vaporized sodium came in contact with air. The reaction would take place as a rapid but non-violent burning of a vaporized sodium. The only effect of this burning would be to increase the pressure in the reactor's vapor container. Since the vapor container would be designed to withstand the pressure increase resulting from the burning of all the sodium in the reactor, this particular reaction would not be expected to cause a container rupture.

The second reaction would take place if air entered a ruptured reactor vessel and came into contact with hot fuel elements. The result would be rapid oxidation or burning of the metal. The reaction would be nonviolent, but it could release a substantial portion of the fission products.

The third type of reaction, which is peculiar to heterogeneous water-moderated reactors, would be the only potentially violent one. The metals employed in the construction of fuel elements which would be reactive at high temperatures are zirconium and aluminum and possibly uranium. The total chemical energy available for these water-metal reactions equals or exceeds the energy that would be released in the worst possible nuclear excursion. However, the conditions for anything like a complete reaction would be difficult to achieve. Experience with water-metal reactions in reactors is at present almost totally lacking; therefore, conclusions must be based on information acquired from foundry practice and a few experiments.

The available information on the aluminum-water reaction may be briefly summarized as follows. In aluminum foundry practice, water is frequently used as a quench to form ingots from molten metal. This practice has infrequently led to violent explosions [5]. The occurrence of these explosions has been found to depend very sensitively on such conditions as the depth of the water, the diameter of the molten stream, and the presence of impurities. For example, a coating of grease on the water container was found to prevent the explosion, while iron rust was found to increase the tendency for explosion. Weils and West [6] at Argonne National Laboratory performed the experiment of pouring molten aluminum into water without obtaining an explosive reaction. Molten aluminum was also poured into water in an experiment at the Aerojet General Corporation Laboratories. The experiment was then modified by using a blasting cap to disperse the metal. Explosions failed to occur in either case; only the formation of an oxide film took place [7]. The conclusion to be drawn from the Argonne and the Aerojet General work is that a violent explosion will not occur under the special conditions of these experiments. Finally, it should be mentioned that, in the destructive Borax experiment, a meltdown of aluminum-clad fuel elements failed to produce an explosive water-metal reaction [8].

Experiments performed at Westinghouse [9], Aerojet General [7], and North American Aviation [10] indicate that the zirconium-water reaction can be either a rapid oxidation or a violent explosion, depending on whether the zirconium is in massive form or finely dispersed. In the first case the reaction becomes noticeable at about 1200° C., well below the melting point of zirconium. In the presence of water the reaction is self-quenching when the external source of heat is removed; while in the presence of steam the reaction is expected to proceed autocatalytically, i.e., the reaction, once started, will proceed without the application of external heat. In the experiments with dispersed zirconium and water the dispersal was brought about either by detonation of a blasting cap below the surface of the water while molten zirconium was poured in or by explosion of zirconium wires in water by means of rapidly discharging condensers. In either case the zirconium present reacted more or less completely with explosive violence.

A theoretical analysis has been made at Westinghouse [4] to determine the maximum possible extent of a water-metal reaction occurring in a pressurized water reactor. It was hypothesized that a major break had occurred in the coolant loop, resulting in loss of water and a complete uncovering of the reactor core. The temperature of the zirconium-uranium fuel elements would soon rise as a result of the fission product decay heat. When the metal reached 1200° C., the fuel elements would begin to react with the steam present in the core. The reaction would then proceed autocatalytically until the metal temperature was brought to the melting point. The melting would take place slowly releasing droplets which would fall into the remaining water below. At this point the water-metal reaction would be quickly quenched. By using experimentally determined heating curves for the water-zirconium system, a calculation was made of the amount of zirconium that could react from the inception of the reaction to the time of its quenching by heat losses from the metal droplets to the water. The maximum possible percentage of the metal which could react in this most favorable case was estimated to be 25 percent.

In the course of a water-metal reaction, hydrogen gas would be evolved which could react with oxygen after leaving the reactor. If the hydrogen exceeds a certain critical concentration, an explosion is possible. But a very substantial amount of hydrogen would be required to raise the hydrogen concentration in the vapor container to this critical level. A certain quantity of hydrogen would be produced within the reactor as a result of its usual operation, but this amount is so small that it would constitute no explosive hazard [4]. Since the evolution of hydrogen from the water-metal reaction would take place slowly, it could be burned before explosive concentrations are reached. In some installations to insure that hydrogen burns as it is evolved, a number of electric igniters are located throughout the vapor container.

To summarize, the chemical reaction which poses the most serious danger in the event of a reactor accident is the water-metal reaction. This reaction, however, would be expected to proceed as a vigorous but incomplete oxidation of the metal at elevated temperatures. In the case of zirconium, it is expected that no more than 25 percent of the metal would react. A violent and more or less complete reaction of the metal would require the metal to be finely dispersed. Such a dispersal could occur only as a result of fuel vaporization, which was previously pointed out to be a highly unlikely event.

The Function of Vapor Containers

Since the energy release (whether chemical, nuclear, or both) which might accompany a reactor accident is expected to be of comparatively mild intensity, it is feasible to construct a steel shell to confine the fission products which might escape from the reactor. Because of the large volume of such a shell, it can be readily designed to withstand the pressure loading resulting from accidents capable of rupturing the reactor vessel. Presumably it would be impractical to design such a vapor container to confine the worst conceivable accidents. It is designed rather to contain all credible accidents. For example, the vapor container for a pressurized water reactor would be designed to withstand either the pressure resulting from a water release or 25 percent of the energy available for a chemical reaction, but not both simultaneously. In this case, calculation [4] indicates that the pressure produced by the first event would be relieved through heat losses from the container before the second event could take place.

There is always the possibility that the vapor container could be penetrated by flying fragments resulting from failures in the system. The use of ductile metals in construction would greatly reduce the probability of such failures and therefore the probability of missile formation. In addition, the resistance of the vapor container to the penetration by missiles could be increased by lining the inside of the shell with a layer of reinforced concrete.

While the vapor shell could probably not withstand severe shock-wave effects, it is considered extremely unlikely that such shock phenomena could be initiated by either a nuclear or a chemical energy release. The speed of a nuclear excursion would be limited by the lack of means of introducing reactivity rapidly into the reactor system, while the speed of a chemical energy release would probably be governed by the rate of mixing of the reactants. In either case the energy release could be expected to be much slower and less destructive than an equivalent energy release from a detonating explosive. Energy releases calculated for reactor accidents are sometimes expressed in TNT weight equivalents. Such comparisons ignore the fact that the rates of energy release in the two cases may be greatly different. The damage in the reactor thus is overestimated.

Thus the vapor container surrounding a reactor may be considered another line of defense for the protection of the public. These structures are not impregnable, but they are designed to be capable of confining the accidents which can be regarded as credible.

The Extent of Fission Product Release

The question is now raised: In the highly unlikely event of a reactor accident which leads to a rupture in both the reactor vessel and its vapor container, what would be the expected percentage release of the fission products? The answer to this question depends in a complicated way on the details of the accident. Various possible accident situations could lead to different amounts of fission product release, e.g., fuel meltdown unaccompanied by a chemical reaction; meltdown followed by a nonviolent oxidation of the metal by water; meltdown in the presence of air accompanied by combustion of the metal; and either violent chemical reaction or vaporization, or both.

The first situation would require that no water be present in the reactor and that no combustion take place. The latter requirement could be met if the fuel elements have a melting temperature well below the temperature required for rapid combustion. In experiments performed at Oak Ridge National Laboratory, Parker [11] has electrically melted uranium-aluminum fuel elements in the presence of air without causing combustion. It can be reasonably assumed that in an accident situation molten fuel metal will quickly assume a physical shape which is no longer conducive to the molten state; e.g., it can form into drops which fall and resolidify. In the previously mentioned experiments Parker observed that, if the irradiated molten uranium-aluminum fuel element is refrozen within a few seconds, about 60 percent of the noble gases, xenon and krypton, leave the metal in addition to about 25 percent of the iodine. The percentage of the bromine escaping can be reasonably assumed to equal that of the iodine. Once resolidification of the fuel has taken place, the escape of radioactivity would be expected to stop. While these fission products make up the bulk of the released radioactivity, minute quantities of less volatile substances such as tellurium were also detected to have escaped from the metal. It is reasonable to assume that other metals having similar volatility, such as strontium, could escape in minute quantities as well.

In the second situation, the release of the more volatile fission products is assisted by the oxidation of the metal by water. Two hydrogen atoms are released for every atom of metal oxidized, and, in the course of escaping, the evolved hydrogen disrupts from the lattice atoms of the more volatile elements, which likewise escape. Experiments have been carried out at the Westinghouse Atomic Power Division to determine what products are released as a result of the corrosion by water of irradiated uranium metal [12]. These experiments were performed at relatively low temperatures (600° F.). The fairly volatile metals cesium and rubidium were observed to escape quantitatively, while the less volatile barium and the biologically important element strontium were found to escape only to the extent of 5 percent. It seems reasonable to assume that the gaseous elements, halogens and the noble gases, would also escape quantitatively although no determination was made. Unfortunately, such data are not available for the corrosion of more typical reactor fuels such as uranium-zirconium alloy at more realistic temperatures. In any case, the evolution and escape of hydrogen gas are expected to govern the release of fission products. It can be argued that the behavior of the hydrogen should not depend strongly on the metal being oxidized and that therefore the fission product release observed for uranium is a likely one for other reactor fuels as well. According to Westinghouse estimates, a maximum of 25 percent of the zirconium-uranium fuel could be oxidized by water. Therefore, the maximum expected release of strontium in case of a complete fuel meltdown in the presence of water would be 5 percent of 25 percent or 1 percent, on the assumption that negligible amounts of strontium are released from the unreacted metal. On the basis of Parker's data the same release could be expected to include 70 percent of the noble gases and 44 percent of the halogens as well as less important percentages of some of the volatile metals.

The third situation could occur if the fuel element melting temperature were high enough for combustion to accompany melting. The process of combustion would involve considerable disruption of the oxidizing material and would cause the release of a substantial fraction of the fission products. Parker observed that uranium-stainless steel fuel elements burned vigorously after rapid heating to 2000° C. and that 50 percent of the total gamma activity of the fuel element was removed as a result. If all the noble gases and halogens are assumed to escape, it could be inferred that 25 percent of the remaining fission products were removed. Zirconium-uranium alloy has a high melting temperature (about 1800° C.), therefore, it might be a candidate for combustion. Parker, however, observed that zirconium-uranium fuel elements heated slowly to the melting point did not burn. Such slow heating should reasonably simulate the melting of fuel elements by decay heat.

Actually, in the case of a pressurized water reactor it is highly doubtful that air could even enter the core while the fuel was in the molten state, the reason being that steam at greater than atmospheric pressure would fill the core for a matter of hours following the loop failure. It is conceivable in some reactor designs that air could enter the core following a coolant loop rupture; however, in view of Parker's observations it appears doubtful that combustion would occur.

The final situation could lead to substantial dispersal of the fuel. Whether this would significantly augment the release of fission products is open to question. It is reasonable to assume that fission products would escape quantitatively from the metal that had reacted or vaporized; but it is doubtful whether major portions of fuel could vaporize or react violently even in the unlikely event that these two processes did take place. The dispersed metal should behave substantially as in the first and second situations already discussed. Thus, even in the case of violent disruption within the reactor, the fission product release should not be expected to exceed substantially the release in the case of fuel combustion.

Conclusions

On the basis of the best available information, the mechanisms of fission product release most likely to occur appear to be either a fuel meltdown or a meltdown accompanied by an oxidation of fuel by water, depending on whether or not water is present in the reactor. In the former case, the release would be confined to about half the noble gases and about a quarter of the halogens contained in the fuel. In the latter case, the release would consist primarily of a somewhat more complete release of these same volatiles in addition to approximately 1 percent of the contained strontium.

A meltdown followed by combustion could result in a release of 50 percent of the contained radioactivity. A conservative guess would be that a like percentage of strontium would be released. In the light of experimental evidence this type of release seems less likely than either of the first two. Finally, a violent release could not reasonably be expected to exceed 50 percent. Such a mode of release would also be unlikely.

Speculation has so far been concerned only with the escape of fission products from reactor fuel and has not taken into account the condensation and absorption of these substances on metal surfaces in the reactor and vapor container during their passage to the atmosphere. The preceding estimates are therefore somewhat conservative, at least in the case of the less volatile fission products; but since these estimates involve uncertainties, there is some justification for conservatism.

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Appendix B

Description of Reactor and Site

Description of Reactor

The reactor chosen for this study is a 500,000 thermal kilowatt reactor. This power rating is in the range of the ratings of the large power reactors now proposed. However, since all the cost analyses that have been performed on reactors show that the cost per kilowatt-hour of electricity decreases with increase in reactor power, it is expected that the power level of future reactors will tend to be large.

The reactor is assumed to be fueled with uranium-235. Also, the fuel reprocessing cycle is taken to be 180 days. This time interval seems appropriate for reactors now proposed.

Description of Site

It is assumed in this report that the reactor would be 30 miles from a large city, and located near a large body of water. It is logical to place the reactor near the users of power, since transmission costs are proportional to distance; on the other hand, land costs are less outside the city than inside. Nearness to a water supply is postulated because water is necessary for steam condensation. All the power reactor sites proposed to date are within 30 to 40 miles of a city and near an adequate water source.

Choice of a typical distribution of population around a reactor site was arrived at by a consideration of the actual distribution around five reactor sites. It develops that the total population within given radial distances (R) of less than 30 miles is remarkably similar for these sites. This population can be calculated by the expression Population = 200 $R^{2.83}$ where R is in miles. Figure 1 shows the population curves for three government controlled sites and two proposed private sites with the above population equation plotted. At medium distances the actual populations around the proposed commercial sites are lower than those calculated from this equation by a factor of up to 4. This is about the same as azimuthal variation. It should be noted that the government sites have been in existence for some time. It would be expected that more people and factories would move into the region 10 to 20 miles from a new reactor as time goes by, so that the areas around commercial sites would become like those around the government sites, for which the population equation is quite good.

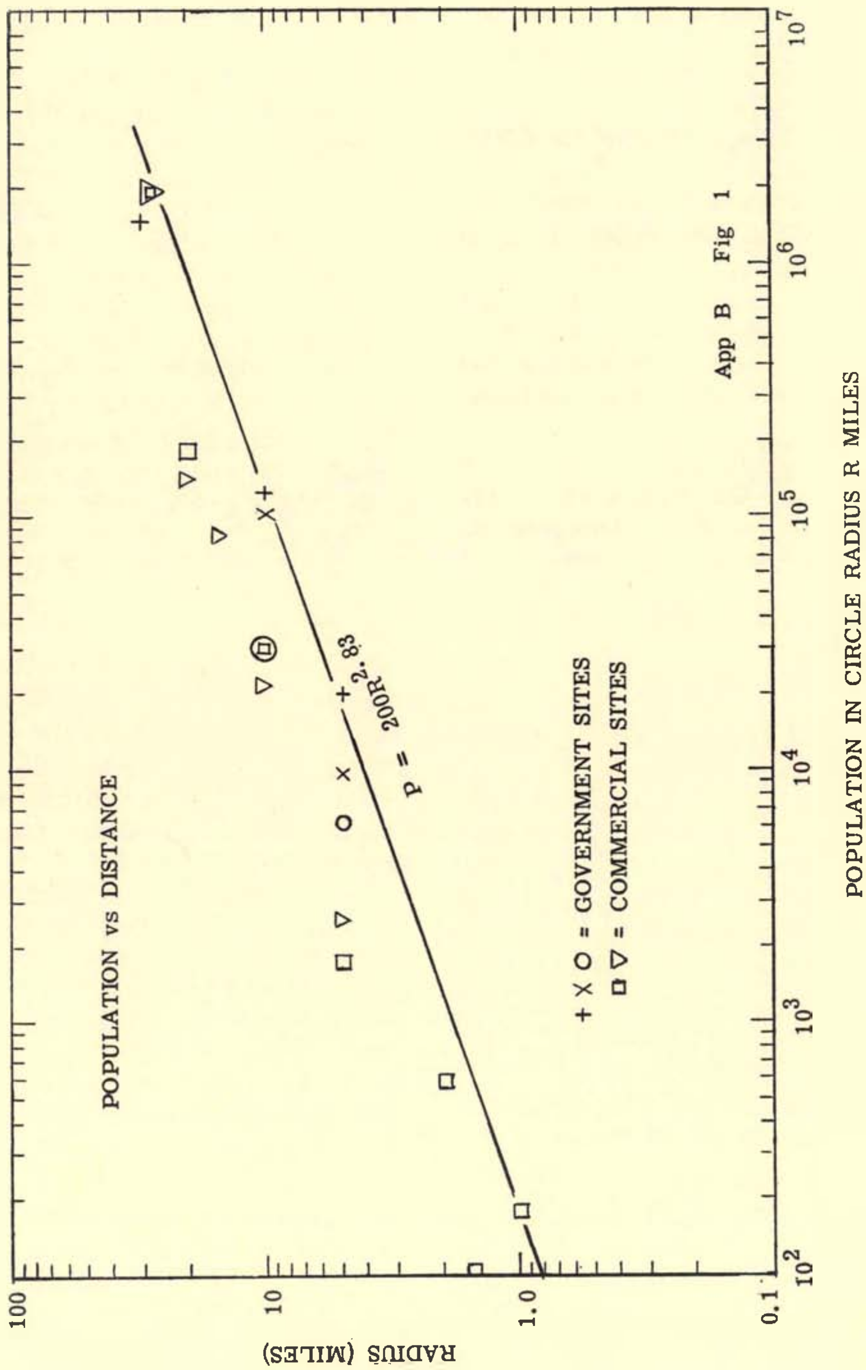
For distances greater than 30 miles, population density is assumed to be 500 people per square mile rather than the United States average of 55 per square mile. The states with high population densities have been deliberately chosen because power reactors are expected to be built in regions where there are many power users. Examples of population densities in some industrial states as given in *The Statistical Abstract of the United States, 1955*, are:

Population Density, people/mi ^{2}

	1940	1950
Rhode Island	674	748
New Jersey	553	643
Massachusetts	545	596
New York	281	309

The above numbers show that population densities are increasing at a very rapid rate.

The choice of the characteristics of the nearby city was difficult. For purposes of calculation the city was assumed to have one million people uniformly dispersed over a circular area of 15-kilometer (about 10 miles) radius. While no city of this exact description exists, it is felt that such characteristics provide a reasonable basis for the calculation of hypothetical damages.



Appendix C

Fission Product Activity in the 500,000-tkw Reactor

Estimates of the fission product activity at one day after 180 days' operation were obtained from three compilations of the fission product decay chains [1–3]. The total activity in curies was obtained from values from figure 1 in the British compilation and from the expression

$$N(I,D) = \frac{N(D) - N(I + D)}{I} = \text{disintegrations/fission-day,}$$

where

I = irradiation time, 180 days;
D = decay time, 1 day; and
$N(I,D) = (1.6 - 0.546)/180 = 5.86 \times 10^{-3}$ disintegrations/fission-day.

Thus the total activity is

$$\frac{(5.86 \times 10^{-3})\ (3.1 \times 10^{10})\ (5 \times 10^{8})\ (180)}{3.7 \times 10^{10}} = 4.4 \times 10^{8} \text{ curies}$$

24 hours after shutdown of the 500,000-tkw reactor after 180 days' operation.

Similarly, the Hanford compilation indicated, from table 3 in reference 2, that the 1 day fission product activity would be 10,000 disintegrations/min in a 200 day old reactor for a fission rate of 10^4 fissions/min. 10^4 fissions/min. result in a power level of 5.34×10^{-9} watts. The activity then is $10{,}000/(5.34 \times 10^{-9}) = 1.873 \times 10^{12}$ disintegrations/watt-min., and the source strength was estimated to be

$$Q = 4.2 \times 10^{8} \text{ curies}$$

in the 500,000-tkw/reactor.

The total activity of the 500,000-tkw reactor one day after a 180-day operation was taken to be 4.1×10^8 curies, a value referred to by Chamberlain and Megaw [4] as well as by Parker and Healy [5].

The activity due to the volatile fission products was inferred from the Argonne compilation [3] and an earlier Argonne report [6]. The curves in figures 1 and 2, which were inferred from similar curves in reference 6, indicated that the bulk of the volatile fission product activity would be due to the iodine, krypton, and xenon isotopes. The Argonne fission product decay chain compilation [3] indicated also that the noble gas activity was due principally to the xenon isotopes, Xe^{133} and Xe^{135}. Thus, the iodine activity, one day after shutdown, was found to be about 5×10^7 curies. The noble gas activity was 3.4×10^7 curies and, consequently, the total volatile activity at one day would be 8.4×10^7 curies.

It was found that the decay of the volatile fission product power after one day could be approximated by $t^{-0.8}$. However it was noted that the decay of the volatile fission product activity (curies) departs significantly from $t^{-0.8}$ at times immediately after shutdown and beyond about 10 days.

Finally, estimates of the Sr^{89}, Sr^{90}, and Ce^{144} activities were obtained. It was thought that Ce^{144} could be important in a radiation dosimetric sense because of its energetic, short-lived daughter, Pr^{144}, which emits a 3-Mev β-particle. The one-day activities inferred from the Argonne compilation were 1.7×10^7 curies of Sr^{89}, 3.8×10^5 curies of Sr^{90}, and 8×10^6 curies of Ce^{144} for the 180-day-old reactor.

The activities used, then, in subsequent meteorological and dosimetric considerations are summarized below.

Activity	*Curies*
Total	4.1×10^8
Volatile	8.4×10^7

Iodine	5×10^7
Noble Gases	3.4×10^7
Sr^{89}	1.7×10^7
Sr^{90}	3×10^5
Ce^{144}	8×10^6

FIGURES

FIGURE 1. Total beta power from volatile fission products, 500,000-tkw operation for 180 days. Only the volatile fission products present at $t = 0$ and their offspring are considered; 100 percent of halogens are assumed to escape. Inferred from ANL–WHZ–299, Figure 23, J. M. West and J. T. Weils, May 7, 1951.

FIGURE 2. Total gamma power from volatile fission products, 500,000-tkw operation for 180 days. Only the volatile fission products present at $t = 0$ and their offspring are considered; 100 percent of halogens are assumed to escape. Inferred from ANL–WHZ–299, Figure 23, J. M. West and J. T. Weils, May 7, 1951.

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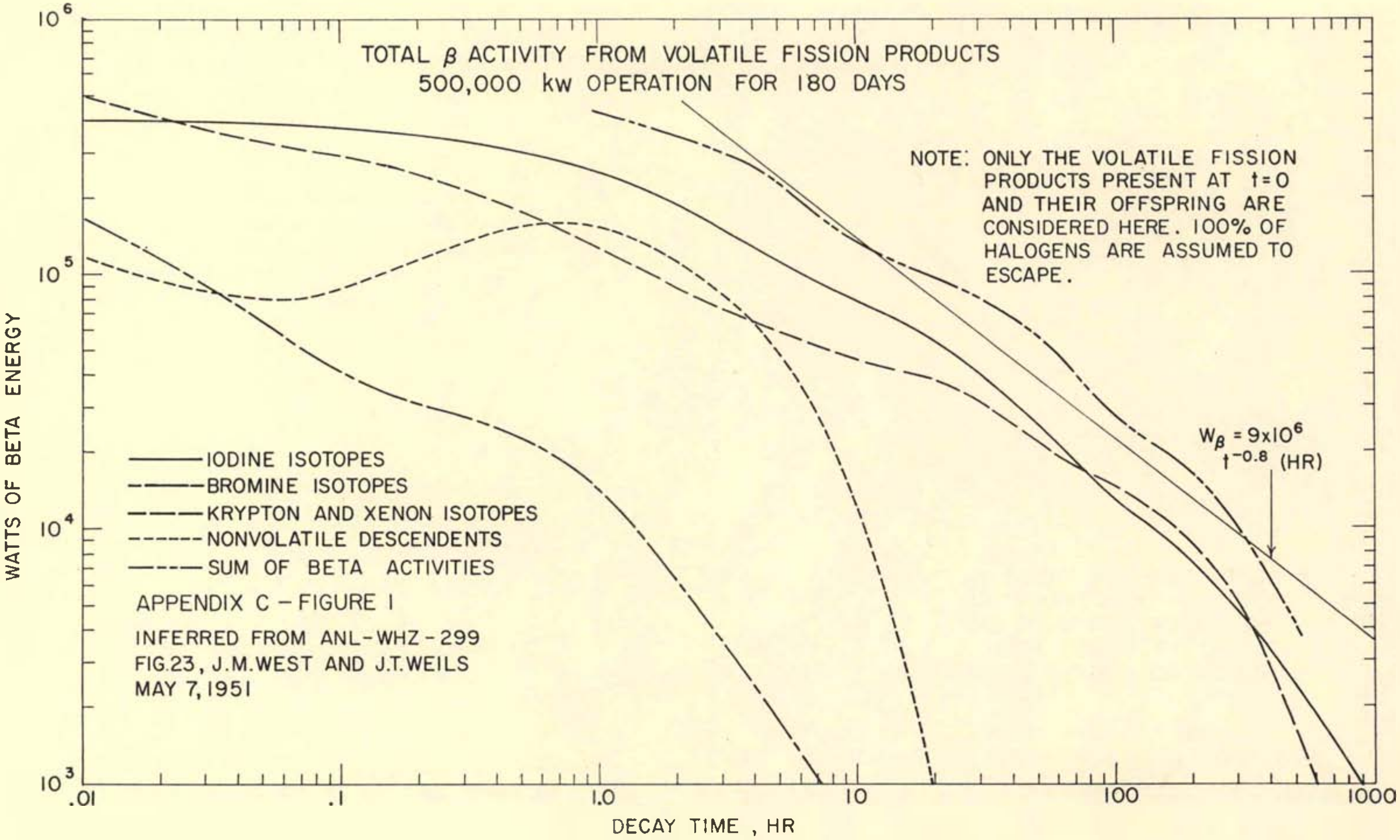
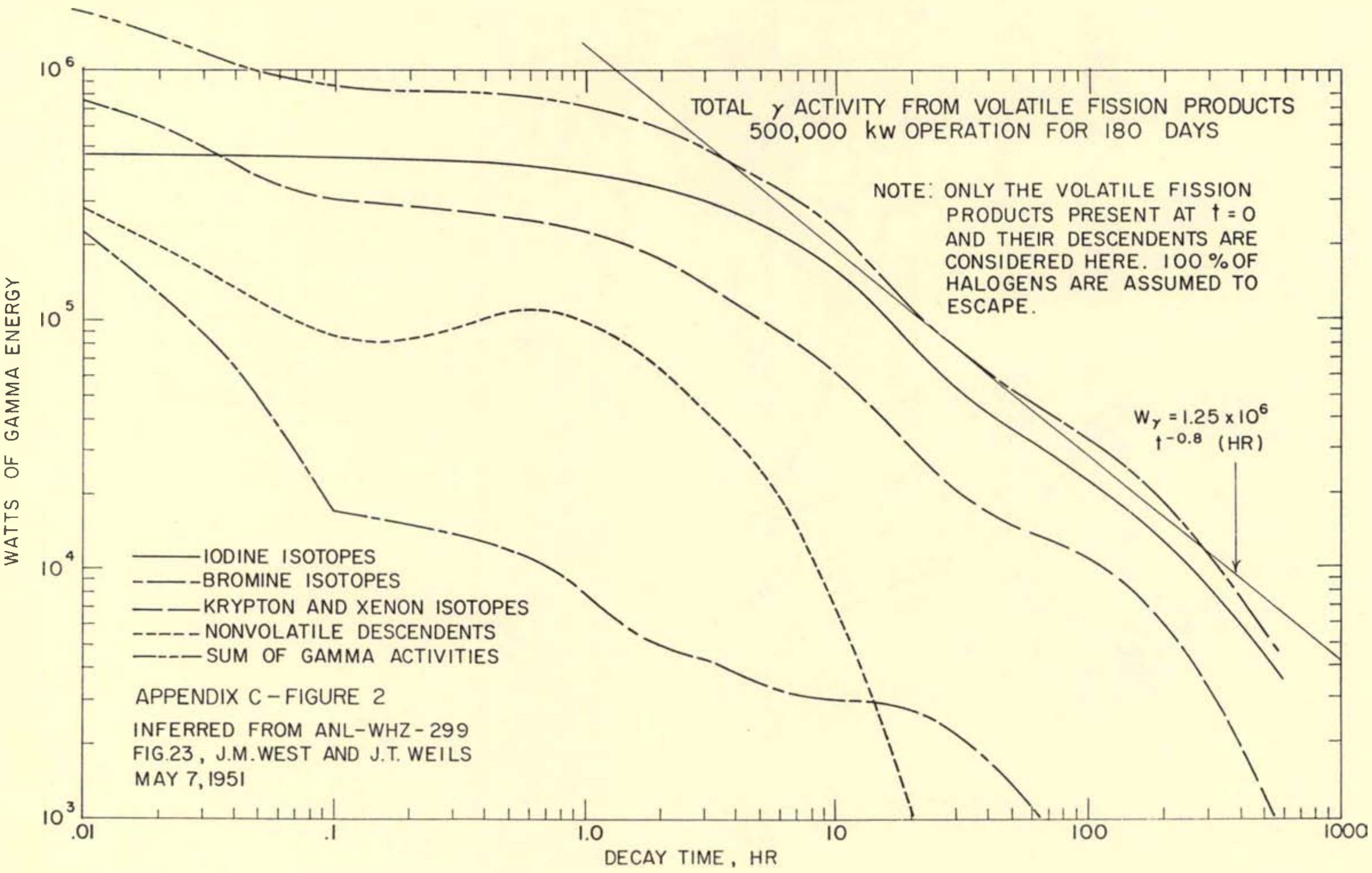

TOTAL β ACTIVITY FROM VOLATILE FISSION PRODUCTS
500,000 kw OPERATION FOR 180 DAYS
NOTE: ONLY THE VOLATILE FISSION PRODUCTS PRESENT AT t=0 AND THEIR OFFSPRING ARE CONSIDERED HERE. 100% OF HALOGENS ARE ASSUMED TO ESCAPE.
Wβ = 9x10^6 t^-0.8 (HR)
IODINE ISOTOPES
BROMINE ISOTOPES
KRYPTON AND XENON ISOTOPES
NONVOLATILE DESCENDENTS
SUM OF BETA ACTIVITIES
APPENDIX C – FIGURE I
INFERRED FROM ANL-WHZ-299
FIG.23, J.M.WEST AND J.T.WEILS
MAY 7, 1951
WATTS OF BETA ENERGY
10^6
10^5
10^4
10^3
.01
.1
1.0
10
100
1000
DECAY TIME, HR


TOTAL γ ACTIVITY FROM VOLATILE FISSION PRODUCTS
500,000 kw OPERATION FOR 180 DAYS
NOTE: ONLY THE VOLATILE FISSION PRODUCTS PRESENT AT t = 0 AND THEIR DESCENDENTS ARE CONSIDERED HERE. 100 % OF HALOGENS ARE ASSUMED TO ESCAPE.
$W_\gamma = 1.25 \times 10^6$ $t^{-0.8}$ (HR)
WATTS OF GAMMA ENERGY
10^6
10^5
10^4
10^3
.01
.1
1.0
10
100
1000
DECAY TIME, HR
IODINE ISOTOPES
BROMINE ISOTOPES
KRYPTON AND XENON ISOTOPES
NONVOLATILE DESCENDENTS
SUM OF GAMMA ACTIVITIES
APPENDIX C - FIGURE 2
INFERRED FROM ANL-WHZ-299
FIG.23, J.M.WEST AND J.T. WEILS
MAY 7, 1951

Appendix D

Effects of Fission Product Release on Humans and Land Use

Introduction

In this appendix an attempt is made to estimate the effects on humans who might be exposed to a cloud of fission products released as a result of an accident to a power reactor and to estimate the effects on land use of contamination by deposition from such a cloud. It will be clear that the conclusions reached can be little more than educated guesses, since the direct effects on humans of exposures of this character are largely unknown. Similarly, setting definite limits on acceptable contamination levels for land to be used in agriculture is risky because of the incomplete state of present knowledge of the soil-plant-animal-human relationships involved.

Assumed exposures of human beings to a radioactive cloud will be divided into four categories. Category D will be considered as representing less than the Acceptable Emergency Dose (AED), which is taken to be 25 r of whole-body gamma radiation in one exposure or 50 r in 3 months. Persons with exposures falling in category D are assumed to have received no injury and hence are assumed not to represent any financial liability although it is realized that exposures in this category might in a few cases have undesirable consequences many years later. Exposures in category C might result in minor symptoms, but it is felt that persons receiving such exposures would be in good health. However, some physical examinations, bioassay procedures, etc., involving some expense might be required. This exposure category would be roughly equivalent to the range of 25 to 100 r of whole-body gamma radiation. Exposures in category B, corresponding to 100 to 450 r, would result in incidence of illness. Finally, a high percentage of fatalities would be expected from category A exposures corresponding to doses in excess of 450 r.

In dealing with the deposition problem there appear to be five possible situations, depending on contamination level, to be considered. In the first, designated as range I, urgent evacuation (i.e., within 12 hours) would be imperative. Next would be range II, in which evacuation would be required, but more time would be available to prepare for it. Where such evacuation would prevent injury it is assumed that evacuation would be accomplished and no injuries are tabulated. In some cases such evacuation would require extensive efforts and arrangements, but discussion of these is not within the scope of this study. In range III, restrictions on agriculture would be necessary and temporary evacuation might be required in some circumstances. Contamination levels in range IV would probably necessitate destruction of standing crops and restrictions on agriculture, at least for the first year. Finally, contamination levels in range V, while still easily detectable, would necessitate no restrictions and, hence, involve no expense other than the cost of radiological monitoring.

Later in this appendix estimates will be given for the exposures in curie-seconds per cubic meter (C–sec/m^3) corresponding to the four categories described above, for two assumed types of reactor incident. In the first case (referred to as "fission product release") a sizeable fraction of all the fission products contained in the reactor is assumed to be liberated. In the second type of accident ("volatile release") it is assumed that reactor fuel melts and that the volatile fission products (primarily noble gases and halogens) are liberated.

Arbitrary assumptions have been made as to the power level and age of the reactor fuel charge in other sections of this study, and computations have been made of the land areas and numbers of people affected. These assumptions have relatively little effect on the levels expressed in C–sec/m^3 chosen for the boundaries of the various exposure categories.

Unfortunately the same is not true in the case of the limits on contamination resulting from deposition. In particular, the boundary between ranges IV and V is determined largely by the strontium-90 concentration in the material deposited, which is almost directly proportional to the elapsed megawatt days of exposure of the fuel charge at the time of the accident. It is necessary to keep this point firmly in mind in any evaluation of the possible cost of a reactor accident. Estimates are given for the boundaries of the various ranges of deposited contamination in terms of curies per square meter (C/m^2). All activities have been referred to a time 24 hours after the postulated accident.

Choice of Units and Approximations Used

The decision to express the various exposure categories in terms of C–sec/m^3 was made for convenience in computation of hypothetical consequences in other sections of this study. Actually in the type of dosage calculations made here it would have been preferable to use watt-seconds per cubic meter and thus take care of the changes in average energy with time. This is particularly true in the volatile fission products release. Here the change in average energy with time would be so marked that the variation in fission product energy was actually used in calculations of dose rates and the results were later expressed in curies.

The decay of the complete fission product mixture can be represented by a $t^{-0.2}$ power law over the times of interest in this study. In the volatile release however the total number of isotopes present is apparently too small for this statistical approach to be valid. It was found empirically that the total beta energy or the total gamma energy of the volatile products can be represented by a $t^{-0.8}$ law from about 2 hours to about 500 hours after an incident (see figs. 1 and 2 in appendix C). This is a fortunate circumstance since otherwise it would have been necessary to resort to graphical integrations to compute dosages.

Also it was necessary to assume an arbitrary time for the passage of the cloud. Otherwise each type of incident would have had to be computed for each probable meteorological situation and the effects on exposed humans estimated separately. No generally applicable limits could have been set for the various exposure categories.

A time of 2 hours after the accident was chosen as representative of the cloud passage. This is of course too late for really close-in areas but is probably early for the more densely populated regions. Because of the slow decay, dose calculations for the fission product release are not very sensitive to the choice of arrival time. In the volatile release, on the other hand, a change in time of arrival of the cloud would make a significant difference in the estimated limits for the various exposure categories.

Estimation of Exposure to Cloud

In estimating the exposure received by a person exposed to the radioactive cloud from a reactor accident, the assumption is made for convenience in computation that the individual is immersed in a cloud of practically infinite dimensions. "Infinite" in this case means large compared to the mean free path of the average gamma-ray. Expression of the exposure in terms of C–sec/m³ implies that the passage of the cloud takes more than a few seconds so that the subject will take enough breaths for his alveolar air to come into equilibrium with the surroundings. The time will, however, be considered short enough that the dose can be considered as delivered in one single exposure. It is clear that within these limits it makes no difference whether a dose of 100 C–sec/m³ results from 100 seconds' exposure to a cloud concentration of 1 C/m³ or 10,000 seconds' exposure to a cloud concentration of 10 mC/m³.

Whole-Body Gamma Dose

An estimate of the whole-body gamma dose resulting from an exposure of 1 C–sec/m³ can be made as follows: Assume the subject is immersed in a semi-infinite medium containing activity. Neglecting back-scattering from the ground, the dose rate would be just half that obtained in an infinite medium, and is given by equation 1:

$$d = \frac{1}{2}\Big[(c\mu\text{C/cc})(3.7 \times 10^4 \text{ dis/sec–}\mu\text{C})(E_\gamma\text{Mev/dis})(1.6 \times 10^{-6}\text{erg/Mev})\Big]\Big[(100 \text{ erg/g–rad})(0.0012 \text{ g/cc air})\Big]^{-1} \text{rad/sec} \quad (1)$$

$$d = 0.246\, cE_\gamma \text{ rad/sec}$$

where

d = dose rate in rad/sec,

E_γ = average gamma quantum energy in Mev and

c = concentration of activity in μC/cc = C/m³.

This equation is derived on the assumption that in an infinite medium in equilibrium as much energy will be absorbed in each cc of air as is generated in it.

An average gamma energy, E_γ, of 0.7 Mev is assumed to represent the fission products at this age. Further, although the activities are stated as of 24 hours after the accident, exposure to the cloud would presumably occur at some earlier time, say 2 hours after the accident. Therefore it is necessary to correct the dose rate from the 24-hour to the 2-hour value. In the time range of interest the entire fission product activity is assumed to be proportional to $t^{-0.2}$, while the energy of the volatile fission products is assumed to decay according to a $t^{-0.8}$ law. Thus, exposure to 1 C–sec/m³ (24-hour value) of fission products, at 2 hours after the accident, would give a whole-body dose,

$$D_f = 0.246 \cdot 1 \text{ C/m}^3 \cdot 0.7 \text{ Mev} \cdot 1 \text{ sec} \cdot (2^{-0.2}/24^{-0.2}) \text{ rad}$$
$$= 0.173\,(24/2)^{0.2} = 0.173 \cdot 1.64 = 0.28 \text{ rad} \quad (2a)$$

Correspondingly, for the volatile release, the dose would be

$$D_v = 0.246 \cdot 1 \cdot 0.7 \cdot 1 \cdot (2^{-0.8}/24^{-0.8})$$
$$= 0.173\,(24/2)^{0.8} = 0.173 \cdot 7.3 = 1.26 \text{ rad.} \quad (2b)$$

If 25 r is taken as equal to 1 AED, and the usual assumption is made that 1 rad equals 1 roentgen, then these exposures amount to 0.0112 and 0.0505 AED, respectively.

It should be pointed out that assumption of an infinite cloud will make the calculated result too high. On the other hand, neglect of radiation scattered back from the ground and gamma radiation received when not in the cloud at all makes the result too low. The two effects have been assumed to cancel each other in the first approximation.

Whole-Body Beta Exposure

Whole-body beta exposure from the passing cloud would be less than the gamma exposure and, since it affects principally the skin, should not contribute significantly to the acceptable emergency dose. However it should be borne in mind that beta dosage may become important if material is deposited on the body and not washed off promptly.

Calculation of Activity Inhaled

The standard man is assumed to have a respiratory minute volume of 20 liters at work and 10 liters during rest or light activity, and he is assumed to be at work 8 hours a day, or one-third of the time. The average minute volume is $[20 + (2 \times 10)]/3 = 13.3$ liters, and the respiratory rate is 13,300/60 or 220 cc/sec. An exposure of 1 C-sec/m^3 thus involves the inhalation of 220 μC since 1 C/m^3 = 1 μC/cc.

Only a fraction of an inhaled aerosol will be retained in the lungs. Gaseous activities and activity associated with very small particles will be exhaled and hence can contribute to the radiation dose only during the cloud passage. Activity associated with the larger particles will be removed in the upper respiratory tract or the bronchial epithelium and will never reach the alveoli. Activity that is thus prevented from contributing to the lung dose is likely, however, to be swallowed and thus to present a possible hazard by ingestion. It is customary to estimate that 20 or 25 percent of the inhaled activity will be retained in the alveoli. If the 25 percent figure is used, then for the fission product release an exposure of 1 C-sec/m^3 would result in retention of 55 μC as measured at 24 hours. For the volatile case, it is assumed that 40 percent of the activity is in the form of noble gases so that only 22 μC would be retained per C-sec/m^3.

Computation of Lung Dose

It is evident that the beta dose to the lungs resulting from material deposited in the alveoli will greatly exceed the exposure due to direct inhalation of the cloud unless cloud passage is assumed to take several hours. This is in marked contrast to the situation after the explosion of a weapon, where the decay is much more rapid. The beta dose rate to the lungs, assuming a standard weight of 1 kg for the lungs and neglecting edge effects, is given by equation 3.

$$d = \frac{1}{100} \frac{q \cdot 3.7 \times 10^4 \cdot E_\beta \cdot 1.6 \times 10^{-6}}{1000 \text{ g (av lung)}}$$

$$= 5.9 \times 10^{-7}\ qE_\beta \text{ rad/sec} \qquad (3)$$

where

q = μC of activity retained in lungs, measured at 24 hr, and

E_β = average energy of beta-particle in Mev.

To compute the dose accumulated in the first day (i.e., from $t = 2$ to $t = 24$ hr) this expression must be integrated by using the appropriate decay law. For the fission product release,

$$D_f = 5.9 \times 10^{-7} E_\beta \int q(t)\,dt$$

where $q(t) = q(t^{-0.2}/24^{-0.2})$. First-day dose is

$$D_f\Big]_2^{24} = 5.9 \times 10^{-7} E_\beta \cdot 3600 \ \frac{q}{24^{-0.2}} \int_2^{24} t^{-0.2}\,dt$$

$$= 2.12 \times 10^{-3} E_\beta\, q \ \frac{24^{-0.2}}{0.8} (24^{0.8} - 2^{0.8})$$

$$= 2.12 \times 10^{-3} E_\beta\, q \cdot 25.9$$

$$= 5.5 \times 10^{-2} E_\beta\, q \text{ rad} \qquad (4a)$$

An average beta-particle energy of 0.4 Mev being assumed, 55 μC in the lungs would give a dose of 1.21 rad. In this case the corrected dose is only about 18 percent larger than that calculated from equation 3, neglecting decay.

For the volatile release, from the $t^{-0.8}$ law, the first-day dose is

$$D_v\Big]_2^{24} = 5.9 \times 10^{-7} E_\beta \cdot 3600 \ \frac{q}{24^{-0.8}} \int_2^{24} t^{-0.8}\,dt$$

$$= 2.12 \times 10^{-3} E_\beta\, q \ \frac{24^{-0.8}}{0.2} (24^{0.2} - 2^{0.2})$$

$$= 2.12 \times 10^{-3} E_\beta\, q \cdot 49 = 0.104 E_\beta\, q \text{ rad.} \qquad (4b)$$

An average particle energy of 0.4 Mev again being assumed, 22 μC in the lungs would give a dose of 0.9 rad. Here the decay correction is a factor of 2.23.

There is no firm basis on which to convert lung dose to equivalent whole-body gamma dose. However, it is noted that the recommendations of *Handbook 59, National Bureau of Standards,* permit 5 times as much beta exposure to the basal layer of the skin (whole-body as gamma and also permit 5 times as much exposure to the extremities as to the whole body. It seems quite conservative to use a factor of 5 in reducing lung exposures to whole-body equivalents. Thus it is estimated that the fission products case would give 0.24 r equivalent or 0.0096 AED per C-sec/m^3, and the volatile case 0.18 r or 0.0072 AED.

Based on the assumptions of *Handbook 52, National Bureau of Standards,* the quantity retained on the second day would be half that on the first. Allowing for some decay, the dose in the rest of the week would be about twice the first-day dose for the fission product case.

Composition of the Cloud

It is estimated that a 500,000-tkw reactor after 180 days of operation and 24 hours of cooling would contain the following activity:

Total fission products	4.1×10^8 curies
Strontium-90	3.8×10^6
Strontium-89	1.7×10^7
Cerium-144	8×10^6
Plutonium-239	3.8×10^3
Iodines	5×10^7
Noble gases	3.4×10^7
Total volatile fission products	8.4×10^7

In the full fission product release, taken to involve half the material in the reactor, 20 percent of the activity measured at 24 hours would be volatile; 12.2 percent would be in the various iodine isotopes; 4.1 percent would be Sr^{89}; and 0.075 percent, Sr^{90}.

For the volatile release the assumption is made that 1 percent of the Sr^{90} would escape, so composition would be 40 percent noble gases, 60 percent iodines, and 0.0035 percent Sr^{90}. Thus in the volatile release the iodines are relatively enriched on a curie/curie basis by a factor of 4.9, while Sr^{90} is depleted by a factor of 20. Plutonium is much less volatile than strontium, hence can be neglected in the volatile case.

It is interesting to note that the amount of Sr^{90} contained in the postulated reactor would be equal to that produced in the explosion of 3.8 megatons of fission weapons. If the fuel cycle were longer then, of course, the amount of Sr^{90} would be proportionately greater.

Deposition of Activity in the Body

It has been calculated above that in the full fission product release 55 μC of activity would be retained in the lungs after 1 C-sec/m^3 of exposure. It is now necessary to consider the subsequent behavior of this material.

The soluble fraction probably remains in the lungs only a few hours before it gets into the blood. Some of the insoluble material will be removed and probably swallowed in the first few days; the rest will remain indefinitely. A convention sometimes used is to assume that half the insoluble material is retained for 24 hours and the balance indefinitely. Material caught in the upper respiratory tract or the bronchi will mostly be swallowed, although some will be removed by blowing the nose and coughing up and expectoration.

Strontium-90. For Sr^{90} the maximum permissible body burden (occupational) is 1μC maintained over a working lifetime, taken to be 40 years. With the biological half-life of Sr^{90} in the bones taken as 2200 days (6 yr) the average amount over 40 years would be

$$\frac{1}{40}\int_0^{40} \exp\left(-\frac{0.693}{6}\,t\right)dt = \frac{1}{40}$$

$$\cdot - \frac{6}{0.693}\exp\left(-\frac{0.693}{6}t\right)\Big]_0^{40}$$

$$= [-6/(0.693 \cdot 40)]\ (e^{-4.6} - 1)$$

$$= (1/4.6)\ (1 - e^{-4.6}) = 0.21 \qquad (5)$$

of that originally present.

It seems reasonable to consider 1 μC in the bones as 1 AED, with the decay factor used in lieu of the customary factor of 10 between occupational and general exposures. According to *Handbook 52,* 22 percent of the inhaled strontium would be deposited in the bones, but it appears that less than half of that remains more than a few months. Hence it seems reasonable to consider inhalation of 10 μC Sr^{90} as an AED.

An exposure of 1 C-sec/m^3, or 220 μC inhaled, would contain 0.16 μC Sr^{90}, and therefore would be considered on the basis of the strontium alone as 0.016 AED for the full fission product release. In the volatile case the strontium is depleted by a factor of 20, thus 1 C-sec/m^3 is 0.001 AED.

Strontium-89. No standards have been set on maximum permissible levels of bone seekers for a single emergency exposure, but a lifetime dose to the bones of 50 rad would seem reasonable. It might further be assumed that the relative hazard from different isotopes which go to the same critical organ would be proportional to the average particle energy multiplied by the effective half-life. On this basis an acceptable single dose of Sr^{89} would be $(2200 \times 1.0)/(52 \times 0.55) = 77$ times as large as that of Sr^{90}.

On the assumption that 770 μC Sr^{89} were inhaled and 22 percent or 170 μC reached the bones (assumed to weigh 7 kg), the dose rate would be

$$\frac{1}{100} \cdot \frac{170 \cdot 3.7 \times 10^4 \cdot 0.55 \cdot 1.6 \times 10^{-6}}{7 \times 10^3}$$

$$\cdot 3600 \cdot 24 = 0.68 \text{ rad/day.} \qquad (6)$$

Integration of this dose using a 52-day effective half-life gives a lifetime dose of

$$0.68\int_1^{\infty} \exp\left(\frac{0.693}{52}\,t\right)dt = 0.68\,\frac{52}{0.693}\,e^{-0.0133}$$

$$= 51 \cdot 0.987 = 50 \text{ rad.} \qquad (7)$$

Actually not all the 22 percent reaching the bones will be fixed, since it is known that it takes several weeks for the excretion rate to settle down to its final value after an inhalation incident, therefore this value seems acceptable.

Hence the Sr^{89} inhaled in an exposure of 1 C-sec/m^3, amounting to 9 μC, would contribute 0.0116 AED in the fission product release. In the volatile release the corresponding figure would be 0.00058 AED.

Cerium-144 plus Praseodymium-144. From calculations on the same basis as that used for Sr^{89}, an acceptable single dose of Ce^{144} appears to be $(52 \times 0.55)/(180 \times 1.29) = 0.12$ times the Sr^{89} dose. In this case, however, absorption from the intestines is very slight, and *Handbook 52* gives 10 percent for the fraction of the inhaled amount that reaches the bones. Therefore inhalation of $(22/10) \times 0.12 \times 770 = 203$ μC Ce^{144} should be acceptable. This gives a dose rate of 0.19 rad/day and an integrated dose of 49.5 rad.

A 1 C-sec/m^3 exposure involves inhalation of $220 \times (8 \times 10^6)/(4.1 \times 10^8) = 4.3$ μC Ce^{144}, which would contribute $4.3/203 = 0.021$ AED in the fission product release. For the volatile case cerium would be negligible.

Plutonium-239. To be conservative, it is assumed that plutonium would be in insoluble form and therefore the lungs would be the critical organ. *Handbook 52* gives an MPL of 0.008 μC in the lungs, with a half-life of 1 year. For a single exposure it seems reasonable to permit 5 times the lifetime occupational level or 0.04 μC. In *Handbook 52* it is stated that 12 percent of the inhaled Pu reaches the lung; this of course implies a particular particle size distribution. Here it seems safer to estimate 25 percent retention. In the fission product release Pu^{239} would comprise 0.00093 percent of the total. A 1 C-sec/m^3 exposure would involve inhalation of $220 \times 9.3 \times 10^{-6} = 2 \times 10^{-4}$ μC Pu. This corresponds to $(2 \times 10^{-4})/(4 \times 0.04) = 0.0012$ AED. Plutonium would be quite negligible in the volatile release.

Iodines. The iodine isotopes present after 24 hours' cooling are chiefly I^{131}, I^{133}, and I^{135}. Their properties are as follows:

Isotope	*Half-life*	*Fission yield, %*	*Average* E_β,*Mev*
I^{131}	8 days	2.9	0.2
I^{133}	20.5 hr	6.5	0.45
I^{135}	6.7 hr	5.9	0.3

The activity of this mixture falls to one-half in 30 hours after the first day, decays to one-fourth in another 56 hours, and thereafter behaves like that of I^{131}. The dose in the first week would be roughly 4 times the daily dose rate as measured at $t = 24$ hr. The critical organ is, of course, the thyroid, which appears to be relatively radioresistant. A dose of 25,000 to 30,000 rad is estimated to result within 6 months in sufficient symptomatology in one-sixth to one-half of the persons so irradiated to cause them to seek medical care for apparent deterioration in their well-being. There are, however, cases of thyroid malignancy in adolescents who are believed to have received doses of the order of 200 r to the thyroid incidental to irradiation of the thymus or adenoids as young children. Such cases are fortunately very rare, although large numbers of children received irradiation in the 1930's and 40's. It seems reasonable to set the AED at one-tenth the lowest figure at which symptoms may be expected, or 2,000 rad to the gland, although the possibility of an occasional tumor must be admitted.

Taking the average beta energy as 0.3 Mev to allow for the I^{133} and I^{135}, 1 μC in the thyroid would give a dose rate of 0.77 rad/day, or about 3 rad in the first week. In this calculation neglect of the shorter-lived isotopes causes the first-day dose to be underestimated, but this is offset by the fact that the inhaled iodine will take appreciable time to reach the gland. Allowing another 2 rad for the dose received after the first week, 400 μC in the thyroid would seem to be acceptable. According to *Handbook 52,* 15 percent of inhaled iodine reaches the gland, hence $400/0.15 = 2660$ μC inhaled corresponds to the AED. Exposure to 1 C-sec/m^3 would involve inhalation of $220 \times (5 \times 10^7)/(4.1 \times 10^8) = 27$ μC or 0.01 AED for the full fission product release. In the volatile case, where the iodines amount to 60 percent of the total, 1 C-sec/m^3 would correspond to 0.049 AED.

Dose to the Gut

It does not appear feasible to estimate the dose to the intestines or other organs in even the crude fashion used above for the lung, bone, and thyroid doses. This is partly because most of the activity would have been swallowed after removal from the bronchi by ciliary action, a process which would continue for days. As a rough guess, perhaps as much material as is estimated to be retained in the lungs would go through the intestinal tract. Assume that passage requires 24 hours and that the tract weighs 2 kg. In the fission product release 1 C-sec/m^3 is considered to leave 55 μC in the lungs. This amount of activity in the intestines would give (by use of equation 3 corrected for the difference in mass of the organ) a dose of 0.56 rad. Although the intestines are, generally speaking, rather radiosensitive, a dose of 50 rad in a day or two would probably be acceptable. Therefore 1 C-sec/m^3 is taken to give $0.56/50 = 0.0112$ AED to the intestinal tract. The volatile release results in practically no activity except from the noble gases and iodines, therefore the dose to the intestines would be negligible.

Total Direct Exposure

At this point it becomes necessary to sum up these various effects. Almost no data exist on the additivity of partial body exposures. In the case of the limit for no injury (category D) it is conservative simply to add up the partial exposures as expressed in AED, but this will not work for the sickness or lethal limits. One cannot half kill a man by hanging and half kill him by shooting and end up with just one dead man.

Table 1 recapitulates the effects (expressed in AED) of 1 C-sec/m³ of exposure for the two types of release considered.

From Table 1, it seems safe to pick an exposure of 10 C-sec/m³ as the limit for category D in the full fission product release. In the volatile case it appears that practically nothing counts except the external gamma dose and the dose to the thyroid. There is no reason to suppose that these effects are synergistic; in fact the thyroid appears to have no particular relation to radiation sickness. It seems conservative to pick the same figure, 10 C-sec/m³, for the category D limit in this case too.

The situation becomes much less clear when an attempt is made to pick the lethal dose (the limit for category A). Probably the bone seekers may be added together, although the long time over which the Sr^{90} delivers its dose makes this somewhat doubtful. Also, the lung beta dose and the Pu dose may possibly be additive; the Pu is almost negligible in comparison with the other in any case. An exposure of 400 C-sec/m³ would then give a dose of 112 r whole-body, 540 rad to the lungs in the first day or 1620 in the first week, 942 rad to the bones over a few years and 224 rad to the intestinal tract. In addition there would be an undetermined amount of radiation to the blood and other organs, and 8000 rad to the thyroid, which would not be considered as contributing to morbidity. Whether this combination of insults would be sufficient to cause death is certainly not known, but it does not seem unlikely. Therefore, a figure of 400 C-sec/m³ will be adopted as the lethal limit for the fission product release.

TABLE 1

EFFECTS OF 1 C-SEC/M³ OF EXPOSURE EXPRESSED IN AED

	Full F.P. Release	*Volatile F.P. Release*
External γ dose	0.0112	0.0505
Lung β dose	.0096	0.072
Bone dose from Sr^{90}	.016	.001
Bone dose from Sr^{89}	.0116	.00058
Bone dose from $Ce^{144} + Pr^{144}$	.021	([1])
Lung dose from Pu	.0012	([1])
Thyroid dose	.01	.049
G.I. tract dose	.0112	([1])
Total	.092	.108

[1] Negligible

In the hypothetical volatile release the situation is much less complicated. The lung beta dose will result principally from iodines on the way to the thyroid, therefore probably only the first day need be considered. The thyroid dose will be neglected since even complete destruction of the gland is not lethal. An exposure to 350 C-sec/m³ would result in 450 r whole-body plus 325 rad to the lungs and 28 rad to the bones. This exposure seems a good choice for the category A limit, since the lung and bone exposures are trivial compared to the whole-body gamma dose.

Selection of a figure for the boundary between categories B and C is fraught with uncertainty because of the varying individual susceptibilities and possible synergic efforts. In principle, of course, a tumor might be induced by a very small dose, but the chances are small. Perhaps the best way to proceed is by simple interpolation. If 450 r whole-body is the mean lethal dose and 100 r may produce illness, it seems reasonable to suppose that $(100/450) \times 350 = 78$ C-sec/m³, rounded off to 80 C-sec/m³, would be the illness limit for the assumed volatile release.

The same procedure gives a figure of about 90 C-sec/m³ for the illness limit in the assumed full fission product release, but this figure is to be regarded as much less reliable than the corresponding one for the volatile release.

Effects of Ground Contamination

Comparatively little is known about the problems involved in living in an environment heavily contaminated by radioactive material. It is obvious that external whole-body gamma irradiation would be significant at sufficiently high contamination levels, and that even at low levels problems would exist in agriculture, particularly dairy farming. Very little can be said, on the other hand, about the intermediate situation. The extent to which dust deposited on the landscape would find its way into food and water supplies is not known. For the purposes of this study, however, it may be sufficient to consider only the relatively straightforward problems.

Whole-Body Gamma Dose from Deposition

From *The Effects of Atomic Weapons* (fig. 8.33), it appears that at 3 feet above a plane surface uniformly contaminated with 1 megacurie/mi² of material emitting 0.7-Mev gamma-rays, the radiation dose rate would be 4.2 r/hr. The conditions assumed in this calculation are not stated explicitly, but a check computation indicates that this figure applies to a perfectly smooth surface and that the build-up factor has been ignored. The roughness of any ordinary ground surface would give some shielding and this might in general more than offset the build-up due to "sky shine." Since 1 mi² = 2.59 km² = 2.59 × 10⁶m², 1 MC/mi² = 0.3861 C/m², thus level ground contaminated with 1 C/m² of 0.7-Mev gamma emitters would give a dose rate of 2.59 × 4.2 = 10.6 r/hr.

With the previously used assumption that the cloud would pass over 2 hours after an accident, the integrated dose for the first day ($t = 2$ to $t = 24$ hr) would be 10.6 × 25.9 = 226 r (using the decay correction factor obtained in equation 4a) for the fission product release. In the volatile case the corresponding dose (see equation 4b) would be 10.6 × 49 = 520 r. The dose rates that would be observed at $t = 2$ hr would be 10.6 × 1.64 = 17.4 r/hr and 10.6 × 7.3 = 77.5 r/hr, respectively (using the factors found in equations 2a and 2b).

A calculation similar to that of equation 4 is needed to get the dose that would be received in 3 months. The dose after the first day to the 90th would be

$$D_{f90} = 10.6 \cdot 24 \int_1^{90} t^{-0.2} dt = 254 \frac{1}{0.8} \times (90^{0.8} - 1^{0.8})$$
$$= 318(36.6 - 1) = 11{,}300 \text{ r} \qquad \text{(8a)}$$

to which must be added the first-day dose of 226 r, the total being 11,500 r for the fission product case. At the 90th day the dose rate would still be $90^{-0.2} = 1/2.46 = 40.6$ percent of what it was on the first day, apart from the decontamination by weathering or other means.

For the volatile release the 90-day dose would be

$$D_{v90} = 10.6 \cdot 24 \int_1^{90} t^{-0.8} dt = 254 \frac{1}{0.2} \times (90^{0.2} - 1^{0.2})$$
$$= 1270(2.46 - 1) = 1850 \text{ r} \qquad \text{(8b)}$$

plus the first-day dose of 520 r, or a total of 2370 r. The dose rate after 90 days would be $90^{-0.8} = 1/36.6 = 2.7$ percent of the rate at $t = 24$ hr. Actually the $t^{-0.8}$ law is not valid for this long a time. The longest-lived iodine, I^{131}, would be down to 1 percent of its initial value in 56 days, thus all that would remain would be the strontium or some long-lived daughters of the noble gases.

It is to be noted that the doses calculated above for 1 C/m^2 apply to an individual who spends all his time outdoors on smooth ground. For most people, except outdoor workers, it would seem reasonable to allow a factor of 5 for ground irregularities and the shielding effect of ordinary buildings.

Whole-Body Beta Dose from Deposition

As noted above, material from the cloud deposited on the body might result in serious beta dosage if allowed to remain. No attempt has been made to evaluate this type of exposure as its magnitude would depend strongly on local circumstances. It is presumed that most individuals involved could wash and change clothes promptly enough to make this component of exposure relatively unimportant. In a few cases in ranges I and II, particularly where coupled with direct exposures in category B, skin burns caused by beta radiation might be a contributing factor to the overall injury.

Evacuation Limits

A dose rate such that 25 r would be received in the first 12 hours would appear to call for urgent evacuation. Such a rate would be given by about 0.178 C/m^2 for the fission product release and 0.075 C/m^2 for the volatile release. The first might be rounded off to 0.2 C/m^2 for the range I limit and the second to 0.1 C/m^2.

It is noted that the first-day dose in the volatile release would be nearly a quarter of the 90-day dose. Therefore, if good shelter is available, such as the cellar of a large building, it would be better to wait a day before evacuating. Of course, if adequate shelter is not available, immediate evacuation would be required.

The limit for range II can be set by stipulating a three-month dose of 50 r as the maximum acceptable. With a factor of 5 allowed for shielding, this means that people spending most of their time indoors would have to be evacuated from regions with $(5 \times 50)/11{,}500 = 2.18 \times 10^{-2}$, say 2×10^{-2} C/m^2, in the fission product case and $(5 \times 50)/2370 = 0.105$ C/m^2 for the volatile release.

A limit of 50 r in three months does not appear at all conservative in the fission product case since the dose in the first year would be 3.1 times the 90-day dose. There should, of course, be considerable weathering of the deposition but it seems best to set the range II limit for this case no higher than 10^{-2} C/m^2, although 10^{-1} C/m^2 may be used for the volatile release.

It is obvious that severe restrictions on living habits, and particularly on outdoor work, would be required at considerably lower contamination levels. A person who spends 10 hr/day outdoors and lives in a small house of light construction or a trailer might easily receive seven-tenths of the 24-hr outdoor dose, instead of one-fifth as assumed above. Such a person would get 50 r in three months from 6×10^{-3} C/m^2 of fission products or from 3×10^{-2} C/m^2 of volatile deposition. Considering that unless there was considerable decontamination by weathering a large dose would be accumulated after the first 90 days, and that a person working outdoors would be likely to pick up additional exposure from inhaled or ingested radioactive material, the lower limit for range III should certainly not be higher than 10^{-3} C/m^2 in the fission product release. As far as the gamma-ray exposure of persons is concerned, for the volatile case a figure of 10^{-2} C/m^2 seems reasonable. In the volatile release the restrictions would probably be temporary for a period not greater than 3 months, but for the full fission product release, some activities such as dairy farming might have to be prohibited indefinitely.

Effects on Agriculture

In the fission product release 4.1 percent of the activity is assumed to be Sr^{89} and 0.075 percent, Sr^{90}. Libby uses 1 μC of Sr^{90} to 1 kg of calcium as the maximum permissible concentration (MPC) in any medium. One MPC in an adult human would be 1 μC since the average skeleton contains 1 kg Ca. This corresponds to the occupational limit. It is customary to allow an additional factor of one-tenth for large populations, although the reasons for doing this may be less cogent in the case of Sr, which has negligible genetic effects. There appears to be considerable discrimination against strontium and in favor of calcium in the pasture-cow-milk transfer. It seems reasonable to assume that this discrimination factor may be used instead of the customary factor for large populations, and to accept 1 MPC in the soil.

Average soil contains 20 g/ft^2 of Ca in the top 2.5 inches, and experiments show that strontium leaches out of the soil very slowly. Unless it is moved by plowing, the deposited Sr^{90} would remain in the top 2.5 inches indefinitely. Since 20 g/ft^2 of Ca $= 20 \times 10.76 = 215$ g/m^2 Ca, 1 MPC $= 215/1000$ μC/m^2 $Sr^{90} = 2.15 \times 10^{-7}$ C/m^2 Sr^{90}.

For the postulated reactor 1 MPC in average soil would correspond to a total activity of $(1/0.00075) \times 2.15 \times 10^{-7} = 2.8 \times 10^{-4}$ C/m^2 as measured 24 hours after release. After the first year, when the Sr^{89} and most of the other activities would have decayed, the Sr^{90} would be the limit on use of land, particularly for dairy farming. If it is assumed that the deposited material could be diluted with calcium by plowing to a depth of about 10 inches, and that substandard soils are brought up to normal by application of lime, it appears that land contaminated to the extent of 10^{-3} C/m^2 of fission products could be returned to production after a year. Land more heavily contaminated than this probably could not be used for dairying for a very long time, but other types of farming might be permitted. This figure of 10^{-3} C/m^2 happens to be the same as that suggested above for the lower limit of range III on the basis of external exposure. The agreement is fortuitous.

It seems reasonable to pick a figure of 10^{-4} C/m^2 for the lower limit on range IV although there is very little if any safety factor here. At this level the Sr^{89} would be about 10 times the long-term MPC calculated on the occupational exposure limit, and many other isotopes would appear in crops. It is probable that anything raised on land contaminated to more than this extent would be barred from distribution for human consumption.

For the volatile release the strontiums would be depleted by a factor of 20. There might, however, be some troublesome daughters from the noble gases. It seems reasonable to allow 10 times as much contamination here as in the fission product case and to set the lower limit for range III at 10^{-2} C/m^2 as suggested above. Correspondingly, the lower limit for range IV would be 10^{-3} C/m^2. Here it might not be necessary to lose a whole year's production as in the fission product release. Only if a crop were well along toward harvesting at the time of an accident would it be necessary to destroy it.

In range V, below 10^{-4} and 10^{-3} C/m^2 respectively, there probably would be no need for restrictions, although anyone with a Geiger counter could demonstrate the presence of radioactivity. Of course, vegetables and other food crops grown on this land should be thoroughly washed before eating. The fact that most people in this country get their vegetables and fruits from widely separated places would be a very helpful factor in reducing the intake of activity. A family in a contaminated area trying to be self-sufficient by growing most of its own food and keeping a cow might ingest somewhat more activity than intended during the first year even at levels of contamination below the range IV limits. This would probably not be serious, as such cases would represent a small fraction of the population, and the exposures would be acceptable when averaged on a long-term basis.

Reoccupation

If the standard 30 mr/week for non-occupational exposure is taken as the criterion for reoccupation it appears that, even at the lower limit for evacuation, it would take more than a year for weathering and decay to effect the necessary reduction in levels in the fission product case. The situation would be considerably brighter in the volatile release case, but in any event the uncertainties about the effectiveness of weathering make prediction of reoccupancy time very risky.

In the case of a city, the higher real estate values would make it worth while to do some decontamination with fire hoses and perhaps detergents.

Summary

The various limits suggested here are summarized for convenience in Table 2.

Remarks

It will be noted that two of the personal exposure category limits agree with those proposed by Marley and Fry. This agreement is fortuitous since their calculations appear to have been made on rather different assumptions from those used here. It would be unfortunate if this agreement tended to make these figures acquire more stature than they deserve.

Appropriate action by local authorities and the people in the area would cut the number of exposures in categories A to C very markedly. This implies the existence of an effective local civil defense organization with special training in these matters. If the affected population could be warned to get into shelter with the windows closed while the cloud passes, there should be negligible inhalation of radioactivity and a great reduction in the gamma dose. Warning would probably not come in time to help those in the immediate vicinity of the reactor, of course, but should be effective at distances greater than a mile or two. It is likely that the fallout would be in a narrow band downwind from the reactor and that evacuation crosswind would be successful.

TABLE 2

SUGGESTED LIMITS

		Full F.P. Release	*Volatile F.P. Release*
Category		*C-sec/m*^{3}	*C-sec/m*^{3}
A	Lethal exposure............	>400	>350
B	Illness likely...............	400 – 90	350 – 80
C	Injury unlikely, but some expense may be incurred.	90 – 10	80 – 10
D	No injury or expense.......	<10	<10
Range		*C/m*^{2}	*C/m*^{2}
I	Urgent evacuation (within 12 hr) necessary.	>0.2	>0.1 *
II	Evacuation necessary.......	$>10^{-2}$	>0.1
III	Severe restrictions on land use, possible temporary evacuation, restrictions on outdoor work.	$10^{-2} - 10^{-3}$	$0.1 - 10^{-2}$
IV	Probable destruction of standing crops, restrictions on agriculture for first year.	$10^{-3} - 10^{-4}$	$10^{-2} - 10^{-3}$
V	No expense likely..........	$<10^{-4}$	$<10^{-3}$

*Unless adequate shelter is available.

In this connection it should be pointed out that if the local defense organization is to be prepared to organize and direct emergency procedures following a reactor accident, the fallout of material released from such an accident would differ in several important respects from fallout from a weapon, and therefore some regular civil defense practices would have to be modified.

The regular tables for decay and reducing meter readings to a standard time would be useless. Also, normal civil defense practice for weapons fallout would be to keep people in shelters as long as possible to take advantage of decay. However, except for an initial period of 1 day in the volatile case, the best thing to do in the event of a reactor accident would be to evacuate promptly, if at all.

The possibility of effective decontamination, at least in built-up areas, should be mentioned. Fire hoses, with or without detergent, could accomplish a great deal in reducing contamination levels. In lawns or open country, rain would gradually wash activity down into the soil so that the external exposures would be gradually decreased. This process could be speeded, of course, by plowing, but it should be mentioned that the effect would only be to lower gamma exposures. The activity would remain in the soil and be available for plant uptake until it finally decayed.

In a study of this sort it is obviously necessary to make many arbitrary assumptions and to set up definite levels for evacuation, etc. It is clear that this results in some rather embarrassing inconsistencies. For example, a person in a region contaminated to range II would be evacuated and not permitted to return for over a year at least. A neighbor a few hundred yards away falling in range III might not be evacuated but would receive a very sizeable radiation dose, particularly if his house were of light construction. The person who was evacuated might happen to live in a substantial house and spend most of his time indoors so that he would have received a smaller dose than his neighbor if he had remained.

In estimating the dollar costs of a postulated reactor accident it must be borne in mind that the contamination levels proposed in this section are not "standards" to be rigidly adhered to. Rather they are guesses as to what action might be taken by public health authorities in the circumstances. This is particularly true of the limits for ranges III and IV. If only a small area were affected, it is likely that the land would be taken out of production rather than try to set limits for acceptance of slightly contaminated crops. On the other hand, if hundreds of square miles were in question, it would become worth while to try to find out just what crops might safely be grown. Obviously assignment of fixed dollar costs on a per person or per acre basis to the various contamination ranges can only be approximate.

It must be pointed out that several of the limits suggested, particularly those for ranges III, IV, and V, are quite sensitive to the strontium-90 levels, and therefore the situation would be much worse for a reactor incident involving fuel that had been irradiated longer than 180 days as postulated here.

Finally, it should be pointed out again that the attempted estimation of the effects on people and land use of so many different isotopes is only a rough guess. Even with a great deal more data than is now available it would still be very hard to find out how the effects add up.

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Appendix E

Diffusion, Deposition, and Rainout of the Radioactive Cloud

A reactor safety analysis has essentially three natural subdivisions, dealing respectively with release, distribution, and consequences of the radioactive discharge. Meteorology dominates the second category, because variations in weather factors will alter the extent and location of damage to a very important degree.

The treatment of the problem in this study is similar to that in others which have been completed as independent efforts or as portions of hazard reports, and in most respects the material is based on earlier work. However, there are several important differences which deserve specific attention. The first reflects the general philosophy of this study, in that there has been no deliberate attempt to maximize the hazard. Despite limitations in knowledge, analytical techniques and numerical values have invariably been selected without regard to injury or damage. Second, there is no duplication of effects implicit in the work. It is not considered realistic, for example, to postulate the removal of radioactive particles from the cloud by one process, and yet retain them for purposes of another computation. Finally, meteorological occurrences of extremely low probability are not explored in this study. Because of the limitations in time and staff, only those cases constituting a significant portion of the meteorological record have been fully investigated. This study includes a set of calculations for the nocturnal temperature inversion, as well as for daytime conditions, and is believed to give a representative picture of the probable behavior of a radioactive cloud. It is considered neither unduly pessimistic nor optimistic. A more complete study including a much wider range of conditions would obviously be a computer project of considerable size, and also would require a major research effort in many fields to provide a firmer base for the analysis.

The order of presentation of the work is unusual and should be explained. It is customary in meteorological studies to begin with a detailed description of the site and its climatology, and then to show the significance of these features in terms of the problem. This presupposes considerable familiarity with the subject, and is the actual order of the original development of the work. However, the processes described are not especially familiar, and the significance of the climatological variations is much clearer, if reviewed after an understanding of the problem is assured.

Initial Cloud Behavior

As will become strikingly apparent, the initial conditions of release would have an important bearing on the fate of the cloud. In addition to the amount of radioactivity, the cloud temperature and the time period over which the release occurs would both be significant. A rapid release of warm effluent, for example, will form a rough sphere that will tend to rise until it reaches the density of the surrounding air. A slower release of the same amount of warm effluent will give a much less impressive result in terms of height. Variations in the existing atmospheric temperature, lapse rate, and turbulence will also influence this process to an important degree.

Since it is almost impossible to specify the precise nature of such an improbable event as a major reactor failure, both the rapid and the slow releases are considered. The upward motion of the warm cloud must be taken into account, and the cloud is represented initially as a sphere having a uniform temperature. This "bubble," of lower density than its surroundings, will rise and move downwind simultaneously. The temperature differential is continuously reduced by entrainment, by adiabatic expansion as it rises to regions of lower pressure, and by thermal radiation until it attains the density of the surrounding air.

Both the selection of a mathematical model for this process and the choice of appropriate values for the parameters present difficult problems. Previous attention has been devoted largely to clouds resulting from nuclear explosions, which are much hotter and of greater size than any assumed in the present study. Furthermore, even these have shown no consistent relation with meteorological conditions [1]. Some data derived from the burning of fuel oil [2] are available, but these really pertain to continuous point sources having rates of emission decreasing with time rather than instantaneous sources. Also, these data do not include all pertinent parameters with the required accuracy. Many of the same comments apply to tests involving the detonation of explosives. The problem is discussed in *Meteorology and Atomic Energy* [3], in which the merits of several treatments are explored.

The Sutton formula [4] has been chosen to represent daytime (lapse) conditions in this study. It is relatively conservative in terms of low-level behavior, in the sense that it predicts a modest rise. For a release sufficient to rupture the container, the equation predicts a cloud height of 860 meters (equation 1).

$$h = \left[\frac{2(3m + 2p)Q_1}{9C_p\, \rho\, \pi^{3/2} C^3 a} \right]^{1/[p+(3m/2)]} \quad (1)^*$$

*See list of symbols at the end of the section.

A similar treatment is used to estimate the height to which the cloud representing a 50 percent release would rise at night. The Sutton formula gives a negative result with a temperature inversion, and the Holland [3] modification is substituted as shown in equation 2.

$$h = \left(\frac{Q_1}{2C_p\, \rho\, \pi^{3/2} C^3 \theta_a'} \right)^{0.276} \quad (2)$$

As would be anticipated in stable air, this equation gives a smaller rise (400 m). Both calculations apply only to clouds consisting essentially of dry air at 3000° F. The results applicable to a release consisting of air and steam at 300° F. were also derived, but these more optimistic estimates were discarded since the condensation and subsequent reevaporation of the water vapor is very complex and difficult to approximate. It seems likely that the net upward motion of the two clouds is similar.

It is proper to question the error in these estimates, since the ground level concentrations calculated in later work are strongly dependent upon them. This is difficult with the available data, but it seems doubtful that a cloud would reach a height more than twice that calculated. It is easier to define the other limit since the release of the fission products might occur slowly at essentially the temperature of the surrounding atmosphere. This implies no ascent of the cloud, and is treated as such. In the accident postulating a 15 percent release, consisting largely of the noble gases and halogens, no large source of heat seems likely, so that this case also may be approximated as a cloud at ground level.

Diffusion

Many attempts have been made to derive expressions for the diffusion of gases or small particulates in the atmosphere. None of these can be defended rigorously on theoretical grounds, but most could be used with acceptable accuracy, if appropriate values of the diffusion parameters were introduced. The treatment of Sutton [5] seems especially appropriate, since it possesses the flexibility necessary for the study, and is familiar to all engaged in micrometeorology. In particular, the basic equation for a continuous point source serves as the diffusion model:

$$\bar{\chi}(x,y,0) = \frac{2Q}{\bar{u}\,\pi\, C_y C_z x^{2-n}} \exp\left[-\frac{1}{x^{2-n}}\left(\frac{y^2}{C_y^2}+\frac{h^2}{C_z^2}\right)\right] \quad (3)$$

As previously stated, it is difficult to specify both the rate and the time interval over which the release would occur, but if the total release in curies is substituted for the rate of release (Q), the result is given in the convenient dosage unit of curie-seconds per cubic meter (C-sec/m^3), which is of direct use in evaluating the consequences of the accident.

Considerable field work has been undertaken to determine appropriate numerical values of n, C_y, and C_z. The results are adequately summarized elsewhere [3, 6–8] and there is little need for review here. Very few of the data apply to nocturnal temperature inversions, nor do they pertain to distances many miles from the source. Both points are extremely important to this study, and fortunately it has been possible to obtain some data concerning dispersion over very long distances from Thomas [9] of the Tennessee Valley Authority. These supplement short-distance inversion studies made at Brookhaven, and have helped greatly in the final selection of parameters given in table 1. Data from nuclear bomb tests are not pertinent because of the great difference in cloud heights involved. Conditions in the stratosphere are quite unlike those near ground level.

TABLE 1

DIFFUSION PARAMETERS USED IN THE STUDY[1]

Meterological conditions	*Height* (m)	*n* (*dimensionless*)	*Cy* (m$^{n/2}$)	*Cz* (m$^{n/2}$)	$\bar{u}$ (*m/sec*)
Typical lapse . . .	0	0.25	0.40	0.40	5.0
	860	0.25	0.40	0.40	15.0
Typical inversion	0	0.55	0.40	0.05	3.0
	400	0.55	0.40	0.05	15.0

[1] Numerical values of the Sutton diffusion parameters selected for the analysis.

Since the diffusion parameters are critical to all other aspects of the study, it is important to examine table 1 carefully. The most noticeable feature is that no allowance has been made for variation of the parameters with height, except in the case of the mean wind speed ($\bar{u}$). This stems from the fact that the diffusion occurs over greater distances than any previously studied, and it is doubtful that the variations with height shown in short-distance tests are pertinent. To include such variation would be more sophisticated, but not necessarily more accurate. In terms of wind speed, it is well known that an important increase usually exists in approximately the first 2000 feet above ground, and this is reflected in the wind speed values shown. In view of the selection of a shallow valley as a typical site location, it may well be argued that the ground-level inversion wind speed should be reduced to 1 or 2 m/sec. This might be true if it could be specified that the release actually occurred at ground level and that only short distances were involved. Inasmuch as neither is necessarily correct, it is felt that wind speeds up to a 50-m height are as probable as those at ground level. Therefore, a 3 m/sec wind speed seems a good mean value. The winds at higher levels normally range from 0 to 30 m/sec, and the selection of 15 is a reasonable figure.

No serious quarrel is anticipated with the use of 0.25 for n in the daytime conditions, since most investigations have shown values close to this. The use of 0.55 during the inversion case is considerably less firm. Sutton originally suggested 0.50, but based this on data that are hardly applicable to this study. Brookhaven tests at 100 m above ground give n values up to 1.00 but these apply to a small oil-fog source and distances of less than 2 km. The selected value fits the TVA data extending to 50 miles very well indeed. The C_z and C_y values of 0.40 for daytime conditions are perhaps larger than might be anticipated, primarily because many tests have suggested a tendency for an increase in both parameters with time, as well as an additional increase in C_y with distance. The choice of 0.05 for the nocturnal C_z is in rough accordance with the meager information available. It is almost certainly no larger, and it may be as small as 0.02. The use of 0.40 for C_y during the inversion largely reflects the belief that strong horizontal wind shear is maintained even during very stable conditions. The very recent unpublished data from TVA and Brookhaven support this view.

The foregoing should make it quite clear that it is impossible to select precisely the correct values for the problem under consideration. However, since the range of variation is unlikely to exceed that shown in table 2, reasonable limits can be defined.

The results of the diffusion calculations are summarized in figures 1 to 4 in which the solid lines represent the dosage in C-sec/m³ directly downwind of the reactor for a release of 2×10^8 curies, or 50 percent of the total fission products. Figures 1 and 2 refer to the cold release in which the cloud centerline begins and remains at ground level. This approximation is obtained by setting $y = h = 0$ in equation 3. The very great difference between night and day is immediately evident, for important dosages extend to hundreds of kilometers at night as compared to approximately ten during the daytime. This is primarily associated with the very small vertical diffusion ($C_z = 0.05$) and the very large stability parameter ($n = 0.55$) applied to the inversion condition. It is important to note that inversion and lapse conditions usually alternate on a diurnal basis so that the computed values at great distances are not completely realistic.

TABLE 2

PROBABLE LIMITS OF DIFFUSION PARAMETERS[1]

Meteorological conditions	*Height* (m)	n (*dimensionless*)	C_y ($m^{n/2}$)	C_z ($m^{n/2}$)	$\bar{u}$ (*m/sec*)
Typical lapse	0	0.20 to 0.30	0.30 to 0.50	0.30 to 0.45	3.0 to 8.0
	860	0.20 to 0.35	0.25 to 0.45	0.30 to 0.45	5.0 to 25.0
Typical inversion	0	0.40 to 0.75	0.08 to 0.50	0.02 to 0.07	1.0 to 6.0
	400	0.40 to 1.00	0.08 to 0.50	0.02 to 0.06	5.0 to 25.0

[1] Limiting values have been chosen from values defined by various experiments.

Figures 3 and 4 represent the same dosage information derived from the assumption of a rapid, hot release sufficient to rupture the container, but including the same amount of fission products. In these cases, the dosage is not continuously present at the ground because of the fact that the cloud first rises and then diffuses back toward the surface. This results in what might be described as a skip-distance between the source and the bulk of the ground contamination. Obviously, in practice there would be some radioactivity present in this region between the source and the area predicted by the equation, since some portion of the cloud would initially remain close to the ground, but the general pattern of a maximum at a distance from the source is valid, provided the particles are small. In both lapse and inversion the highest dosage fails to reach 10 C-sec/m³, but the distances of the maxima are very different (10 and 250 km, respectively).

Figures 1 to 4 are indicative only of conditions at the ground along the cloud centerline. Obviously, the width of the cloud must be defined, if its true relation to injury and damage is to be evaluated. This has been accomplished for the cold releases by computing dosage isolines. These horizontal plots (figs. 5 and 6) emphasize the differences in area represented by night and day cases. No similar calculation has been made for the corresponding hot clouds for the obvious reason that none of the dosages are significant in terms of this study.

The mathematical model chosen assumes that the terrain downwind is at the same elevation as the reactor. Certainly this is not a reliable assumption in many areas. Although few field tests have shed much light upon the problem, it seems safe to treat higher land as though the cloud height increment (h) were reduced. It is particularly important during the inversion case, and it is fortunate that very recent tests conducted in Tennessee can be utilized in the study. They support the contention that an effluent flows around and envelopes small terrain features extending up to the level of the plume, and does not rise over them as many wind tunnel tests suggest. Thus, it must be remembered that isolated elevations or land sloping upward may effectively eliminate the initial rise of a hot cloud.

The analysis has included estimates of the dosage in units of C-sec/m^3 from which beta dosage and particulate ingestion in the lungs can be derived directly, but no mention has been made of the gamma dose during the cloud passage. The latter is proportional to the C-sec/m^3 values only at large distances where the spatial variation of the concentration is small. However, this approximation makes little difference in the final injury and damage figures, so that simple proportionality is used, and the direct gamma dose is included in the limiting radiation values for the appropriate cases, described in appendix D.

The postulated accidents considered in this study include a 15 percent release of noble gases and halogens as well as the 50 percent fission product release already described. Dosages for the smaller release may be derived as a direct percentage (42 percent) of those given in figures 1 and 2, since only the release (Q) differs. In all respects, the characteristics are identical with those of the cold, ground-level clouds of greater radioactive content.

Deposition and Rainout

The diffusion studies have provided a basis for evaluating the direct effects of the cloud as it passes over the countryside, but they give no indication of the particulate residue that may be transferred to ground surfaces, vegetation, and buildings. The term "transferred" is used initially instead of "fallout" or "washout" to suggest the lack of knowledge concerning the physical processes actually involved. It is known, for example, that small particles may be influenced by many forces other than simple gravitational settling in dry weather. Ranz and Johnstone [10] have shown that impaction, electrostatic, and thermal forces may be equally important for 1-μ particles. Similarly, a simple treatment probably does not describe scavenging by rain, in which the hygroscopic nature of the particles may be as important as the size and shape. Forms of precipitation other than rain present even more complicated problems.

Unfortunately, scientific knowledge of the right type for this study is even more inadequate than that applying to diffusion. The main reason is that complete field experiments in deposition and rainout are extremely difficult to conduct, and there has been little need for them until the present. Theoretical work and most laboratory studies have dealt with idealized spherical particles under conditions grossly unlike those in the atmosphere. Field experience, such as that described by Chamberlain [11], Gregory [12], and McCully [13], is not sufficiently complete to have an important influence on this analysis. For these reasons, it seems best to utilize simple approximations for such effects rather than to become involved in complex treatments which may not fit the facts any better.

The first problem is to establish a physical description of the particles themselves. It seems most probable that the release would occur as a result of or in combination with combustion, with the particles having the general characteristics of a fume. The size distribution fitting this description would certainly be very small. However, the possibility cannot be ruled out that a much larger particle size distribution would be caused by an accident of a different nature or by unknown processes. Table 3 shows the two distributions selected for consideration in this study. That size is an important consideration is probably already evident from the data given in figures 1 and 2, where the dashed curves represent dosages corrected for removal of the two size ranges in dry weather and rain.

TABLE 3

PARTICLE SIZE DISTRIBUTIONS*

	Size (μ)	Percent by number	Percent by weight
Group having 1.0 μ .... mass median diameter	0.5	95	40
	1.5	5	60
Group having 7.0 μ .... mass median diameter	1.5	15	1
	3.5	60	16
	7.0	23	45
	15.0	2	38

*Typical fume and dust distributions are shown.

A straightforward approach to both dry deposition and rainout has already been presented by Chamberlain [11]. Since it is well suited to this study, it is used without alteration. In dry weather it is assumed that the small particles (even 15.0-μ particles are small from this viewpoint) are brought close to the ground by turbulent diffusion, and that deposition occurs from this lower portion only. This is stated in equation 4,

$$\Delta = \frac{2Q_oV_g}{\bar{u}\,\pi\,C_yC_zx^{2-n}}\exp\left(-\frac{4V_gx^{n/2}}{n\bar{u}\,\pi^{1/2}C_z}\right)\exp\left[-\frac{1}{x^{2-n}}\left(\frac{y^2}{C_y^2}+\frac{h^2}{C_z^2}\right)\right] \quad (4)$$

which is simply the basic diffusion equation multiplied by a settling velocity (V_g) and corrected for removal of particles by the first exponential term. The settling velocity is presumed to follow Stokes' Law for spherical particles of density 2.5 as shown in table 4.

TABLE 4

GRAVITATIONAL SETTLING OF SMALL PARTICLES

Particle diameter (μ)	Settling velocity [1] (m/sec)
0.5	2.5×10^{-5}
1.5	2.0×10^{-4}
3.5	1.0×10^{-3}
7.0	4.0×10^{-3}
15.0	2.0×10^{-2}

[1] Computed from Stokes' Law, a particle density of 2.5 assumed.

This equation applies rigorously to ground-level sources and a different depletion term should be used for elevated clouds. This can lead to underestimation of the affected area amounting to 30 or 40 percent for large particles under nocturnal conditions, and, of course, should be evaluated properly in individual site studies. However, the practical implications are small in terms of a generalized study and equation 4 has been used for both cold and hot releases.

From equation 4 and these settling velocities, deposition curves for each of five particle sizes are established, and then combined in accordance with the mass percentages of table 3 to arrive at the centerline deposition curves shown in figures 7 to 10. These are counterparts of figures 1 to 4, showing deposition instead of dosage along the cloud centerline in curies/m². In both lapse and inversion cases with a hot cloud (figs. 9 and 10) the larger particulate distribution would produce much greater deposition, by approximate factors of 70 and 12 at the respective positions of the maxima. Figure 7 shows that the same would be true for the cold cloud during the lapse conditions, but the two size distributions would give nearly equal deposition at 300 km, if a cold cloud should disperse during an inversion (fig. 8). This reflects the rapid depletion of larger particles from a radioactive cloud during its slow travel downwind.

Rainout[1] has been treated in a similar manner by use of the same two particle distributions and settling rates, and with all precipitation considered as rain. It would not be proper, however, to assume that rain affects only those portions of the cloud very close to the ground, since a given droplet quickly traverses an entire vertical section. Therefore, integration with respect to height gives equation 5, expressing rainout:

$$P=\frac{\Lambda Q_o \exp(-\Lambda_{x/\bar{u}}}{\bar{u}\,\pi^{1/2}C_y x^{(2-n)/2}}\exp\left(-\frac{y^2}{C_y{}^2x^{2-n}}\right) \quad (5)$$

Certain implications of this analysis are very important. No advantage is gained from the rise of a hot cloud; therefore, all releases are effectively treated as cold, except for the important variation of wind speed with height. The vertical diffusion parameter (C_z) disappears from the equation in the same way that the height (h) does.

The depletion factor (Λ) is related to many factors other than rainfall characteristics and particle size, but research to define these is far beyond the scope of this study. The values given in table 5 are taken from the excellent summary prepared by Chamberlain [11]. The two rates of rainfall shown in this table are a probable figure (0.02 in./hr), and a higher rate (0.15 in./hr) representing the value exceeded by only 10 percent of the hourly rates in Brookhaven studies. A proper description of natural rainfall would reflect its inconstant nature, for it is almost certain that in any given period a rapidly varying rate would be found. This merely states that sharp departures above and below the rainout curves shown in figures 11 to 14 would be anticipated in an actual case. In the last two figures, it is easily seen that the rise of the hot cloud is no longer helpful. In fact, the highest deposition rates at great distances are now found with the fast-moving clouds aloft. Noteworthy too is the reversal of the importance of particle size, for in rainout it is the smaller particles that contribute to substantial deposition at distances greater than 500 km. The heavier rainfall rate (0.15 in./hr) has the effect of increasing deposition close to the source, but decreasing it further away because of more rapid depletion of the total available radioactivity.

[1] Strictly speaking, some dry deposition accompanies rainout and should be included in the analysis. However, in all cases except the groundlevel cloud at night, the rainout process gives values about an order of magnitude greater than deposition, and the latter is ignored.

TABLE 5

RAINOUT OF SMALL PARTICLES[1]

Particle diameter (μ)	Proportion of cloud removed per second	
	Rainfall (0.02 in./hr)	Rainfall (0.15 in./hr)
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}

[1] Values derived from Chamberlain [1].

Site and Climatology

In keeping with the concept of a typical example, no attempt has been made to review and compare a number of possible sites. A single, highly idealized model illustrating the major problems in realistic fashion will serve the purpose effectively. Accordingly, such a site is outlined in the succeeding paragraphs.

The first premise is that a power reactor is likely to be designed to serve a municipal area, and would normally be placed fairly near the population centers, i.e., 30 to 35 miles. Since a substantial source of fresh water is a necessity, it is also possible to specify location near a lake or river; of the two, the river is more probable. These assumptions permit construction of a rough map of the idealized site, shown in figure 15. The 2-mile valley width with 200-foot ridges parallel to the river and north-south orientation is purely imaginative, but in no way unrealistic.

From a survey of United States climatological records and available micrometeorological studies, a synthetic microclimatology has been developed and is presented in tables 6 and 7. The first entry in table 6 may be surprising to persons unfamiliar with microclimatology, for the temperature inversion is still generally thought of as an uncommon phenomenon. Actually, the assignment of 50 percent of all hours to the inversion category is quite in keeping with microclimatological studies such as those at Savannah River [14] and Brookhaven [15]. Oak Ridge data [16] would even suggest the possibility of a value greater than 50 percent for a valley location.

TABLE 6

METEOROLOGICAL PARAMETERS FOR AN IDEALIZED SITE[1]

Frequency of occurrence	Thermal stability	
	Lapse	Inversion
	50 percent (normally day, but many nights also)	50 percent (generally night and early morning)
Lapse rate (°C/100m)	—1.0	+1.0
Mean air temperature (°F).	60	40
Hours with precipitation (percent).	13	2
Mean wind speed at ground level (m/sec).	5.0	3.0
Mean wind speed at 400 to 800 meters (m/sec).	15.0	15.0

Total annual precipitation = 40 in./yr; most probable rainfall rate = 0.02 in./hr; rainfall rate exceeded by 10 percent of hours = 0.15 in./hr.

[1] Typical values chosen from nationwide climatological studies and limited micrometeorological investigations.

TABLE 7

WIND DIRECTION FREQUENCIES FOR AN IDEALIZED SITE[1]

(Percent)

Direction	Ground level		Aloft (400 to 800 m)
	Lapse	Inversion	Lapse and inversion
North	7.5	22.5	10
Northwest	10.0	5.0	20
West	5.0	5.0	20
Southwest	7.5	5.0	20
South	10.0	2.5	10
Southeast	2.5	2.5	5
East	2.5	2.5	5
Northeast	5.0	5.0	10
Total	50.0	50.0	100

[1] An extension of the data in table 6.

With reference to the alternation of inversion and lapse conditions between night and day, an important limitation of the mathematical models becomes apparent. Neither condition can normally be expected to last more than a total of 12 to 14 hours, and the curves extending to hundreds of kilometers are therefore somewhat inconsistent. Actually, any diffusion pattern would change after a period of time, but this is not simple to represent mathematically. It is also doubtful that such refinements would have an important bearing on a general study of this type.

The selection of typical lapse rates and mean air temperatures needs little explanation or justification. There are wide variations in both over the United States, but the numbers used are realistic. The same may be said of the percentage of hours of rainfall and the association with lapse and inversion cases. The normal and moderate rainfall rates were selected from unpublished studies at Brookhaven.

The choice of wind speeds has been discussed under the topic of diffusion parameters, but wind direction variations have not. The upper level distribution in the final column of table 7 reflects a predominant westerly flow very common in middle latitudes. The division of the ground-level winds into lapse and inversion hours is in accordance with the well-known "channeling" effects of valleys, and is especially noticeable in relation to the 22.5 percent frequency assigned to northerly (down-valley) inversion winds. It is also common knowledge that a relation usually exists between wind direction and rainfall, but this is such a widely varying feature of climatology that it has been decided to consider rainfall hours independent of wind direction.

This completes the representation of the hypothetical site, providing all the parameters necessary for the computation of the probability of various cases existing at the time of an accident. The analysis begins with the assumption that a release may occur at any time of the day or night, and for this portion of the work, no probability distinction need be made among types of releases. Table 8 is the result of these computations, showing the percentage chance of each condition for the two proposed reactor locations.

For the conditions postulated, regardless of the location or the nature of the accident, it is always probable that there will be no rain and that the cloud will not move toward the city, with a slight preference for an inversion condition over a lapse. Only in the case of the northern location is there a relatively large chance of movement of the cold, ground-level cloud toward the city during an inversion, and this reflects the channeling of the wind flow at night. Rain occurring at the time of an accident would usually be associated with lapse conditions and the movement would tend to be away from the city. The combination of rain and inversion conditions is relatively uncommon.

TABLE 8

FREQUENCY OF OCCURRENCE OF VARIOUS METEOROLOGICAL CONDITIONS [1]
(*Percent*)

Reactor North of City

Cold, Ground-Level Cloud	*Lapse conditions*	*Inversion conditions*
No rain — Wind toward city [2]	3	11
No rain — Wind away from city	34	37
Rain — Wind toward city	1	<1
Rain — Wind away from city	12	<1
Hot Cloud Aloft		
No rain — Wind toward city	2	3
No rain — Wind away from city	35	45
Rain — Wind toward city	<1	<1
Rain — Wind away from city	12	2

Reactor South of City

Cold, Ground-Level Cloud	*Lapse conditions*	*Inversion conditions*
No rain — Wind toward city	4	1
No rain — Wind away from city	33	47
Rain — Wind toward city	2	<1
Rain — Wind away from city	11	2
Hot Cloud Aloft		
No rain — Wind toward city	2	3
No rain — Wind away from city	35	45
Rain — Wind toward city	<1	<1
Rain — Wind away from city	12	2

[1] The percentages shown may be combined directly with accident probabilities to obtain an estimate of the percentage chance of specific injuries or damage.

[2] Toward city is defined as one-half the north or south wind direction probability because of the narrow path necessary to include the city full within the plume.

Special Conditions

It has been assumed in the calculations that at night most people will be indoors. This was included in the calculations by the assumption that cloud concentrations would be down by a factor of 2 for the inversion conditions. This factor was chosen from Federal Civil Defense Administration data.

Another assumption used in this study was that during rainout, 90 percent of the fission products landing on the city can be made to go immediately down the sewer system if the streets and buildings are being copiously hosed down before and during rainout. This could be done since a large city will have equipment and men available from the fire department, and there should be sufficient warning time to get them into operation. If no hosing is done, only 25 percent of the fission products can be assumed to be washed down the sewer by the rain itself.

Effect of Release on Meteorology

Completeness requires some mention of the possibility of a nuclear release affecting meteorological conditions. On the local scale, a release described as cold in this study would have no measurable effect. A hot cloud would disturb the lapse rate and wind flow in the immediate vicinity of the reactor, but only over very short distances and time periods.

Only two mechanisms can be visualized by which an accident could conceivably influence the general weather over a larger area. The first assumes that radioactive particles would be unusually effective in promoting condensation, as is true of dry ice and silver iodide. There is no evidence that this assumption is valid. The other process postulates that radioactivity disturbs the ionization of the atmosphere, and thereby affects the frequency of thunderstorm activity. Regardless of the merit of this hypothesis, the effect of a reactor accident would be infinitesimal from any viewpoint. The conclusion, therefore, is that a reactor accident would have no effect on the general meteorological conditions.

Summary and Conclusions

The foregoing analysis demonstrates the wide variation in radiation dosages and deposition that can be produced by meteorological factors alone. It is not represented as an exhaustive study of the possible results, but rather as a model illustrating typical conditions. In a specific study of an actual site, a complete set of computations would require a machine program. However, even the rough approach used here suggests the degree to which hazard probabilities can be reduced by careful site selection.

In the development of the work, glaring deficiencies in scientific knowledge have become apparent. The most acute is concerned with the removal of small particles from the atmosphere by deposition and rainout processes. Knowledge of pure diffusion in the atmosphere is also inadequate, especially in terms of the stable, inversion condition. It is interesting that previous diffusion experiments have been both too small and too large for the reactor hazard scale. Micrometeorological work has been in the appropriate layers of the atmosphere, but has seldom extended to great distances. Nuclear bomb tests, on the other hand, have been confined largerly to higher layers of the atmosphere. Despite these and other deficiencies, the studies are believed to be of acceptable accuracy for a first approximation of the problem. It is almost certain that all the important meteorological factors are included, and none of the results should be in error by more than a factor of ten. Many portions are assuredly much more precise. A significant improvement in the analysis can rest only on painstaking research.

LIST OF SYMBOLS[1]

Symbol	*Descriptions*	*Units*
h	height of cloud	m
m	$2-n$	dimensionless
n	stability parameter	dimensionless
a	a and p are derived from the relation $\Theta = \Theta_0 - azp$, which defines change of potential temperature with height	10^{-8} °C/m
p	(see above)	dimensionless
Θ	potential temperature	°A
Θ_s'	gradient of potential temperature	0.02°C/m
ρ	density of air	g/m^3
C_p	specific heat	cal/g-deg
C	generalized diffusion coefficient	m^n/s
Q_1	heat liberated in release	28.6 x 10^8 cal
$\bar{\chi}$	mean concentration	C-sec/m^3
Q, Q_0	pollutant emission	curies
C_y	horizontal diffusion parameter	m$^{n/2}$
C_z	vertical diffusion parameter	m$^{n/2}$
$\bar{u}$	mean wind speed	m/sec
x	distance downwind	m
y	distance crosswind	m
z	vertical distance	m
Δ	deposition	curies/m^2
P	rainout	curies/m^2
V_g	velocity of deposition	m/sec
Λ	proportion of cloud removed per sec by rain	1/sec

[1] Those not specified are defined in the text or tables.

FIGURES

FIGURE 1. Diffusion of Fission Products, Ground-Level Cloud, Typical Daytime Conditions. (Note: The dosages directly downwind of the reactor are shown. Since deposition and rainout actually remove a portion of the particles, the corrected curves are included.)

FIGURE 2. Diffusion of Fission Products, Ground-Level Cloud, Typical Nocturnal Conditions. (See note to Figure 1.)

FIGURE 3. Diffusion of Fission Products, Hot Cloud Aloft, Typical Daytime Conditions. (This is similar to Figure 1, except that dosage does not occur continuously at the ground. Curves adjusted for rainout and deposition have not been included since the maximum dosages are so low.)

FIGURE 4. Diffusion of Fission Products, Hot Cloud Aloft, Typical Nocturnal Conditions. (Identical to Figure 3, except for meteorological conditions.)

FIGURE 5. Isopleths of Fission Product Dosage, Ground-Level Cloud, Typical Daytime Conditions. (Isolines of constant dosage (C–sec/m^3) are shown in a horizontal plot. No correction for deposition or rainout is included.

FIGURE 6. Isopleths of Fission Product Dosage, Ground-Level Cloud, Typical Nocturnal Conditions. (Similar to Figure 5, except for different distance scale.)

FIGURE 7. Deposition of Fission Products, Ground-Level Cloud, Typical Daytime Conditions. (Dry weather deposition is shown for the two particle size distributions shown in Table 3.)

FIGURE 8. Deposition of Fission Products, Ground-Level Cloud, Typical Nocturnal Conditions. (Counterpart of Figure 7. Note that 1.0–μ particles become most important beyond 300 km.)

FIGURE 9. Deposition of Fission Products, Hot Cloud Aloft, Typical Daytime Conditions.

FIGURE 10. Deposition of Fission Products, Hot Cloud Aloft, Typical Nocturnal conditions.

FIGURE 11. Rainout of Fission Products, Ground-Level Cloud, Typical Daytime Conditions. (Curves for the two particle size distributions and two rainfall rates are shown.)

FIGURE 12. Rainout of Fission Products, Ground-Level Cloud, Typical Nocturnal Conditions. (Similar to Figure 11, but much more rapid depletion removes much of the material close to the source.)

FIGURE 13. Rainout of Fission Products, Hot Cloud Aloft, Typical Daytime Conditions. (Note that in rainout, the rise of the cloud does not prevent important deposition on the ground.)

FIGURE 14. Rainout of Fission Products, Hot Cloud Aloft, Typical Nocturnal Conditions.

FIGURE 15. Map of Hypothetical Reactor Site. (The sketch represents an imaginary reactor location in the United States.)

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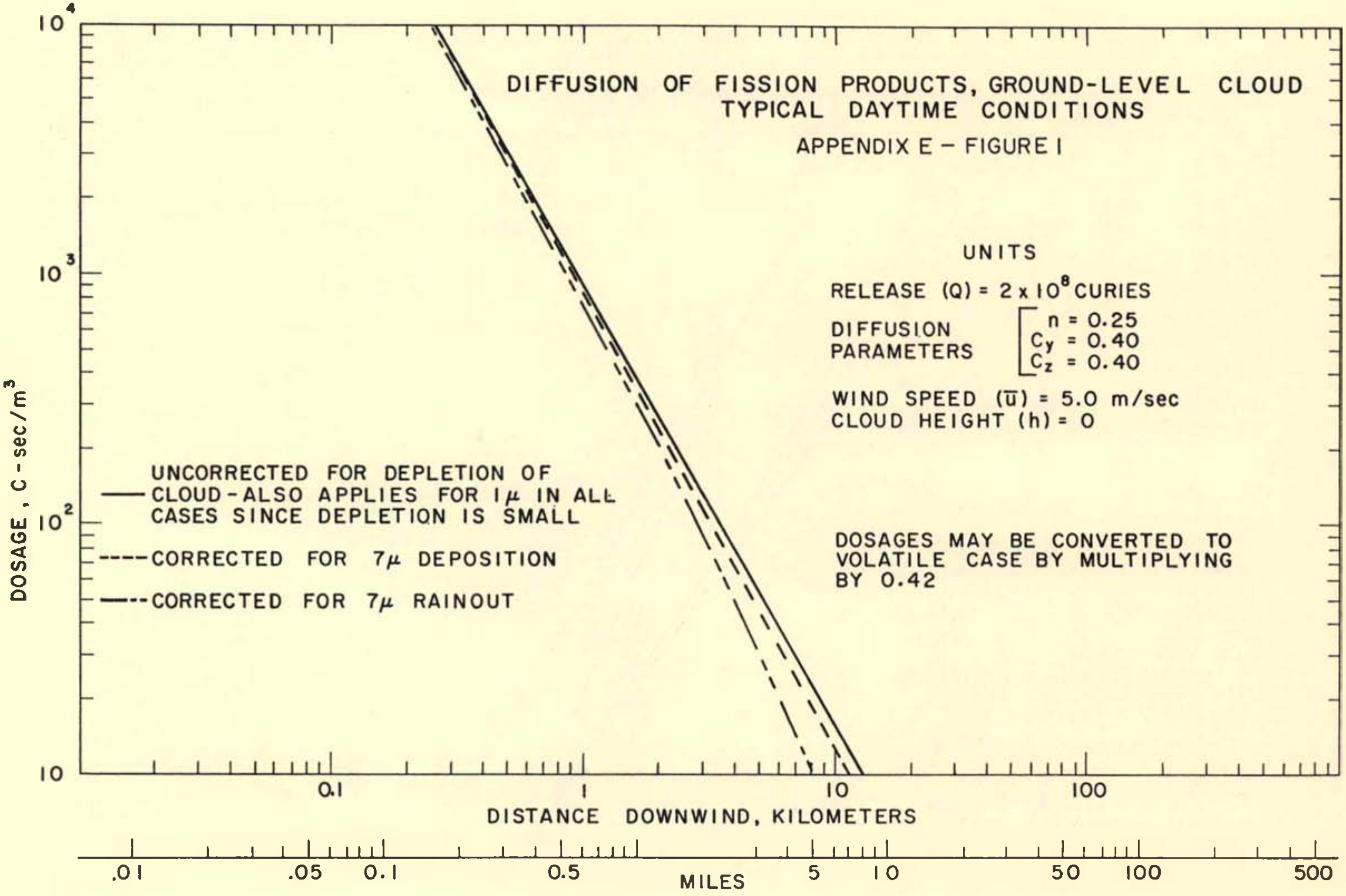
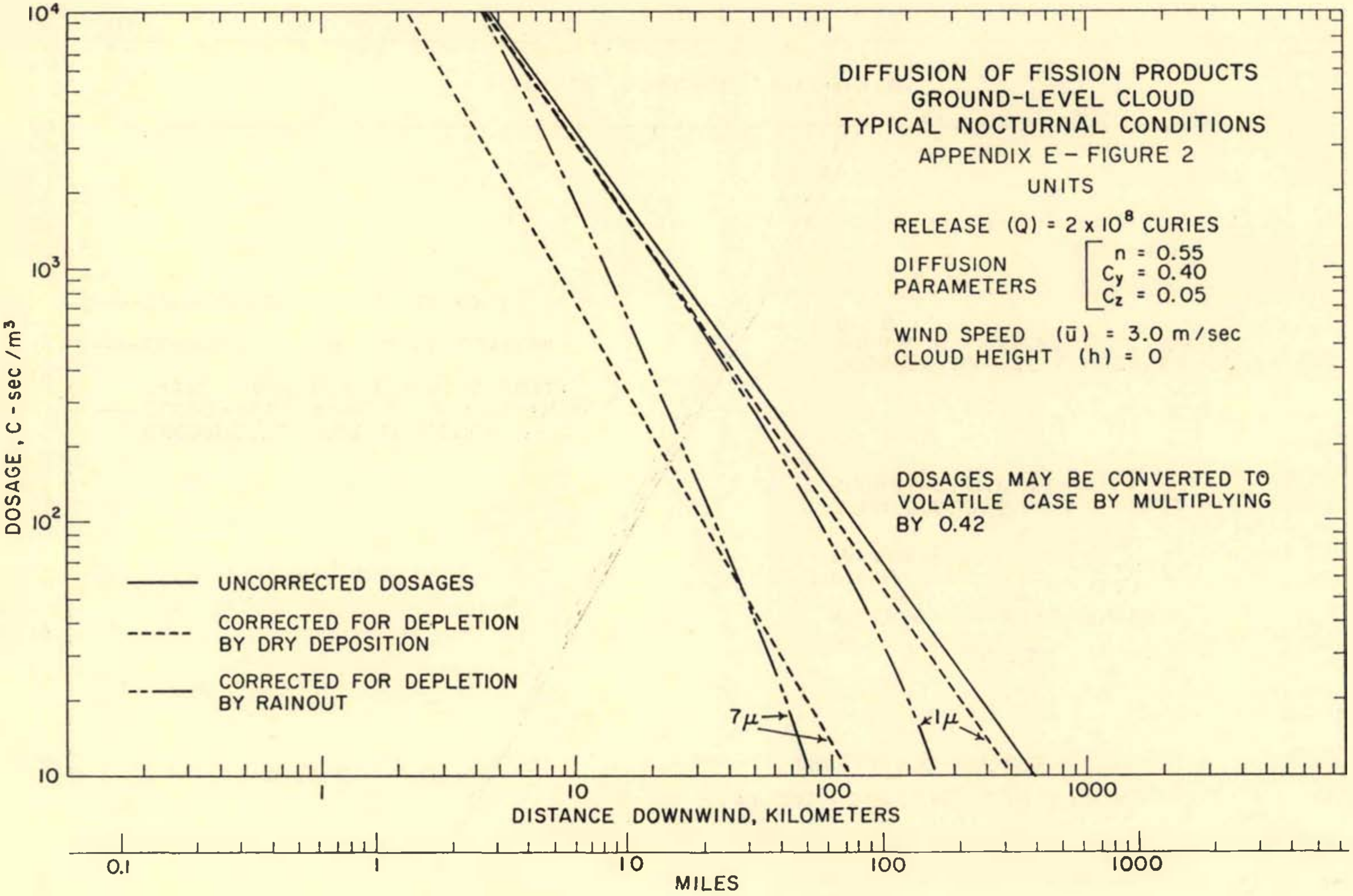
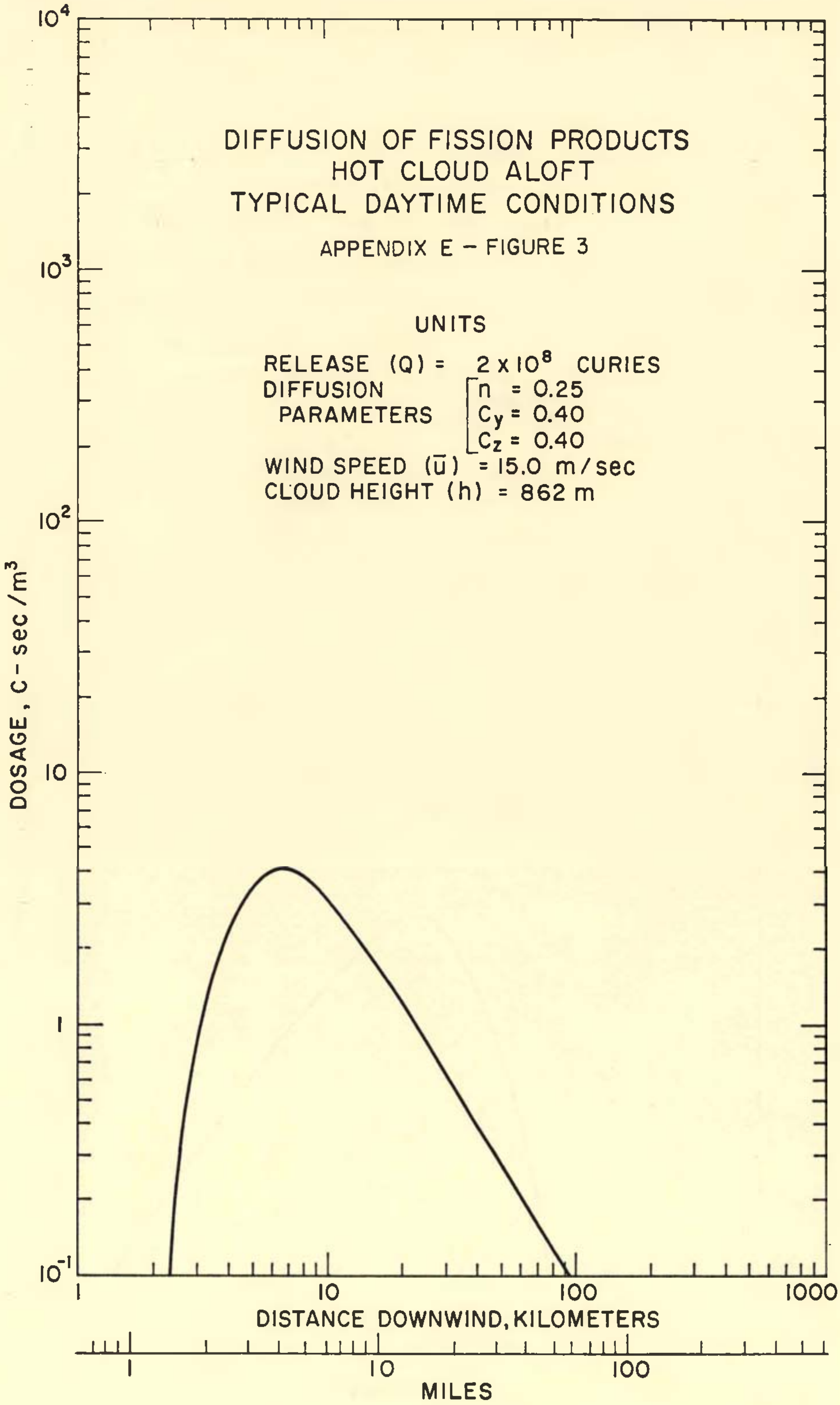
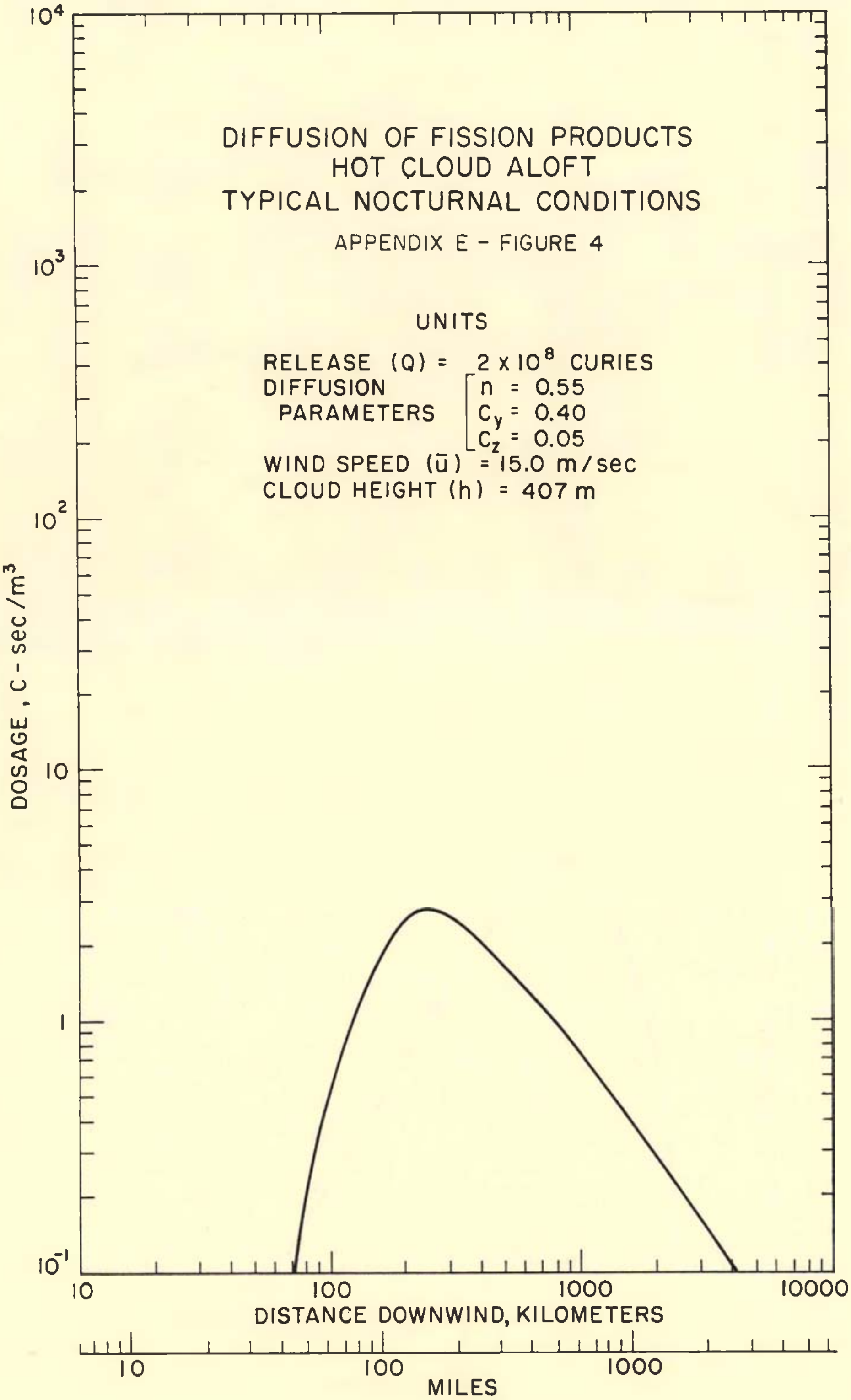
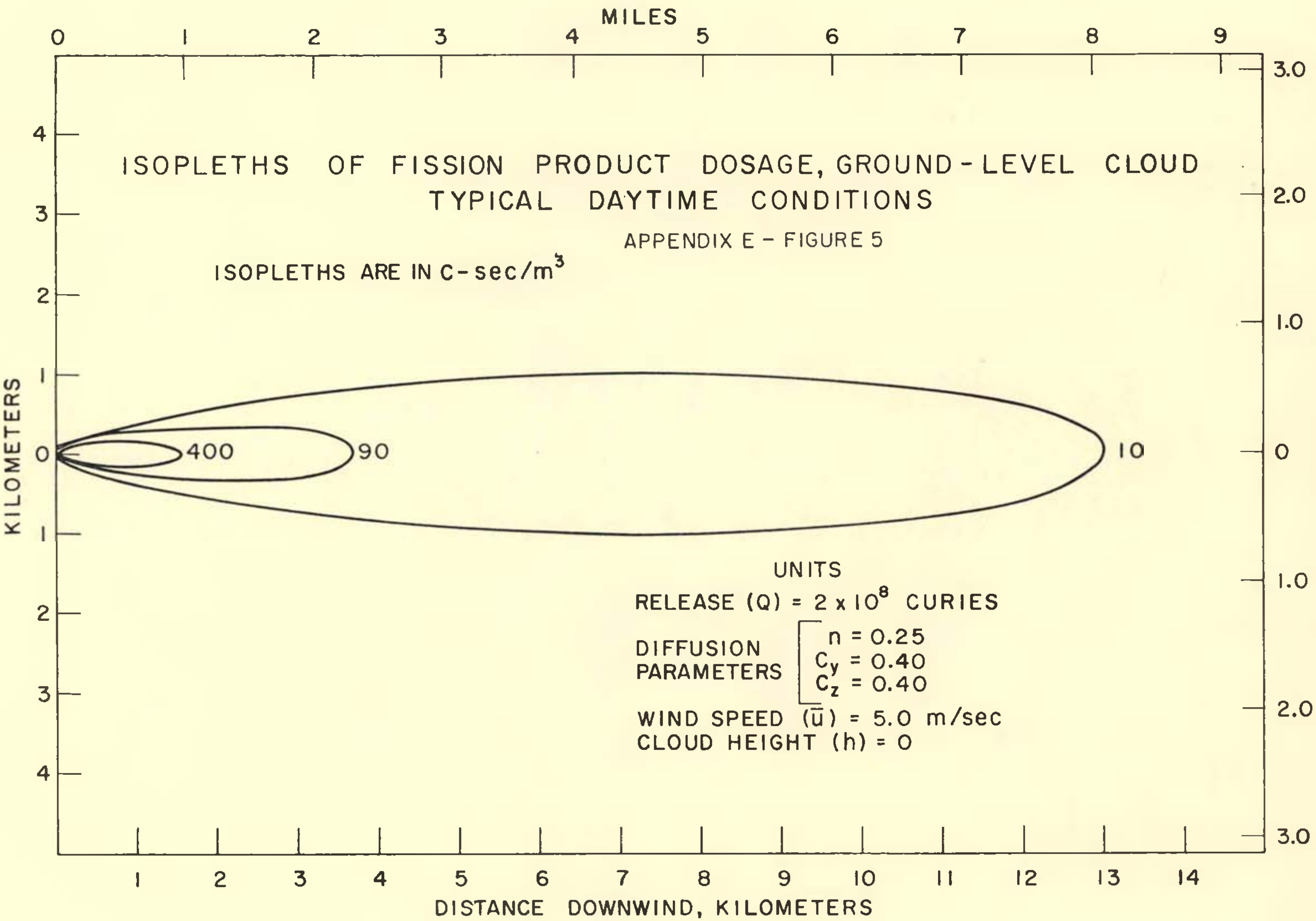
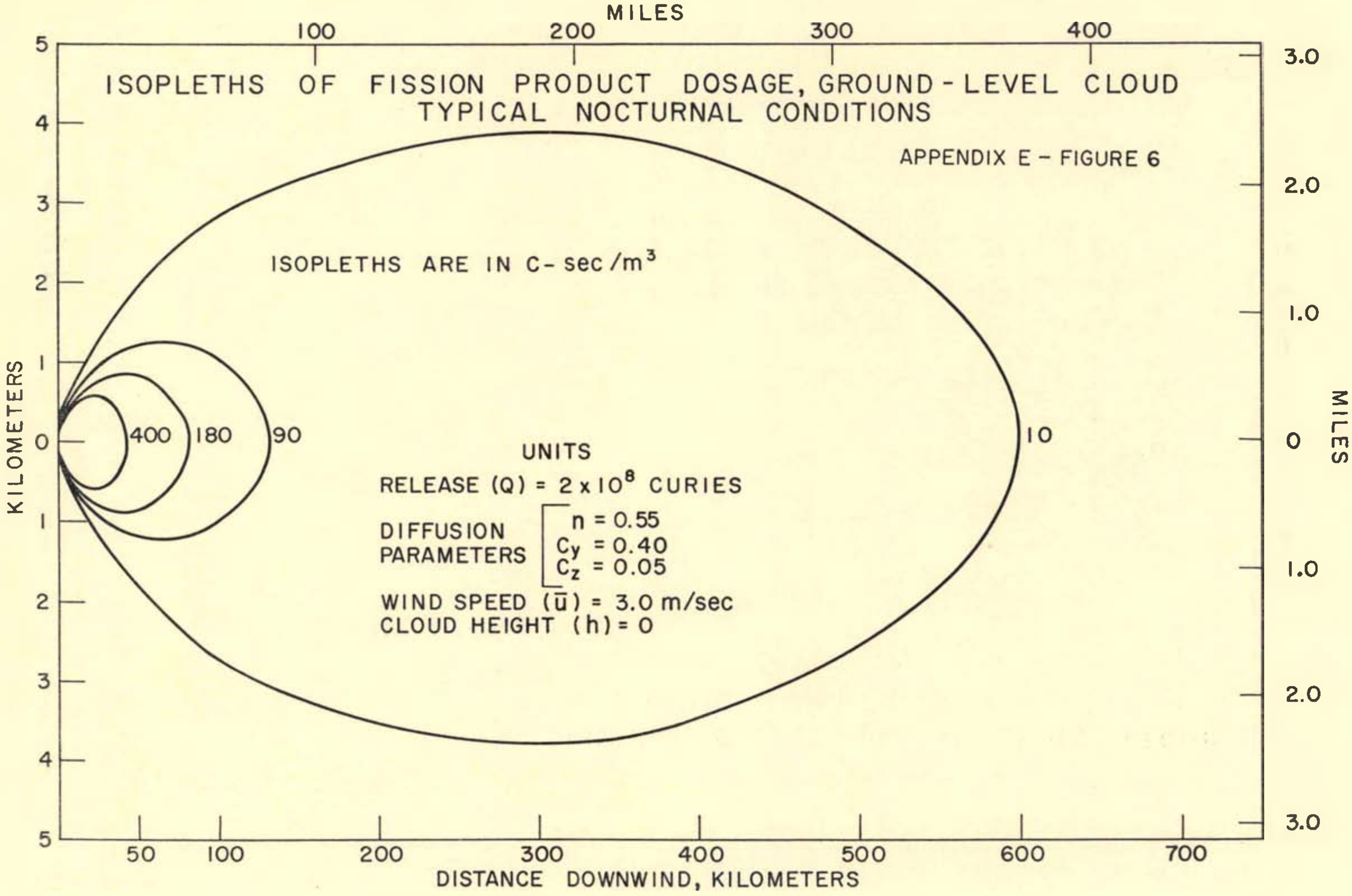

DIFFUSION OF FISSION PRODUCTS, GROUND-LEVEL CLOUD
TYPICAL DAYTIME CONDITIONS
APPENDIX E – FIGURE I
UNITS
RELEASE (Q) = 2 x 10^8 CURIES
DIFFUSION PARAMETERS
n = 0.25
Cy = 0.40
Cz = 0.40
WIND SPEED (ū) = 5.0 m/sec
CLOUD HEIGHT (h) = 0
UNCORRECTED FOR DEPLETION OF CLOUD-ALSO APPLIES FOR 1μ IN ALL CASES SINCE DEPLETION IS SMALL
CORRECTED FOR 7μ DEPOSITION
CORRECTED FOR 7μ RAINOUT
DOSAGES MAY BE CONVERTED TO VOLATILE CASE BY MULTIPLYING BY 0.42
DOSAGE, C-sec/m³
10⁴
10³
10²
10
0.1
1
10
100
DISTANCE DOWNWIND, KILOMETERS
.01
.05
0.1
0.5
5
10
50
100
500
MILES

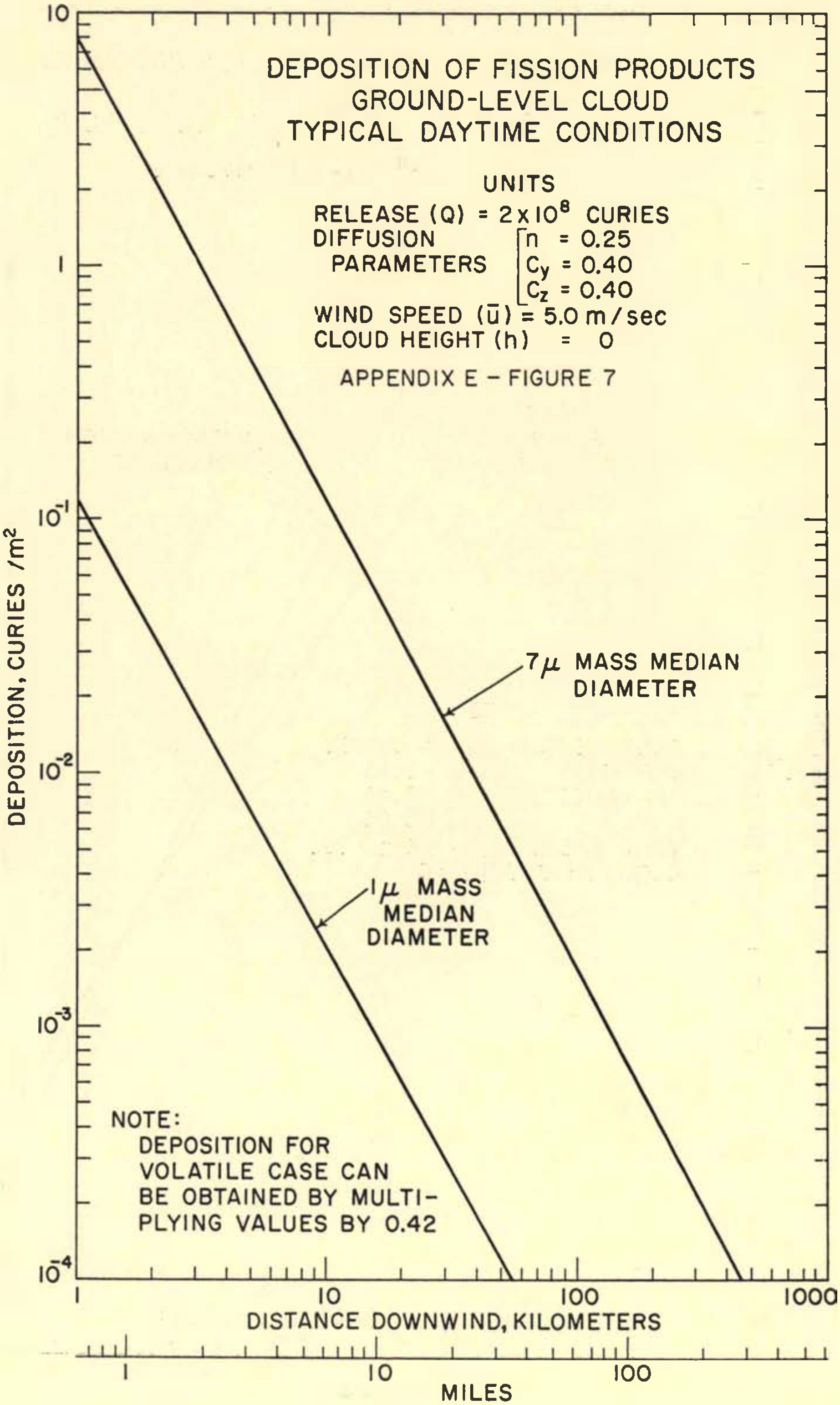

DIFFUSION OF FISSION PRODUCTS
GROUND-LEVEL CLOUD
TYPICAL NOCTURNAL CONDITIONS
APPENDIX E – FIGURE 2
UNITS
RELEASE (Q) = 2 x 10^8 CURIES
DIFFUSION PARAMETERS
n = 0.55
Cy = 0.40
Cz = 0.05
WIND SPEED (ū) = 3.0 m/sec
CLOUD HEIGHT (h) = 0
DOSAGES MAY BE CONVERTED TO VOLATILE CASE BY MULTIPLYING BY 0.42
UNCORRECTED DOSAGES
CORRECTED FOR DEPLETION BY DRY DEPOSITION
CORRECTED FOR DEPLETION BY RAINOUT
7μ
1μ
DOSAGE, C-sec/m³
10⁴
10³
10²
10
1
10
100
1000
DISTANCE DOWNWIND, KILOMETERS
0.1
1
10
100
1000
MILES

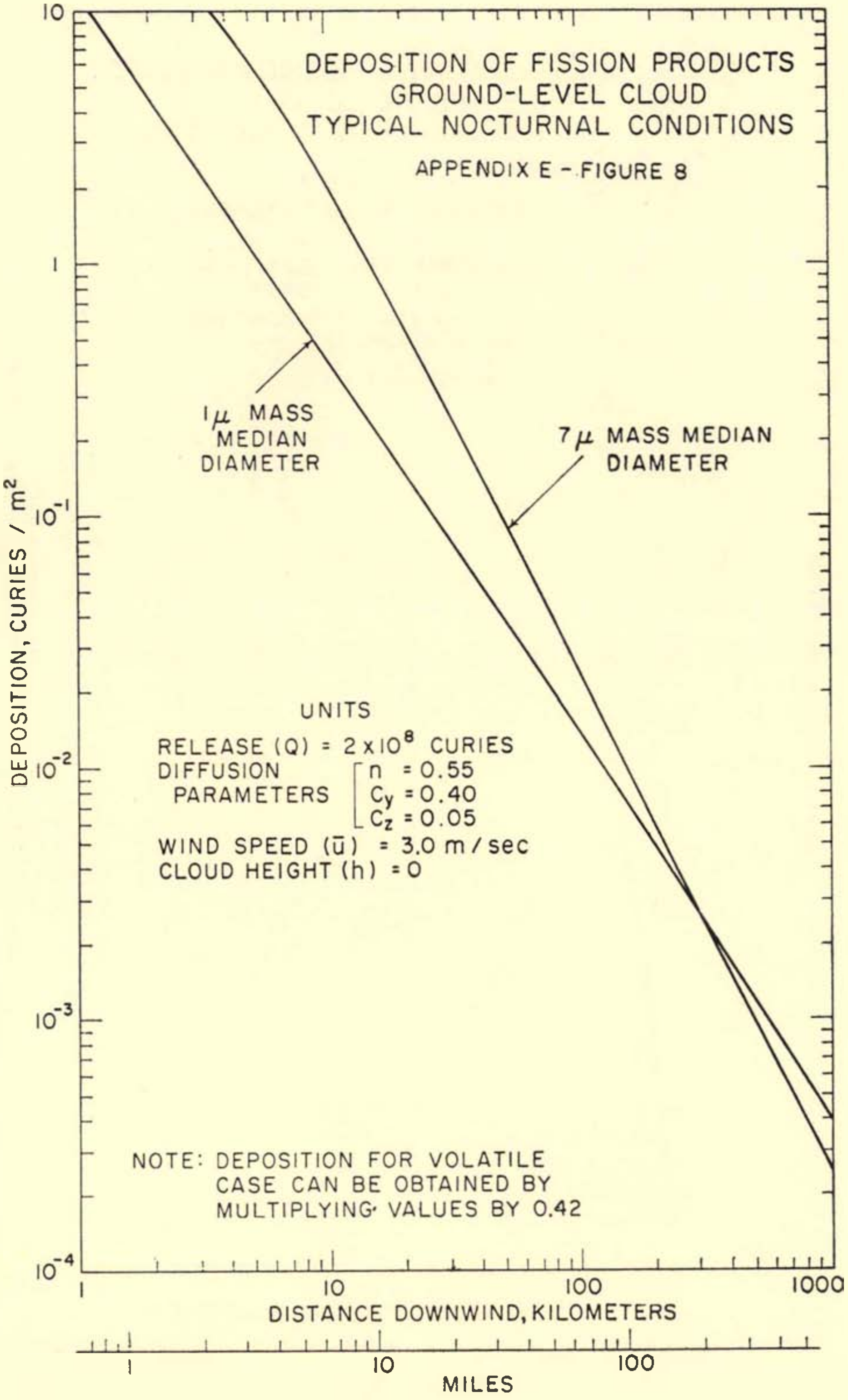

DIFFUSION OF FISSION PRODUCTS
HOT CLOUD ALOFT
TYPICAL DAYTIME CONDITIONS
APPENDIX E – FIGURE 3
UNITS
RELEASE (Q) = 2 x 10^8 CURIES
DIFFUSION PARAMETERS n = 0.25, Cy = 0.40, Cz = 0.40
WIND SPEED (ū) = 15.0 m/sec
CLOUD HEIGHT (h) = 862 m
DOSAGE, C-sec/m^3
10^4
10^3
10^2
10
1
10^-1
1
10
100
1000
DISTANCE DOWNWIND, KILOMETERS
MILES

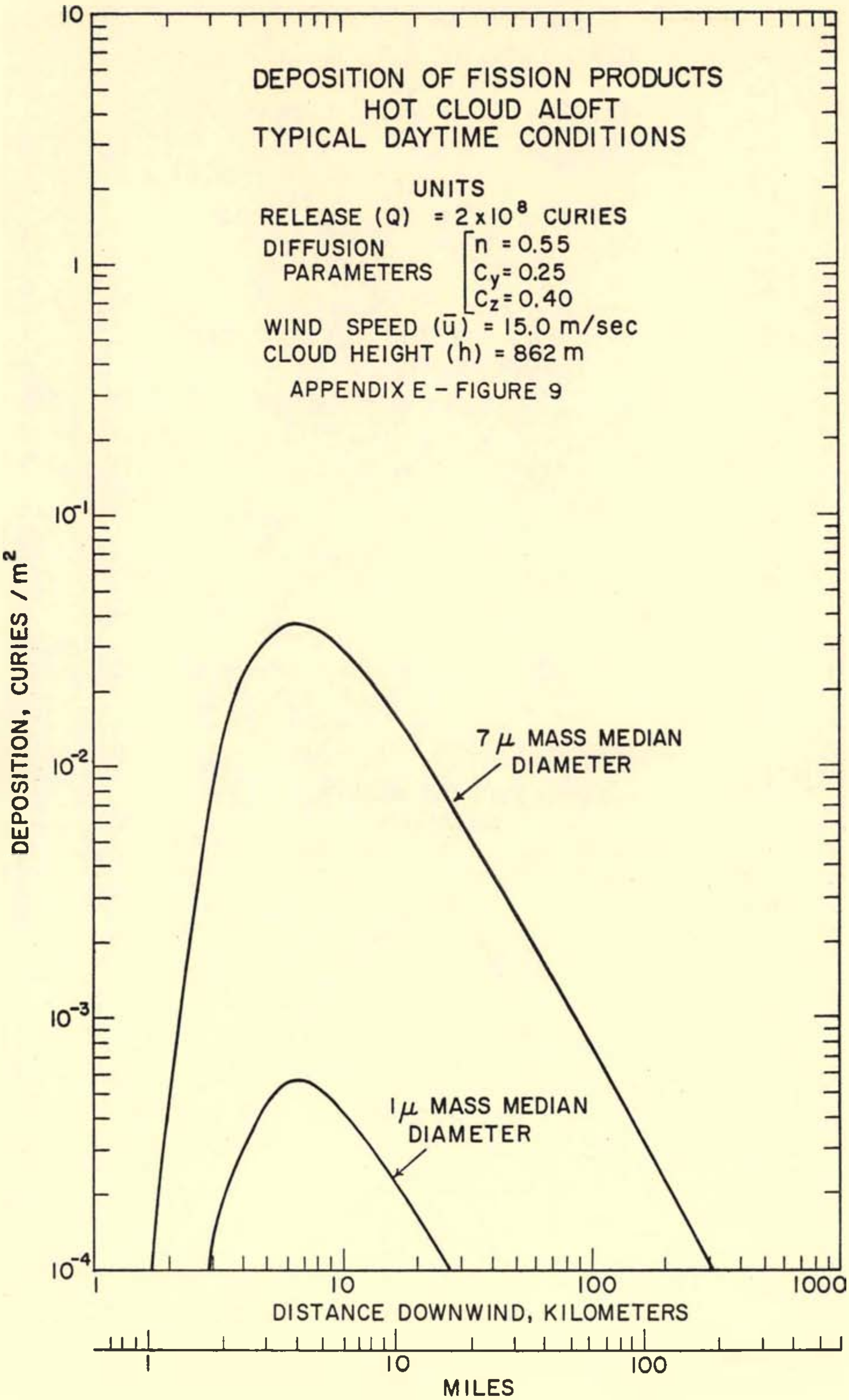

DIFFUSION OF FISSION PRODUCTS
HOT CLOUD ALOFT
TYPICAL NOCTURNAL CONDITIONS
APPENDIX E - FIGURE 4
UNITS
RELEASE (Q) = 2 x 10^8 CURIES
DIFFUSION PARAMETERS n = 0.55
C_y = 0.40
C_z = 0.05
WIND SPEED ($\bar{u}$) = 15.0 m/sec
CLOUD HEIGHT (h) = 407 m
DOSAGE, C - sec/m³
10⁴
10³
10²
10
1
10⁻¹
10
100
1000
10000
DISTANCE DOWNWIND, KILOMETERS
10
100
1000
MILES

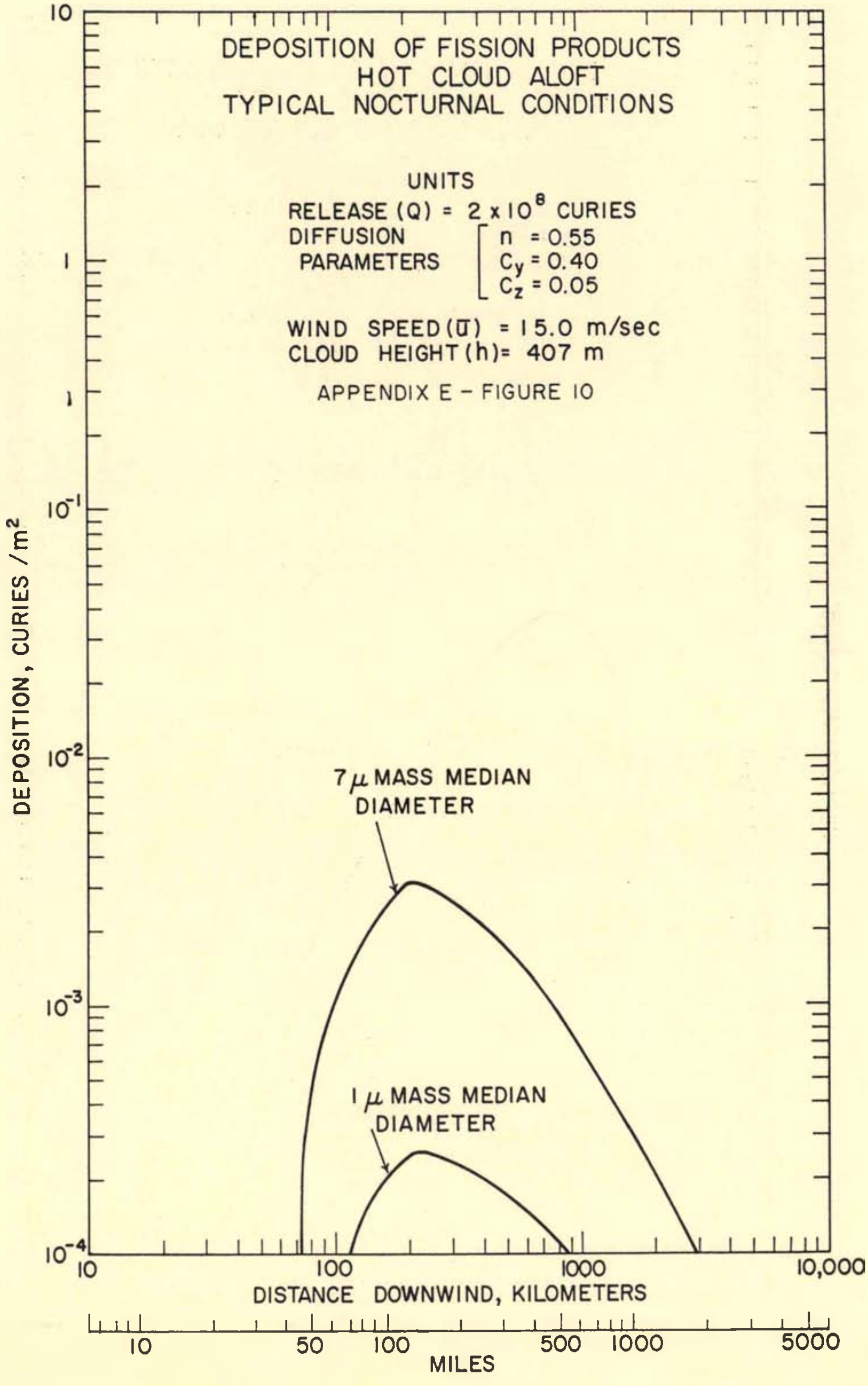

MILES
0 1 2 3 4 5 6 7 8 9
ISOPLETHS OF FISSION PRODUCT DOSAGE, GROUND-LEVEL CLOUD
TYPICAL DAYTIME CONDITIONS
APPENDIX E - FIGURE 5
ISOPLETHS ARE IN C-sec/m³
400
90
10
KILOMETERS
4 3 2 1 0 1 2 3 4
MILES
3.0 2.0 1.0 0 1.0 2.0 3.0
UNITS
RELEASE (Q) = 2 x 10⁸ CURIES
DIFFUSION PARAMETERS
n = 0.25
Cy = 0.40
Cz = 0.40
WIND SPEED (ū) = 5.0 m/sec
CLOUD HEIGHT (h) = 0
1 2 3 4 5 6 7 8 9 10 11 12 13 14
DISTANCE DOWNWIND, KILOMETERS

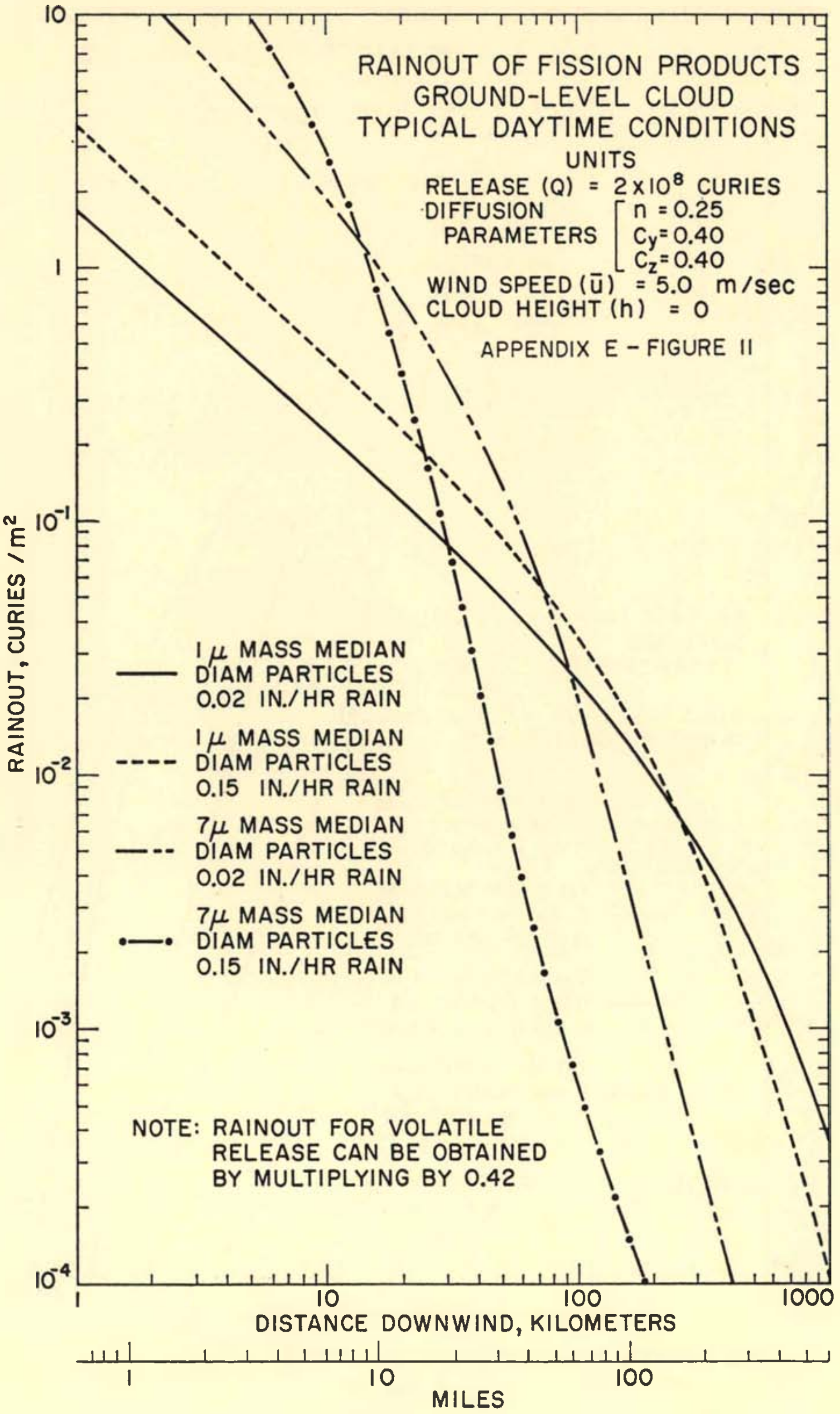

MILES
100
200
300
400
ISOPLETHS OF FISSION PRODUCT DOSAGE, GROUND-LEVEL CLOUD
TYPICAL NOCTURNAL CONDITIONS
APPENDIX E - FIGURE 6
ISOPLETHS ARE IN C-sec/m³
400
180
90
10
UNITS
RELEASE (Q) = 2 x 10⁸ CURIES
DIFFUSION PARAMETERS n = 0.55, Cy = 0.40, Cz = 0.05
WIND SPEED (ū) = 3.0 m/sec
CLOUD HEIGHT (h) = 0
KILOMETERS
5
4
3
2
1
0
1
2
3
4
5
MILES
3.0
2.0
1.0
0
1.0
2.0
3.0
50
100
200
300
400
500
600
700
DISTANCE DOWNWIND, KILOMETERS

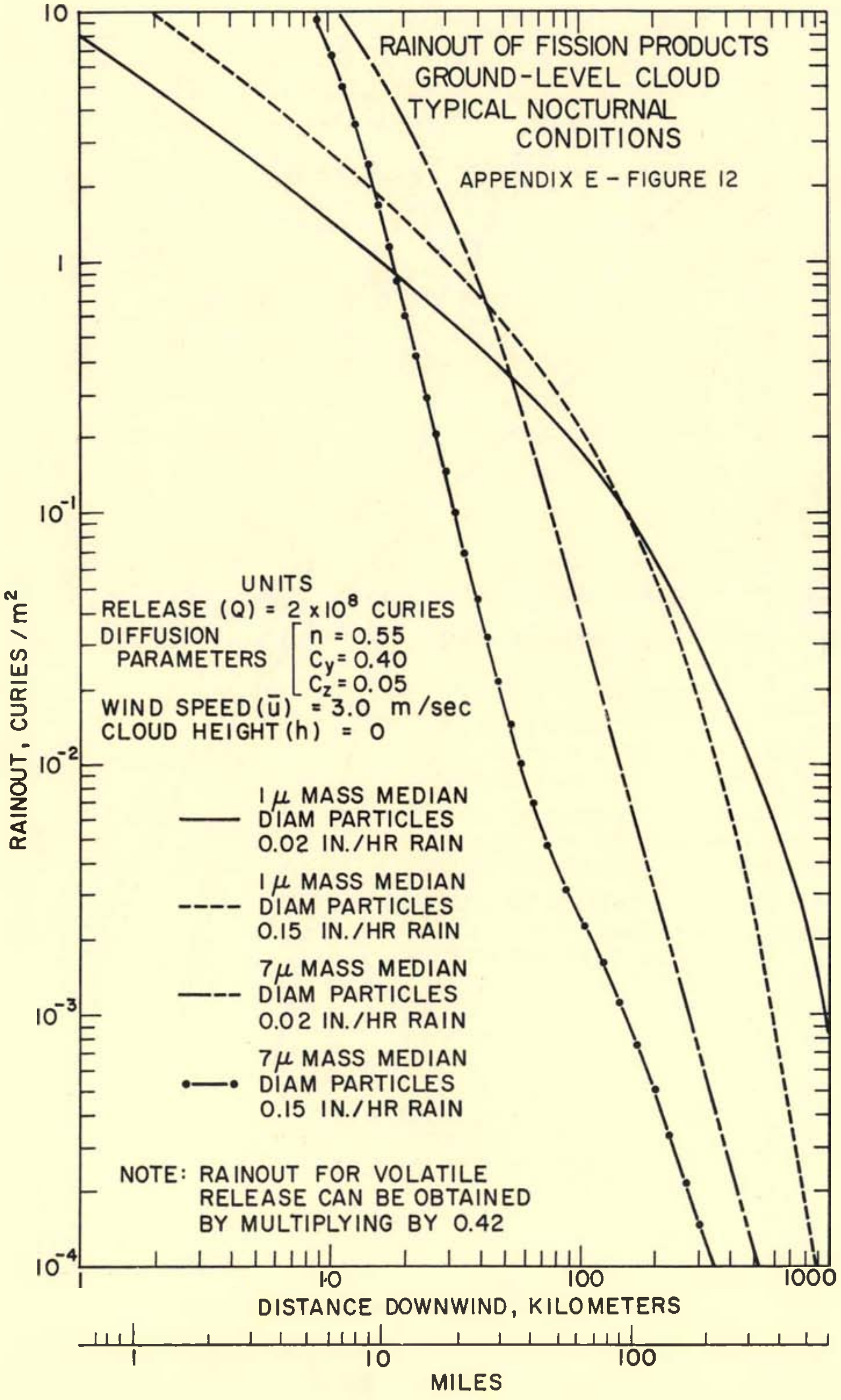

DEPOSITION OF FISSION PRODUCTS
GROUND-LEVEL CLOUD
TYPICAL DAYTIME CONDITIONS
UNITS
RELEASE (Q) = 2 x 10^8 CURIES
DIFFUSION PARAMETERS n = 0.25
Cy = 0.40
Cz = 0.40
WIND SPEED (ū) = 5.0 m/sec
CLOUD HEIGHT (h) = 0
APPENDIX E – FIGURE 7
7μ MASS MEDIAN DIAMETER
1μ MASS MEDIAN DIAMETER
NOTE:
DEPOSITION FOR VOLATILE CASE CAN BE OBTAINED BY MULTIPLYING VALUES BY 0.42
DEPOSITION, CURIES /m²
10
1
10^-1
10^-2
10^-3
10^-4
1
10
100
1000
DISTANCE DOWNWIND, KILOMETERS
1
10
100
MILES

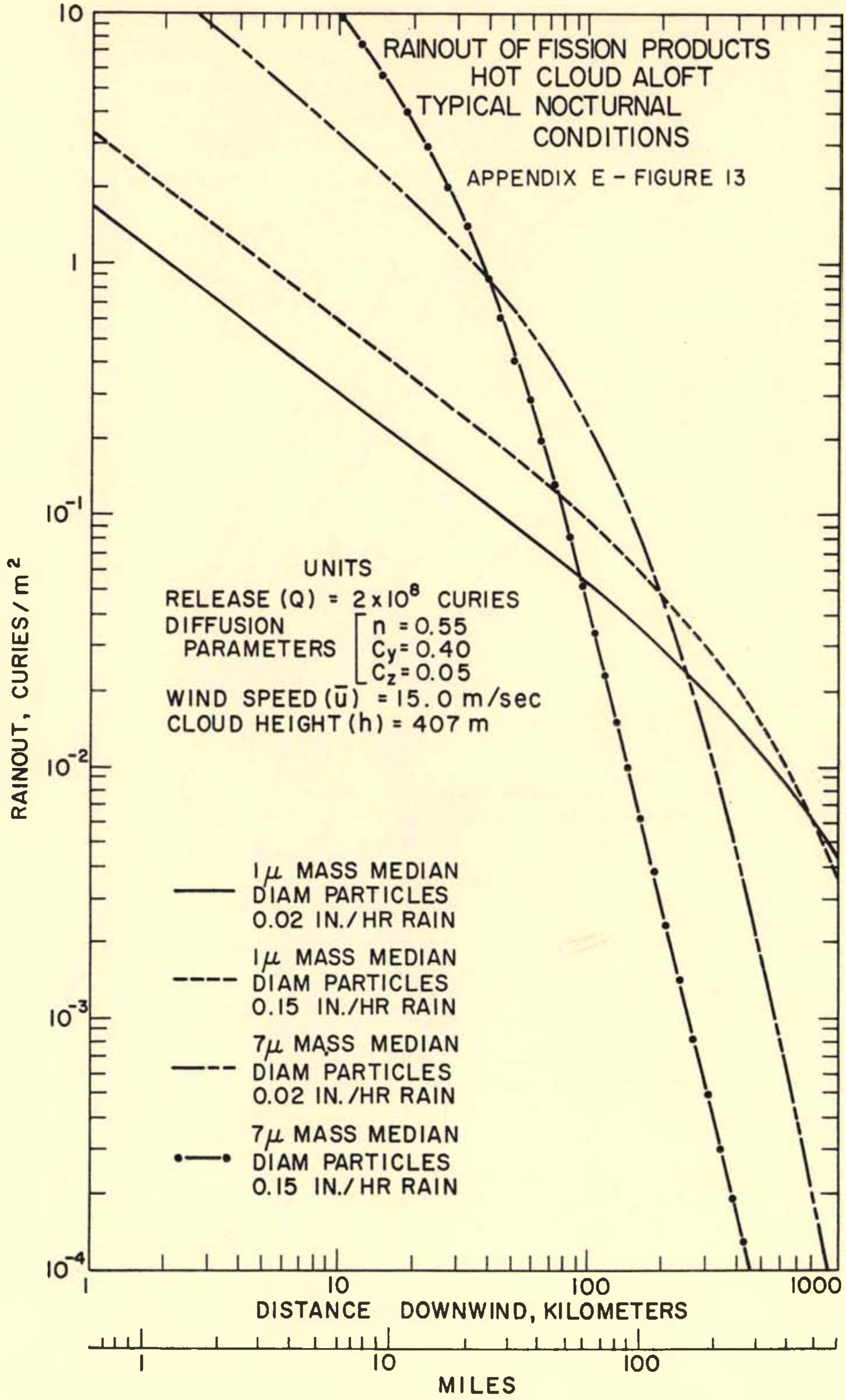

DEPOSITION OF FISSION PRODUCTS
GROUND-LEVEL CLOUD
TYPICAL NOCTURNAL CONDITIONS
APPENDIX E - FIGURE 8
1 μ MASS MEDIAN DIAMETER
7 μ MASS MEDIAN DIAMETER
UNITS
RELEASE (Q) = 2 x 10^8 CURIES
DIFFUSION PARAMETERS n = 0.55, Cy = 0.40, Cz = 0.05
WIND SPEED (ū) = 3.0 m/sec
CLOUD HEIGHT (h) = 0
NOTE: DEPOSITION FOR VOLATILE CASE CAN BE OBTAINED BY MULTIPLYING VALUES BY 0.42
DEPOSITION, CURIES / m²
10
1
10^-1
10^-2
10^-3
10^-4
1
10
100
1000
DISTANCE DOWNWIND, KILOMETERS
1
10
100
MILES

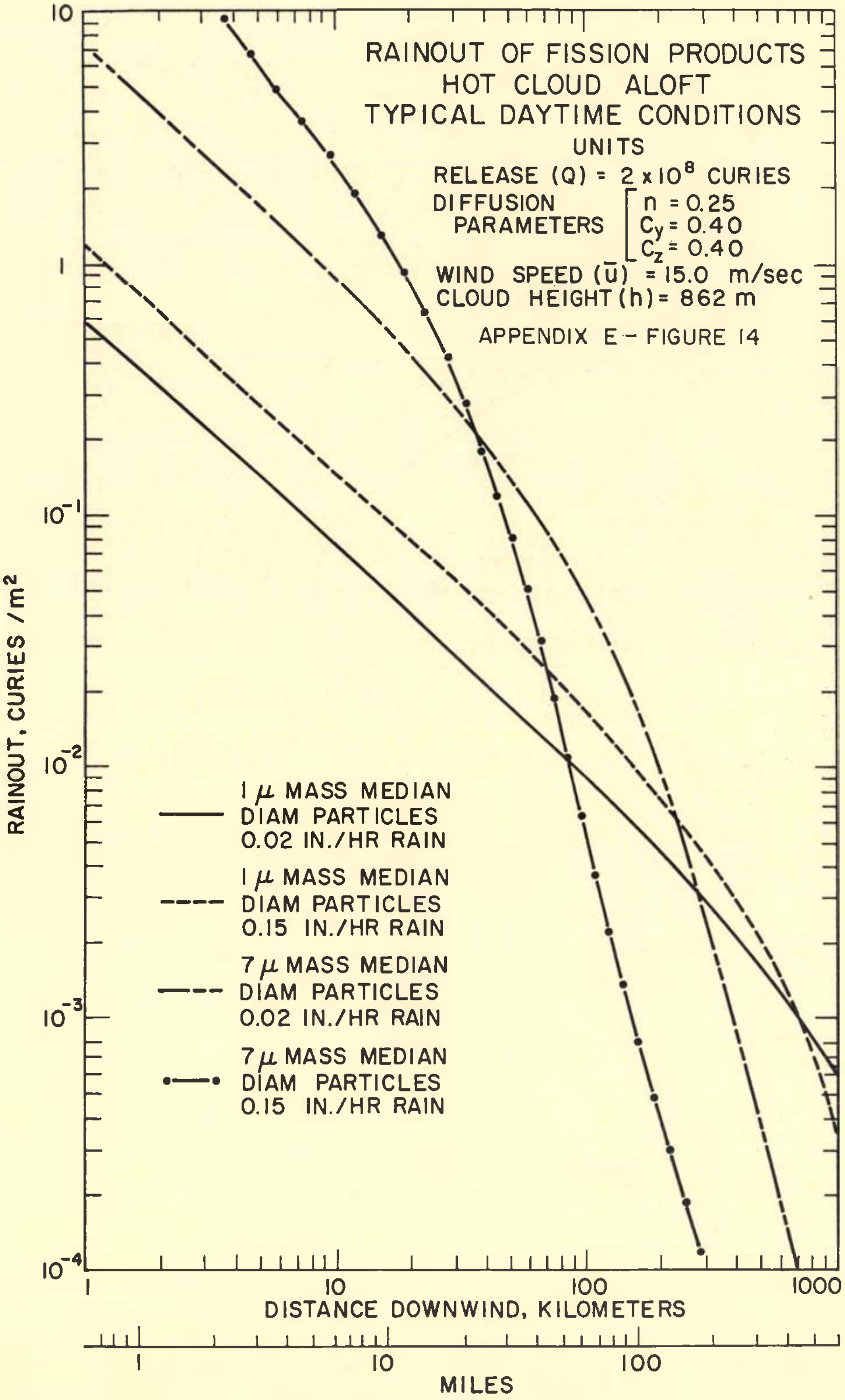

DEPOSITION OF FISSION PRODUCTS
HOT CLOUD ALOFT
TYPICAL DAYTIME CONDITIONS
UNITS
RELEASE (Q) = 2 x 10^8 CURIES
DIFFUSION PARAMETERS
n = 0.55
Cy = 0.25
Cz = 0.40
WIND SPEED (ū) = 15.0 m/sec
CLOUD HEIGHT (h) = 862 m
APPENDIX E – FIGURE 9
7 μ MASS MEDIAN DIAMETER
1 μ MASS MEDIAN DIAMETER
DEPOSITION, CURIES / m²
10
1
10⁻¹
10⁻²
10⁻³
10⁻⁴
1
10
100
1000
DISTANCE DOWNWIND, KILOMETERS
1
10
100
MILES


DEPOSITION OF FISSION PRODUCTS
HOT CLOUD ALOFT
TYPICAL NOCTURNAL CONDITIONS
UNITS
RELEASE (Q) = 2 x 10^8 CURIES
DIFFUSION PARAMETERS
n = 0.55
Cy = 0.40
Cz = 0.05
WIND SPEED (ū) = 15.0 m/sec
CLOUD HEIGHT (h) = 407 m
APPENDIX E - FIGURE 10
7 µ MASS MEDIAN DIAMETER
1 µ MASS MEDIAN DIAMETER
DEPOSITION, CURIES / m²
10
1
10^-1
10^-2
10^-3
10^-4
10
100
1000
10,000
DISTANCE DOWNWIND, KILOMETERS
10
50
100
500
1000
5000
MILES

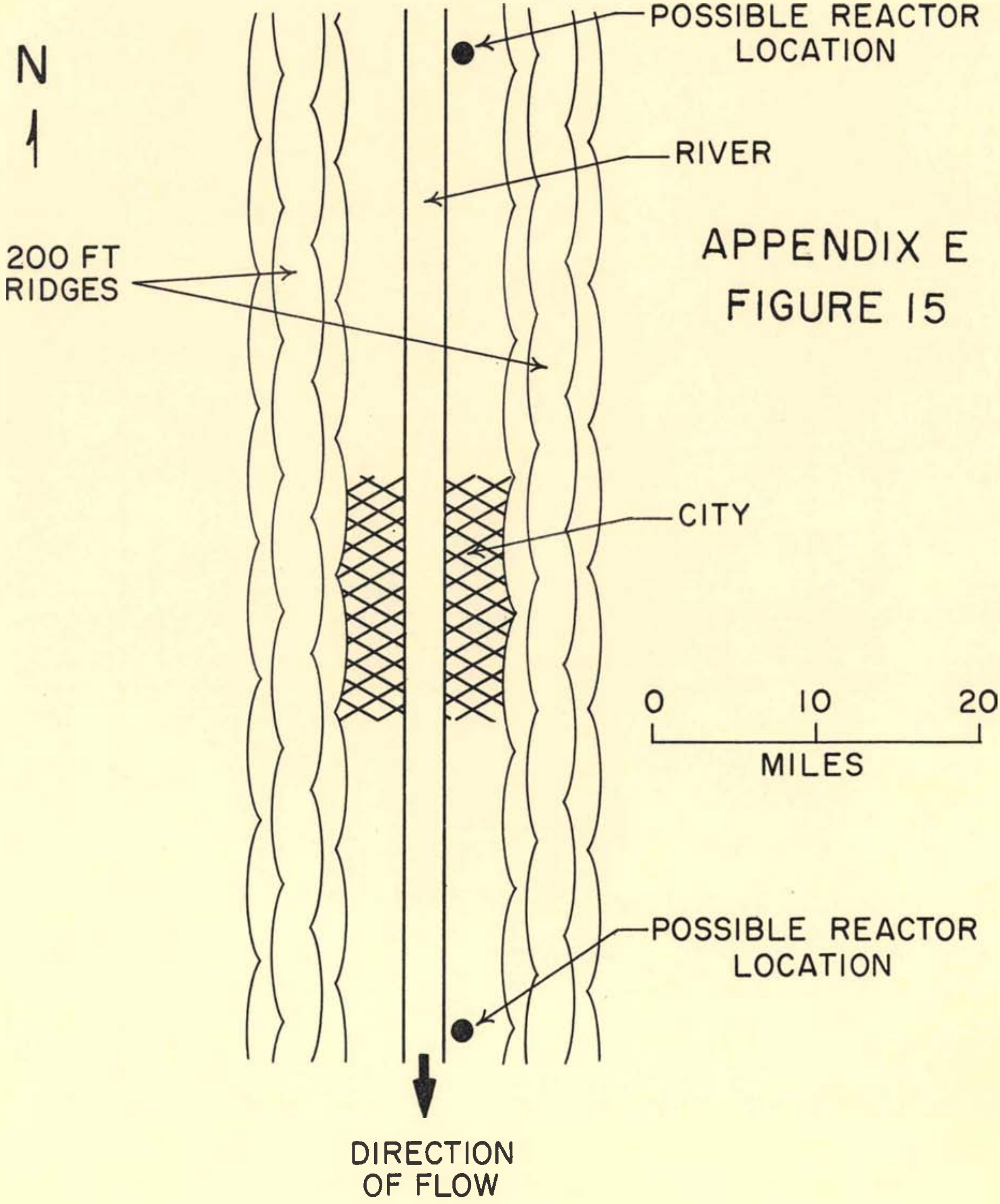

RAINOUT OF FISSION PRODUCTS
GROUND-LEVEL CLOUD
TYPICAL DAYTIME CONDITIONS
UNITS
RELEASE (Q) = 2 x 10^8 CURIES
DIFFUSION PARAMETERS n = 0.25 Cy = 0.40 Cz = 0.40
WIND SPEED (ū) = 5.0 m/sec
CLOUD HEIGHT (h) = 0
APPENDIX E - FIGURE 11
1μ MASS MEDIAN DIAM PARTICLES 0.02 IN./HR RAIN
1μ MASS MEDIAN DIAM PARTICLES 0.15 IN./HR RAIN
7μ MASS MEDIAN DIAM PARTICLES 0.02 IN./HR RAIN
7μ MASS MEDIAN DIAM PARTICLES 0.15 IN./HR RAIN
NOTE: RAINOUT FOR VOLATILE RELEASE CAN BE OBTAINED BY MULTIPLYING BY 0.42
RAINOUT, CURIES / m²
10
1
10^-1
10^-2
10^-3
10^-4
1
10
100
1000
DISTANCE DOWNWIND, KILOMETERS
1
10
100
MILES


RAINOUT OF FISSION PRODUCTS
GROUND-LEVEL CLOUD
TYPICAL NOCTURNAL CONDITIONS
APPENDIX E - FIGURE 12
UNITS
RELEASE (Q) = 2 x 10^8 CURIES
DIFFUSION PARAMETERS n = 0.55, Cy = 0.40, Cz = 0.05
WIND SPEED (ū) = 3.0 m/sec
CLOUD HEIGHT (h) = 0
1 μ MASS MEDIAN DIAM PARTICLES 0.02 IN./HR RAIN
1 μ MASS MEDIAN DIAM PARTICLES 0.15 IN./HR RAIN
7 μ MASS MEDIAN DIAM PARTICLES 0.02 IN./HR RAIN
7 μ MASS MEDIAN DIAM PARTICLES 0.15 IN./HR RAIN
NOTE: RAINOUT FOR VOLATILE RELEASE CAN BE OBTAINED BY MULTIPLYING BY 0.42
RAINOUT, CURIES / m²
10
1
10^-1
10^-2
10^-3
10^-4
1
10
100
1000
DISTANCE DOWNWIND, KILOMETERS
1
10
100
MILES


RAINOUT OF FISSION PRODUCTS
HOT CLOUD ALOFT
TYPICAL NOCTURNAL CONDITIONS
APPENDIX E - FIGURE 13
UNITS
RELEASE (Q) = 2 x 10^8 CURIES
DIFFUSION PARAMETERS n = 0.55 Cy = 0.40 Cz = 0.05
WIND SPEED (ū) = 15.0 m/sec
CLOUD HEIGHT (h) = 407 m
1μ MASS MEDIAN DIAM PARTICLES 0.02 IN./HR RAIN
1μ MASS MEDIAN DIAM PARTICLES 0.15 IN./HR RAIN
7μ MASS MEDIAN DIAM PARTICLES 0.02 IN./HR RAIN
7μ MASS MEDIAN DIAM PARTICLES 0.15 IN./HR RAIN
RAINOUT, CURIES/m²
10
1
10^-1
10^-2
10^-3
10^-4
1
10
100
1000
DISTANCE DOWNWIND, KILOMETERS
1
10
100
MILES


RAINOUT OF FISSION PRODUCTS
HOT CLOUD ALOFT
TYPICAL DAYTIME CONDITIONS
UNITS
RELEASE (Q) = 2 x 10^8 CURIES
DIFFUSION PARAMETERS n = 0.25, Cy = 0.40, Cz = 0.40
WIND SPEED (ū) = 15.0 m/sec
CLOUD HEIGHT (h) = 862 m
APPENDIX E - FIGURE 14
1 μ MASS MEDIAN DIAM PARTICLES 0.02 IN./HR RAIN
1 μ MASS MEDIAN DIAM PARTICLES 0.15 IN./HR RAIN
7 μ MASS MEDIAN DIAM PARTICLES 0.02 IN./HR RAIN
7 μ MASS MEDIAN DIAM PARTICLES 0.15 IN./HR RAIN
RAINOUT, CURIES /m²
DISTANCE DOWNWIND, KILOMETERS
MILES
10
1
10^-1
10^-2
10^-3
10^-4
1
10
100
1000

MAP OF HYPOTHETICAL REACTOR SITE



APPENDIX E
FIGURE 15

Appendix F

A Method for Calculating the Number of People That Could Be Affected by a Fission Product Release

The calculation is based on the following three premises: (*a*) The wind has an equal probability of being in any direction. (*b*) The population as a function of radius x can be written in the form

$$\delta = ax^{\gamma} \qquad (1)$$

where δ = population density (people/meter²). (*c*) Sutton's equation for the cloud dispersion with source at ground level gives

$$X = \frac{2Q}{\pi C_y C_z U x^{2-n}} \exp\left(-\frac{y^2}{C_y x^{2-n}}\right) \exp\left(-\frac{z^2}{C_z^2 x^{2-n}}\right) \qquad (2)$$

where Q = curies released (measured at 24 hours),
X = concentration in air (curies-sec/meter³),
x = radial (downwind) distance (meters),
z = vertical distance (meters),
y = crosswind distance (meters),
C_x, C_y, C_z = meteorological parameters (meters)$^{n/2}$,
n = stability parameter, and
U = wind speed (meters/sec).

For a person at ground level ($z = 0$) the radiation is

$$X = \frac{2Q}{\pi C_y C_z U x^{2-n}} \exp\left(-\frac{y^2}{C_y^2 x^{2-n}}\right). \qquad (3)$$

Let $\dfrac{2Q}{\pi C_y C_z U} = A;$ (4)

then $X = Ax^{n-2} \exp(-y^2/C_y^2 x^{2-n}).$ (5)

Expanding the exponential and keeping only the first two terms gives

$$X = Ax^{n-2}\,[1 - (y^2/C_y^2 x^{2-n})] \qquad (6)$$

or
$$X = Ax^{n-2} - Ay^2 C_y^{-2} x^{2n-4}, \qquad (7)$$

$$-X + Ax^{n-2} = Ay^2 C_y^{-2} x^{2n-4}, \qquad (8)$$

$$y^2 = \frac{-X + Ax^{n-2}}{AC_y^{-2}x^{2n-4}} = \frac{-(X/A) + x^{n-2}}{C_y^{-2}x^{2n-4}}, \qquad (9)$$

$$y = C_y x^{2-n}\,[x^{n-2} - (X/A)]^{1/2}. \qquad (10)$$

From equation 5, for a person at $z = 0$, $y = 0$,

$$X = Ax^{n-2} \qquad (11)$$

or $r = (X/A)^{1/(n-2)}$

where r = maximum downwind interaction distance.

From equation 1, the number of people in an area $dydx$ is given by

$$\delta = ax^{\gamma}\, dydx. \qquad (12)$$

Integration gives

$$P = 2\int_0^{(X/A)^{1/(n-2)}} ax^{\gamma} dx \int_0^{C_y x^{2-n}[x^{n-2} - (X/A)]^{1/2}} dy, \qquad (13)$$

$$P = 2\int_0^{(X/A)^{1/(n-2)}} ax^{\gamma} C_y x^{2-n} [x^{n-2} - (X/A)]^{1/2}\, dx \qquad (14)$$

or $$P = 2_aC_y \int_0^{(X/A)^{1/(n-2)}} x^{2-n+\gamma}[x^{n-2} - (X/A)]^{1/2}\, dx. \qquad (15)$$

Let $$u = x^{n-2} \quad (n - 2 < 0); \qquad (16)$$

then $$x = u^{1/(n-2)} \qquad (17)$$

and $$dx = \frac{u^{[1/(n-2)]-1}}{n-2}\, du = \frac{u^{(3-n)/(n-2)}}{n-2}\, du. \qquad (18)$$

When $x = 0$, $u = \infty$; when $x = (X/A)^{1/(n-2)}$, $u = X/A$. Substituting equations 16, 17, and 18 into equation 15 gives

$$P = 2aC_y \int_\infty^{X/A} u^{(2+\gamma-n)/(n-2)}\, [u - (X/A)]^{1/2} \times \frac{u^{(3-n)/(n-2)}}{n-2}\, du \qquad (19)$$

or $$P = \frac{2aC_y}{2-n} \int_{X/A}^{\infty} +u^{-\beta}\, [u - (X/A)]^{1/2}\, du \qquad (20)$$

where $\beta = (5 + \gamma - 2n)/(2 - n)$.

Let $(X/A)V = u - (X/A)$, then

$$du = (X/A)\, dV. \qquad (21)$$

When $u = X/A$, $V = 0$; when $u = \infty$, $V = \infty$.

Combining equations 20 and 21 gives

$$P = \frac{2aC_y}{2-n} \int_0^\infty \left(\frac{X}{A}V + \frac{X}{A}\right)^{-\beta} \left(\frac{X}{A}V\right)^{1/2} \times \frac{X}{A}\, dV, \qquad (22)$$

$$P = \frac{2aC_y}{2-n} \left(\frac{X}{A}\right)^{(3/2)-\beta} \int_0^\infty - \frac{V^{1/2}dV}{(V+1)^\beta}. \qquad (23)$$

From the definition of a gamma function

$$\int_0^\infty \frac{x^{m-1}dx}{(1+x)^{m+N}} = \frac{\Gamma(m)\,\Gamma(N)}{\Gamma(m+N)}. \qquad (24)$$

Let $m = 3/2$, $N = \beta - (3/2)$, then

$$P = \frac{2aC_y}{2-n}\left(\frac{A}{X}\right)^{\beta-(3/2)} \frac{\Gamma(3/2)\,\Gamma[\beta - (3/2)]}{\Gamma(\beta)}, \qquad (25)$$

$$P = \frac{2aC_y}{2-n}\left(\frac{2Q}{\pi C_y C_z U X}\right)^{\frac{2+\gamma-(n/2)}{2-n}} \times \frac{\Gamma(3/2)\,\Gamma\left[\frac{2+\gamma-(n/2)}{2-n}\right]}{\Gamma\left(\frac{5+\gamma-2n}{2-n}\right)}. \qquad (26)$$

For area $a = 1$, $\gamma = 0$,

$$Area = \frac{2C_y}{2-n}\left(\frac{2Q}{\pi C_y C_z U X}\right)^{\frac{2-(n/2)}{2-n}} \times \frac{\Gamma(3/2)\,\Gamma\left[\frac{2-(n/2)}{2-n}\right]}{\Gamma\left(\frac{5-2n}{2-n}\right)}. \qquad (27)$$

For a uniform population density, people $= K$ times area, where $K =$ people/meter^2, or

$$P = \frac{2KC_y}{2-n}\left(\frac{2Q}{\pi C_y C_z U X}\right)^{\frac{2-(n/2)}{2-n}} \times \frac{\Gamma(3/2)\,\Gamma\left[\frac{2-(n/2)}{2-n}\right]}{\Gamma\left(\frac{5-2n}{2-n}\right)}. \qquad (28)$$

To solve a large number of cases it is convenient to write equations 26, 27, and 28 in terms of the maximum interaction distance. From equation 15

$$r = (X/A)^{1/(n-2)}$$

or $$r^{2-n} = A/X = 2Q/\pi C_y C_z U X. \qquad (29)$$

Substituting in equation 26 gives

$$P = \frac{2aC_y}{2-n}[r]^{2+\gamma-(n/2)} \times \frac{\Gamma(3/2)\,\Gamma\left[\frac{2+\gamma-(n/2)}{2-n}\right]}{\Gamma\left(\frac{5+\gamma-2n}{2-n}\right)}. \qquad (30)$$

Substituting in equation 27 gives

$$A = \frac{2C_y}{2-n}[r]^{2-(n/2)} \times \frac{\Gamma(3/2)\,\Gamma\left[\frac{2-(n/2)}{2-n}\right]}{\Gamma\left(\frac{5-2n}{2-n}\right)}. \qquad (31)$$

For a uniform population density equation 28 becomes

$$P = \frac{2KC_y}{2-n}[r]^{2-(n/2)} \times \frac{\Gamma(3/2)\,\Gamma\left[\frac{2-(n/2)}{2-n}\right]}{\Gamma\left(\frac{5-2n}{2-n}\right)} \qquad (32)$$

where K = people/meter^2.

The number of people who could be exposed to radiation greater than X may be calculated from equation 30 for a nonuniform population distribution, or from equation 32 for a uniform one.

Nomenclature

- Q = curies released (measured at 24 hours)
- δ = nonuniform population density (people/meter^2)
- a = population density at 1 meter (people/(meter)$^{2+\gamma}$)
- γ = gradient of population density
- X = concentration in air (curie sec/meter^3)
- $C_x C_y C_z$ = meteorological parameters (meters)$^{n/2}$
- x = radial (downwind) distance (meters)
- y = crosswind distance (meters)
- z = vertical distance (meters)
- n = stability parameter
- U = wind speed (meters/sec)
- P = people within an area bounded by an X isoline
- K = uniform population density (people/meter^2)
- A = area bounded by an X isoline
- r = maximum downwind interaction distance (meters)

Appendix G

Basic Assumptions in Calculating Potential Losses

Introduction

The potential off-site losses which might be associated with a power reactor accident may involve personal injury or death, property damage, and personal costs due to dislocation and other expense. This study has attempted to group these potential losses under two headings: the first involves injury to persons and the second, all other losses. In the first group, the results are given in terms of the number of persons probably killed or injured. In the second group, the results are expressed in terms of the areas involved, the number of people affected, and the costs involved.

The mechanism used to arrive at an estimate of the costs for the second group involves calculating the number of people who might be involved, dividing these people into four categories according to severity of interaction and establishing for each category an average dollar per person figure. It should be emphasized that each dollar number is based on an average person affected by the average amount of radiation or deposition characteristic of the category. Actually, within any category, individual costs would have a wide range of values; however, the numbers given here are averages. It was found that this method of approach avoided difficulties arising from variations in population density and in differences between urban and rural property values. Also, the cost associated with moving people would be proportional to the number of people and not to property values.

Ranges I and II. Evacuation: $5000/person

People in these ranges would be evacuated and would probably not be permitted to return to their homes for a year or more. Range I includes only those people evacuated on an urgent basis. Range II includes, in addition, those people evacuated at a more leisurely rate. Since the return date would be somewhat indefinite, the assumption is made that the individuals would lose the value of their land and nonuseable other property. The estimate of loss per person is based on a 1949 nationwide average of the "Reproducible Tangible Assets and Land" as reported on page 308 of *The Statistical Abstract of the United States, 1955.* Separate figures are given for urban and farm populations, but the difference is so small that for the purpose of this report these two types of people need not be considered separately (see table 1).

Range III. Temporary Evacuation or Severe Restrictions on Mode of Living: $750/person

In this Range farming would be halted for an extended period; therefore, the loss to farm families is considered to be the same as the loss in Range II. However this is not true for urban dwellers. To arrive at an average cost per person including both rural and urban dwellers the ratio of the two groups must be considered. While the national average ratio of farm people to urbanites is about 1 to 6, the ratio for the region around the reactor may be more like that on the eastern

TABLE 1

ESTIMATE OF LIABILITY FOR EVACUATION

Based on Nationwide Averages
Data from *The Statistical Abstract of the United States, 1955*
Urban Population, 1949 = 125×10^6
Rural Population, 1949 = 25×10^6

A. Reproducible Tangible Assets, Urban:	
Structures:	
Nonfarm Residential $(195 \times 10^9)/(125 \times 10^6)$	\$1,560
Nonfarm Nonresidential $(90.2 \times 10^9)/(125 \times 10^6)$	726
Institutional $(9.9 \times 10^9)/(125 \times 10^6)$	79
Government $(74.2 \times 10^9)/(125 \times 10^6)$	593
Equipment:	
Producer Durables $(104 \times 10^9)/(125 \times 10^6)$	832
Consumer Durables $(99 \times 10^9)/(150 \times 10^6)$	660
Inventories:	
Nonfarm $(58.1 \times 10^9)/(125 \times 10^6)$	464
Total	\$4,914/person
B. Reproducible Assets, Farm:	
Structures $(26.2 \times 10^9)/(25 \times 10^6)$	\$1,048
Livestock $(13.2 \times 10^9)/(25 \times 10^6)$	528
Crop $(6.0 \times 10^9)/(25 \times 10^6)$	240
Land $(54.2 \times 10^9)/(25 \times 10^6)$	2,168
Forests $(4.3 \times 10^9)/(25 \times 10^6)$	172
Consumer Durables $(99 \times 10^9)/(150 \times 10^6)$	660
Total	\$4,816/person
Rough Check Calculation:	
Average Salary per Family of 3.5 Persons	\$5,000
Value of House = Three Years' Salary	15,000
Furnishings = One Half Year's Salary	2,750
Total	\$17,750
\$17,750/3.5 =	\$5,000/person

seaboard, which is about 1 to 20. Therefore the average per person loss for all persons in this Range due to farm evacuation is considered to be \$5,000/20 or \$250/person.

Urbanites would probably be moved temporarily. The loss calculated below is based on an average family of 3.5 people.

Loss for Urbanites in Range III

New lodgings at \$100/month for 6 months	\$ 600
Moving expenses both ways	500
Loss of income during move, day days each way at \$25/day	200
Decontamination of belongings (18 people-days at \$25/day)	450
Loss for family of 3.5	1750
Loss per person	500

The total loss per person therefore would be \$250 + \$500 = \$750/person in this Range.

Range IV. Probable Destruction of Standing Crops with Restrictions on Farming for One Year: \$25,000/mi²

The value of the crop is estimated from tables in *The Statistical Abstract of the United States, 1955*. Table 2 shows the average farm income per square mile for various sections of the United States. This average varies widely in different sections of the country; but, since it has been assumed in this report that the reactor will be near a concentration of people, the figures for the Middle Atlantic and East North Central sections are considered to be most applicable. To these numbers should be added \$2000 to \$3000 per farm for the food grown for home consumption. Thus a figure of \$25,000/mi² was considered to be the best estimate.

City Conditions

Where the cloud is assumed to interact with the major city, the following criteria are used:

- Range I. \$5,000/person as before
- Range II. \$5,000/person as before
- Range III. \$100 per person. Assume 4 days disruption of city business at \$25/person-day.
- Range IV. \$0

TABLE 2

YEARLY AVERAGE FARM INCOME[1]

Section	*Total area [2] of section, mi [2]*	*No. farms [3] per section*	*$/Farm*	*Farms/mi [2]*	*Cash [4] income of farms in section*	*$/mi [2]*
United States	3,022,387	5,382,162	$5,565	1.78	$29,953.9	$ 9,910
New England	66,608	103,225	6,888	1.55	711.0	10,674
Middle Atlantic	102,745	296,702	6,412	2.89	1,902.5	18,517
East North Central	248,283	885,404	6,578	3.57	5,824.6	23,460
West North Central	517,247	982,735	7,727	1.90	7,593.9	14,681
South Atlantic	278,902	958,998	3,411	3.44	3,270.9	11,728
East South Central	181,964	913,002	2,088	5.02	1,906.2	10,476
West South Central	438,885	780,423	4,261	1.78	3,325.2	7,576
Mountain	863,887	194,858	10,164	0.23	1,980.6	2,293
Pacific	323,866	266,185	12,919	0.82	3,438.9	10,618

[1] Data from *The Statistical Abstract of the United States, 1955.*

[2] Table No. 4, p. 9, area in square miles (1950).

[3] Table No. 769, p. 630 (1950).

[4] Table No. 780, p. 642, cash in millions of dollars (1954).

Remarks

The above figures have been used as the basis for the losses in this report. When better data become available for any group, the new number can simply be multiplied by the number of people or area as appropriate, and a new estimate of total loss established. It should be noted that each person in a category would not suffer the same amount of loss nor would each square mile sustain the same amount of damage.

The boundary lines for any Range cannot be set with any degree of exactness; and to subdivide the affected persons and property into smaller Ranges would not improve the accuracy of the estimated total losses. It should again be emphasized that these average losses are not to be applied to any individual case.

Appendix H

Consequences of Gamma Radiation From a 100 Percent Release of the Fission Products into the Containment Shell

Introduction

It has been assumed that a 500,000-kw (thermal) reactor experienced a power excursion after 180 days of continuous operation and that all the fission products were dispersed throughout the assumed 1-inch-thick steel reactor container. The resulting gamma radiation dose rates for different times after shutdown at selected distances from the reactor, as well as the integrated doses, were calculated. Correction was made for the attenuation afforded by a 1-inch-thick steel container, but self-absorption in the fission product dispersion was neglected. Estimates of accident losses involving off-site areas and persons affected by the radiation are presented.

General Calculations

Initially the radiation levels were calculated according to the approximation given by Way [1], which states that the rate of emission of fission product gamma energy is proportional to $1.26\,T^{-0.2}$, where T is the time after fission in seconds, within a factor of 2 for times between 10 sec and about 100 days. Then, at a time τ after reactor shutdown, the gamma energy emission due to all the fissions which occurred during the reactor operating time, τ_o, is

$$E = C\int_0^{\tau_o} 1.26(\tau + T)^{-1.2}\,dT,$$

$$E = 6.3C[\tau^{-0.2} - (\tau_o + \tau)^{-0.2}] \text{ Mev/sec},$$

where C is the number of fissions per second. If the power level is P watts and 3.25×10^{10} fissions produce one watt-second of energy [2], then

$$E = 2.05 \times 10^{11} P\,[\tau^{-0.2} - (\tau_o + \tau)^{-0.2}] \text{ Mev/sec},$$

$$E = 3.28 \times 10^{5}\ P\,[\tau^{-0.2} - (\tau_o + \tau)^{-0.2}] \text{ ergs/sec},$$

$$E = 0.033\,P\,[\tau^{-0.2} - (\tau_o + \tau)^{-0.2}] \text{ watts},$$

at τ seconds after shutdown.

The gamma dose rates for the reactor under discussion after 180 days of operation are

$$R = 1.64 \times 10^{14} K\,[\tau^{-0.2} - (\tau_o + \tau)^{-0.2}] \text{ roentgens/second,} \quad (1)$$

where K involves the exponential and inverse square attenuation and build-up factors due to the steel container and the air traversed, as well as the radiation quantity (ergs/cm^2) to dose (roentgens) conversion [3].

Similarly, the integrated doses from time T_1 to T_2 at selected distances from the reactor are

$$D = \int_{T_1}^{T_2} R\,d\tau \text{ roentgens},$$

$$D = 2.05 \times 10^{14} K\,[T_2^{0.8} - (\tau_o + T_2)^{0.8} - T_1^{0.8} + (\tau_o + T)^{0.8}] \text{ roentgens.} \quad (2)$$

K was evaluated by substituting the appropriate values from TID–7004 [4] into the relationship involving the attenuation of radiation from a point isotropic source in an infinite medium and the energy flux to dose conversion, namely,

$$K=\frac{A}{K'}=\frac{B(\mu r)e^{-\mu r}}{4\pi r^2K'}\text{ roentgens/ergs,}$$

where r = distance from the point source to the point of interest,
μr = the total mean free paths traversed,
$B(\mu r)$ = the build-up factor, and
K' = energy flux to dose conversion.

Build-up factors for water were used because of the lack of appropriate values in air [5]. This approximation should be adequate since the effective atomic numbers for air and water are similar. That is, [6], from

$$Z_{eff}=\left(\frac{\Sigma a_nZ_n^4}{\Sigma a_nZ_n}\right)^{1/3},$$

$$Z_{eff}\ (\text{air})\approx 7.3 \text{ and}$$

$$Z_{eff}\ (H_2O)\approx 8.0.$$

Finally, since the energy of the gamma radiation is known, the dose rates and integrated doses can be calculated from equations 1 and 2. Initially, a mean energy of 0.7 Mev was assumed for the fission products [7]. However, it was soon discovered that calculation of the radiation levels on the basis of a single mean energy can grossly underestimate the actual levels by a factor of 10 or more at the great distances of interest (up to 20 mean free paths), because of the wide range of fission product gamma energies. Thus, the radiation levels employed to estimate accident costs were inferred from the seven fission product gamma energy group treatments appearing in the literature [2, 4, 8].

Radiation Levels

Unfortunately, no available seven fission product gamma energy group data pertains directly to a reactor which has operated for 180 days. Also, the data are not adequate for times less than 30 minutes after shutdown [8]. In any event, the radiation levels were actually inferred from NDA–27–39, a compilation which emphasizes the energy emission during the first day after shutdown.

Plots of dose rates at an hour and one day after both 1,000-hr and infinite reactor operations indicate that the radiation levels due to fission products produced during the stated operating periods differ only slightly at the distances of interest (table 1, figs. 1 and 2). The energy emission data for infinite operation, then, was taken to represent the energy emission due to a 180-day operation. Plots of dose rates at 30 days and 100 days indicate that the dose rates inferred from the 1,000-hr and infinite operation data differ by about a factor of 3 at 6,000 ft (table 1, figs. 3 and 4). However, the effect of a factor of 3 in dose on the estimations of the amount of land and numbers of persons involved appears to be small. For example, a factor of 3 in the 100-day integrated dose changes the distance of affected areas from the reactor by only a few hundred (about 500) feet at about a mile (fig. 7). Actually, since the dose rates for times up to 100 days after shutdown for 1,000-hr and infinite reactor operations differ by up to a factor of 3, it can be said that the integrated 100-day doses for 180-day and infinite operations would differ by less than a factor of 3. In any case, the use of energy emission data derived from an infinite reactor operation to represent the radiation levels during the first 100 days, due to 180 days' operation, would not appear to be unduly pessimistic, especially when the uncertainties in some of the other assumptions are considered, e.g., cost of accident estimates. The values of gamma dose rates appear in

TABLE 1

COMPARISON OF GAMMA DOSE RATES (r/hr), INFERRED FROM NDA-27-39

τ = Time after shutdown

τ_o = Reactor operating time (hours)

Distance (ft)	*τ = 1 hr*		*τ = 1 day*		*τ = 30 days*		*τ = 100 days*	
	$\tau_o = \infty$	*τ_o = 1000*	*$\tau_o = \infty$*	*τ_o = 1000*	*$\tau_o = \infty$*	*τ_o = 1000*	*$\tau_o = \infty$*	*τ_o = 1000*
1,000	337	292	179	136	56	29	19	6.6
2,000	17	15	10	8.1	2.5	1.4	0.73	0.25
3,000	1.4	1.3	0.62	0.51	0.17	0.11	0.035	0.013
4,000	0.15	0.14	0.063	0.054	0.016	0.011	0.0024	0.00082
5,000	0.018	0.017	0.0072	0.0063	0.0017	0.0013	0.00021	0.000067
6,000	0.0025	0.0024	0.00098	0.00085	0.00023	0.00018	0.000023	0.0000070

table 2 and figure 5, and those of integrated doses are shown in table 3 and figures 6 and 7.

Cesium-137 Contribution to Gamma Energy Emission

It was noted that Cs^{137} was omitted from the NDA compilation; consequently, an estimate of the effect of this omission on the 100-day dose was made. Roughly, the number of Cs^{137} atoms produced in the 180-day-old reactor is, simply, fission yield times total fissions. Consequently, the Cs^{137} activity at shutdown would be about 2×10^5 curies, a value corresponding to a gamma energy emission of 10^{10} ergs/sec. The energy emitted dur-

TABLE 2

GAMMA DOSE RATES (r/hr) FOR VARIOUS TIMES AFTER SHUTDOWN, INFERRED FORM NDA–27–29

Reactor power = 500,000 kw

Operating time = ∞

Distance (feet)	*Times After Shutdown*					
	1 hour	*2 hours*	*1 day*	*1 week*	*1 month*	*100 days*
1,000	337	296	179	115	56	19
2,000	17	15	10	5.7	2.5	0.73
3,000	1.4	1.2	0.62	0.44	0.17	0.035
4,000	0.15	0.13	0.063	0.046	0.016	0.0024
5,000	0.018	0.015	0.0072	0.0054	0.0017	0.00021
6,000	0.0025	0.0021	0.00098	0.00074	0.00023	0.000023

TABLE 3

INTEGRATED GAMMA DOSES (r) FOR VARIOUS TIMES AFTER SHUTDOWN, INFERRED FROM NDA-27-39

Reactor power = 500,000 kw

Operating time = ∞

Distance (feet)	Exposure Times Beginning at Shutdown					
	1 hour	2 hours	1 day	1 week	1 month	100 days
1,000	360	670	4,700	24,000	75,000	120,000
2,000	18	34	220	1,200	3,400	5,000
3,000	1.5	2.8	16	89	270	340
4,000	0.16	0.30	1.6	9.2	28	31
5,000	0.020	0.037	0.19	1.1	3.3	3.4
6,000	0.0027	0.0051	0.025	0.15	0.44	0.45

ing the 100 days following shutdown would, then, be 10^{17} ergs. From NDA-27-39, it was estimated that the total energy emitted under the same circumstances was about 2×10^{19} ergs. It would appear, then, that the omission of Cs^{137} would have little effect on gamma doses during the first 100 days.

Discussion of Costs

Figures 8 and 9 show a comparison of gamma dose rates and population as functions of distance for the hypothetical reactor site described in appendix B.

For this contained fission product radiation levels would appear to be unimportant beyond about 6,000 feet, the integrated dose during the first 100 days being less than one roentgen. Thus, it was assumed that, most probably, much less than about 300 people would be affected according to figure 9. Unfortunately, integrated doses beyond 100 days after shutdown were not easily obtained from the NDA compilation, and the estimation of accident costs was hampered somewhat by the lack of long-term integrated doses. Figure 10 indicates that the bulk of the integrated dose would be obtained in about the first month. A rough estimate of the dose rates at 1,000 days, however, indicated that the radiation levels from 100 to 1,000 days would be reduced by a factor of about 60 at 1,000 feet and about 10 at 6,000 feet.

The evacuation costs are the same as those discussed in appendix G. In order to prevent further radiation damage, it would, of course, be necessary to evacuate at least those persons who could get 50 r or more in 3 months (approximately 100 days) if they stayed. It should be pointed out that, for the purposes of this report, it was necessary to set up some sort of division between areas to be evacuated and areas in which evacuation is unnecessary. Consequently, inconsistencies as to the doses received by persons at the division line may occur. Actually, the areas to be evacuated would be determined by measurements of radioactivity, and such inconsistencies would be avoided.

For the purposes of this report, it was assumed that before re-entry would be permitted, the maximum dose rate which could be received by persons moving back into the area would not exceed 0.3 r-week.

In estimating the accident costs, a site radius of 2,000 feet was assumed.

Finally, it was assumed either that (*a*) 2 hours elapsed before an evacuation was completed; or that (*b*) 24 hours elapsed. The calculated results are shown in tables 4 and 5.

If only the volatile fission products were released into the reactor container, gamma radiation levels would of course be less and would decay more rapidly than in the case just discussed. However, the areas requiring evacuation would not be reduced as much as the proportional reduction in the curie content.

Conclusions

To summarize, it would appear reasonable to say that the total cost of the contained accident would quite probably be less than one million dollars. It should be stated that none of the preceding estimates accounted for the possible reduction of radiation levels by local shielding due to buildings and rough ground or self-shielding. Furthermore, it was assumed that all the fission products would remain suspended inside the container indefinitely. It should be noted that if one assumes sufficient isolation or the proper combination of isolation and shielding radiation damage to the public and consequent costs from a contained accident could be completely eliminated.

TABLE 4

2 HOUR EVACUATION — 2,000-FT. SITE BOUNDARY

Personal Injury

	Number of persons
A. Lethal exposure (over 450 r)	....
B. Injury likely (100-450 r)	....
C. Injury unlikely, observation likely (25-100 r).	1

Evacuation Costs

No. of persons	*Area*	*Cost*
67	1.8 sq. mile	$335,000

The use of the infinite medium treatment in calculating the radiation levels might result in a tendency to underestimate the radiation levels which would be expected from a fission product source near the ground. Although no data were found to permit evaluation of the underestimation, it can be said that the errors in the assumptions tend to cancel each other.

As stated earlier, in passing, the radiation levels due to a volatile fission product release into the container were not calculated, but it can safely be assumed that property damage costs would be less than those summarized above.

TABLE 5

24 HOUR EVACUATION — 2,000-FT. SITE BOUNDARY

Personal Injury

	Number of person
A. Lethal exposure (over 450 r)..........	......
B. Injury likely (100-450 r)..............	6
C. Injury unlikely, observation likely (25-100 r).........................	15

Evacuation Costs

No. of persons	*Area*	*Cost*
67	1.8 sq. mile	$335,000

FIGURES

FIGURE 1. Gamma dose rates one hour after shutdown for different reactor operating times (τ_0) (inferred from NDA-27-39).

FIGURE 2. Gamma dose rates one day after shutdown for different reactor operating times (τ_0) inferred from NDA-27-39).

FIGURE 3. Gamma dose rates 30 days after shutdown for different reactor operating times (τ_0) inferred from NDA-27-39).

FIGURE 4. Gamma dose rates 100 days after shutdown for different reactor operating times (τ_0) (inferred from NDA-27-39).

FIGURE 5. Gamma dose rates due to the contained fission products (inferred from NDA-27-39).

FIGURE 6. Integrated gamma doses due to the contained fission products (inferred from NDA-27-39).

FIGURE 7. Integrated gamma doses due to the contained fission products (inferred from NDA-27-39).

FIGURE 8. Comparison of gamma dose rates and population as functions of distance.

FIGURE 9. Comparison of integrated gamma doses and population as functions of distance.

FIGURE 10. Integrated gamma dose as a function of exposure time and distance.

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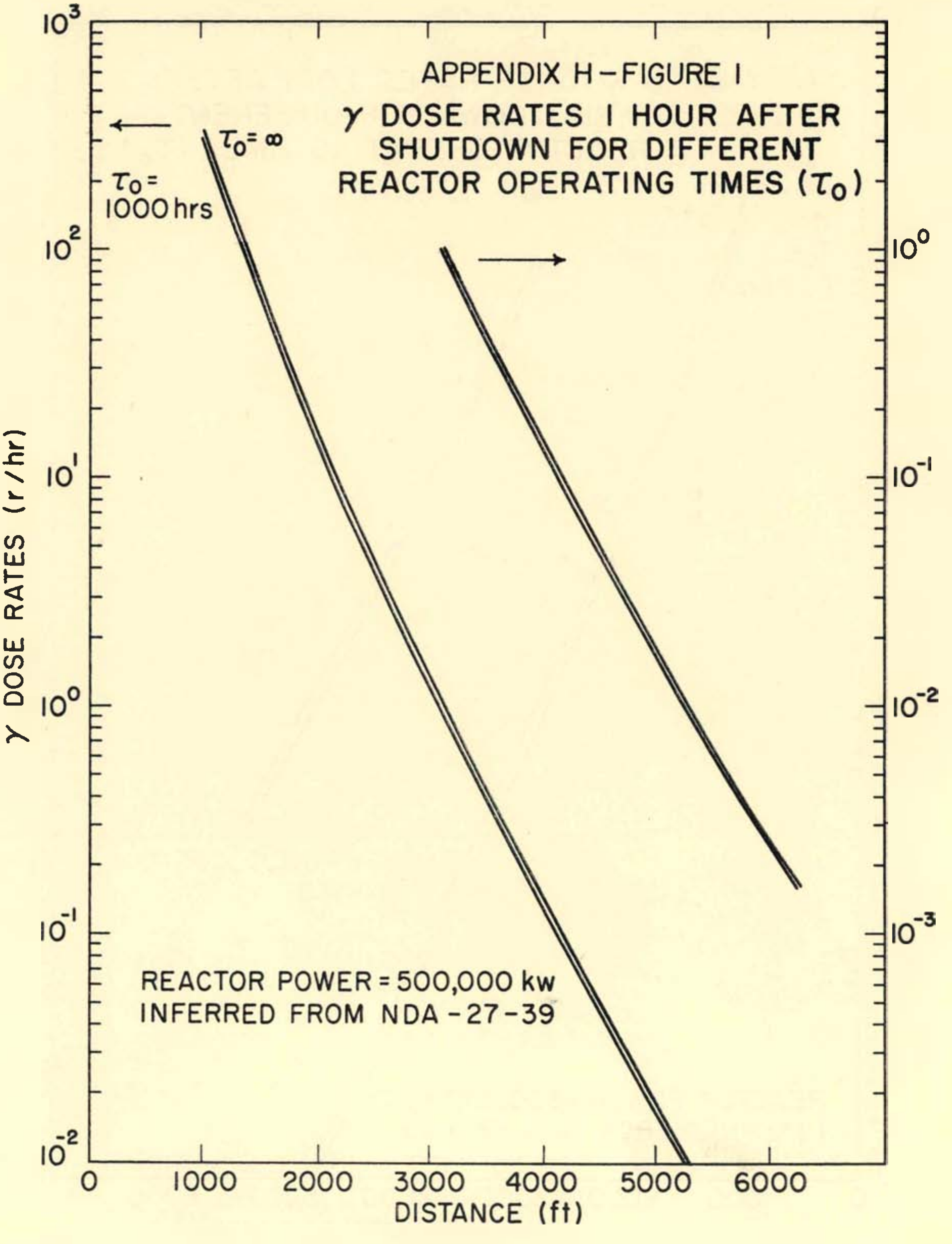
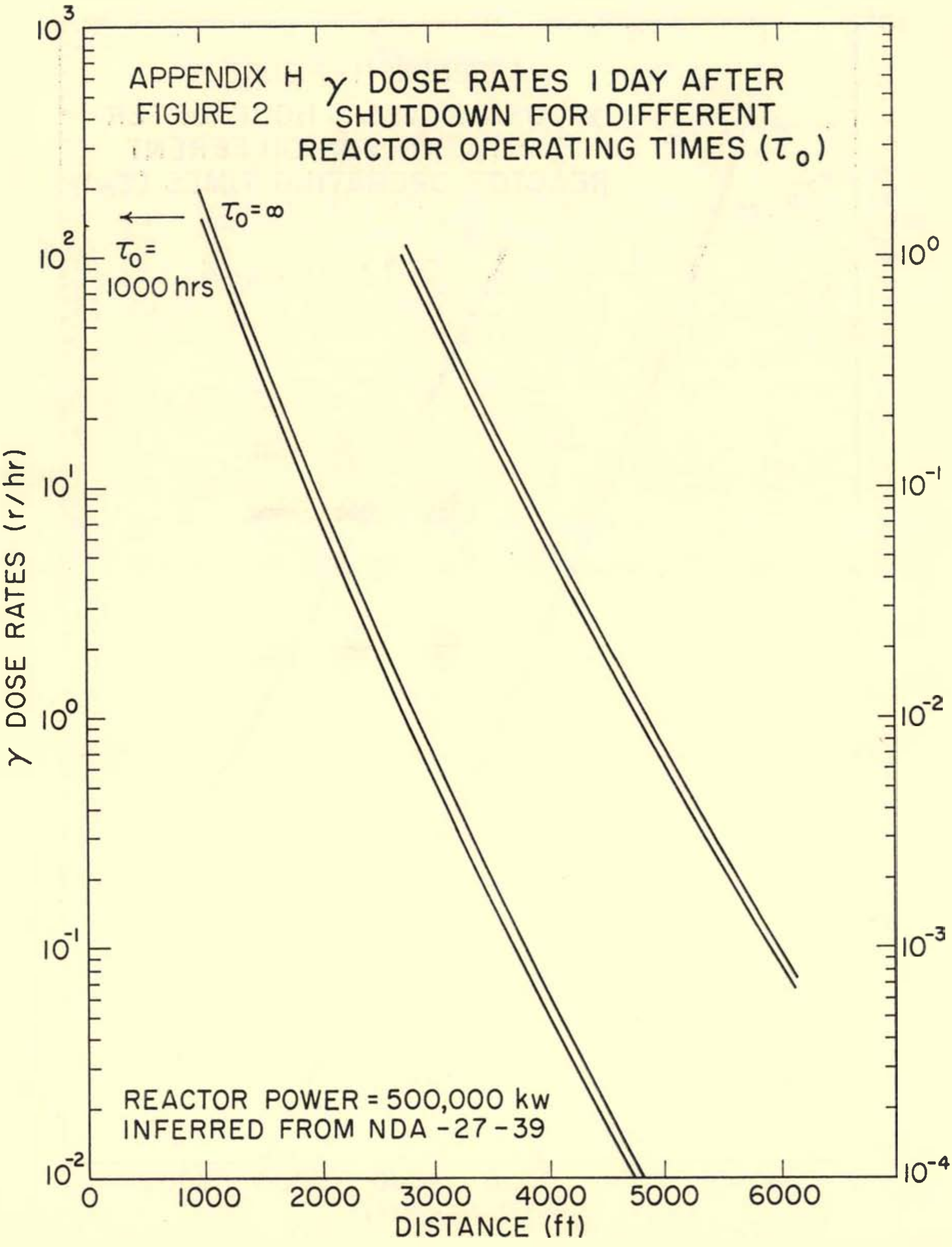
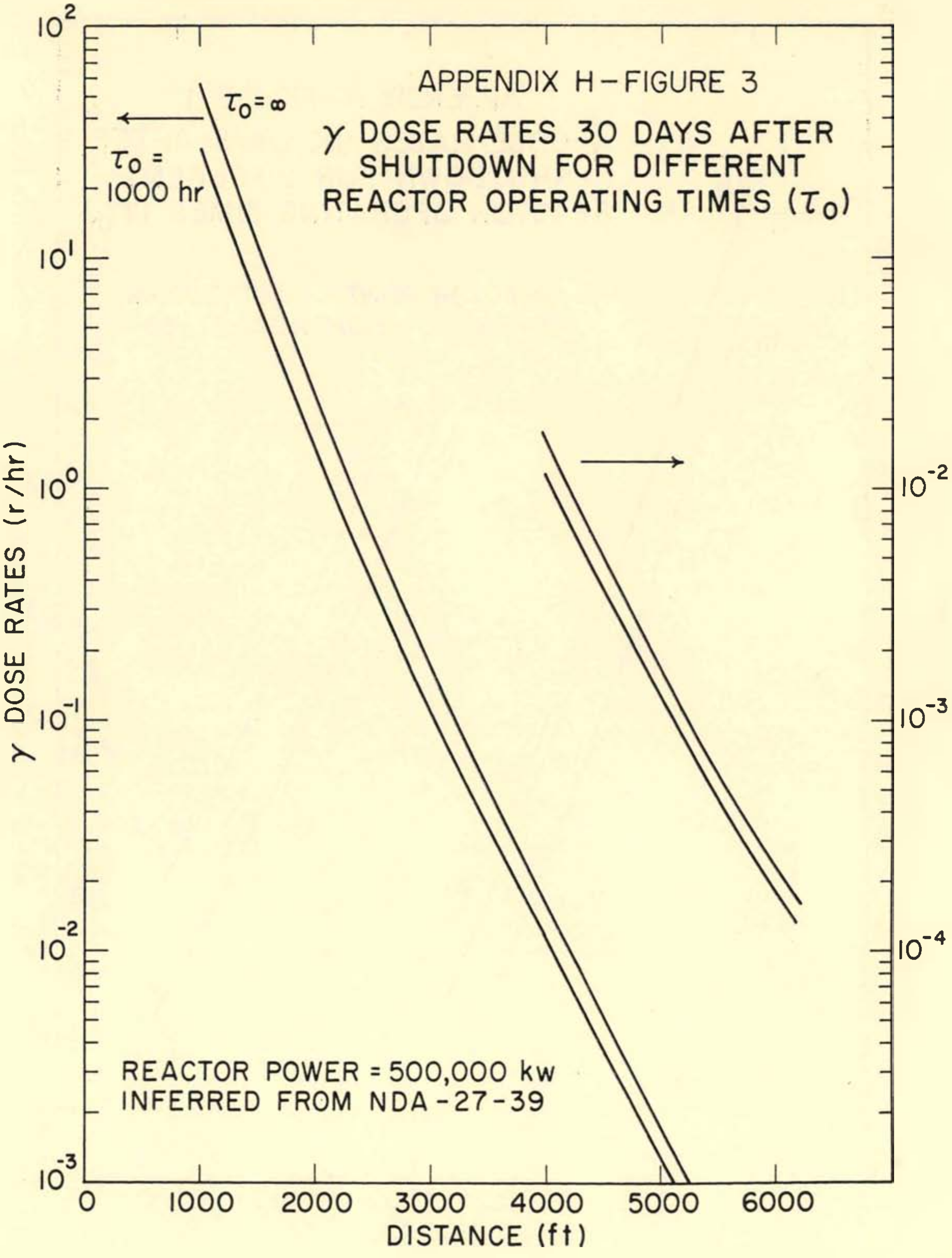
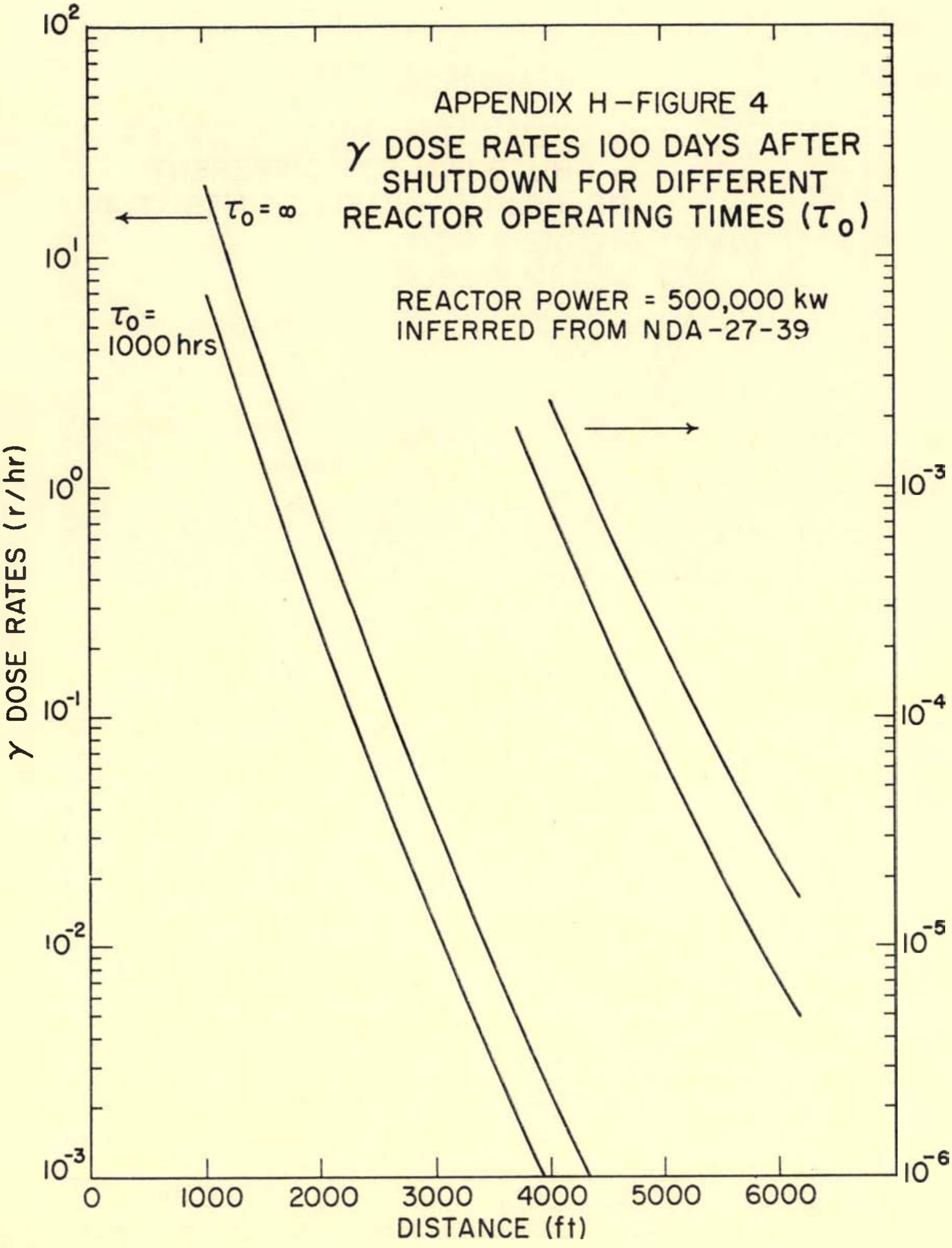
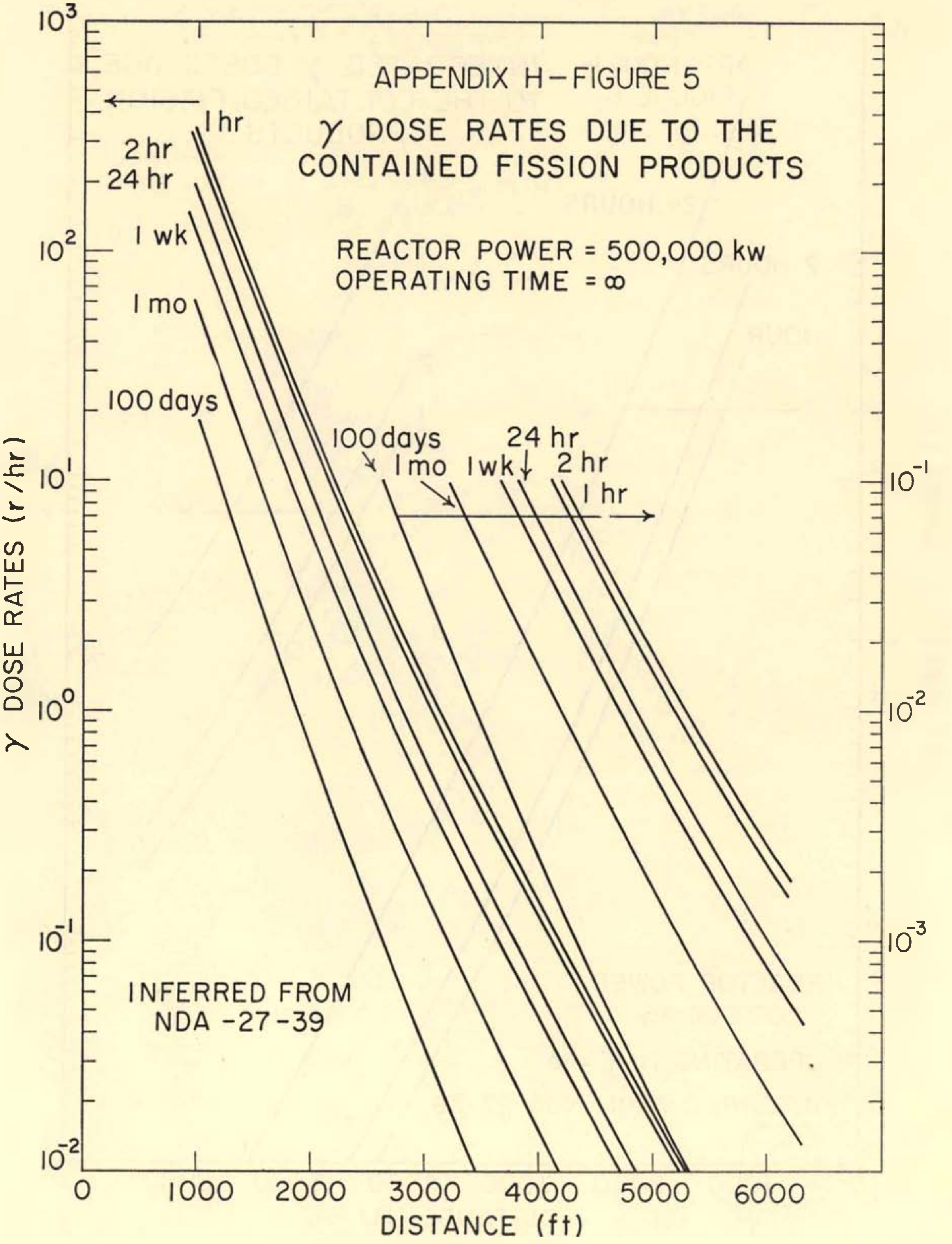
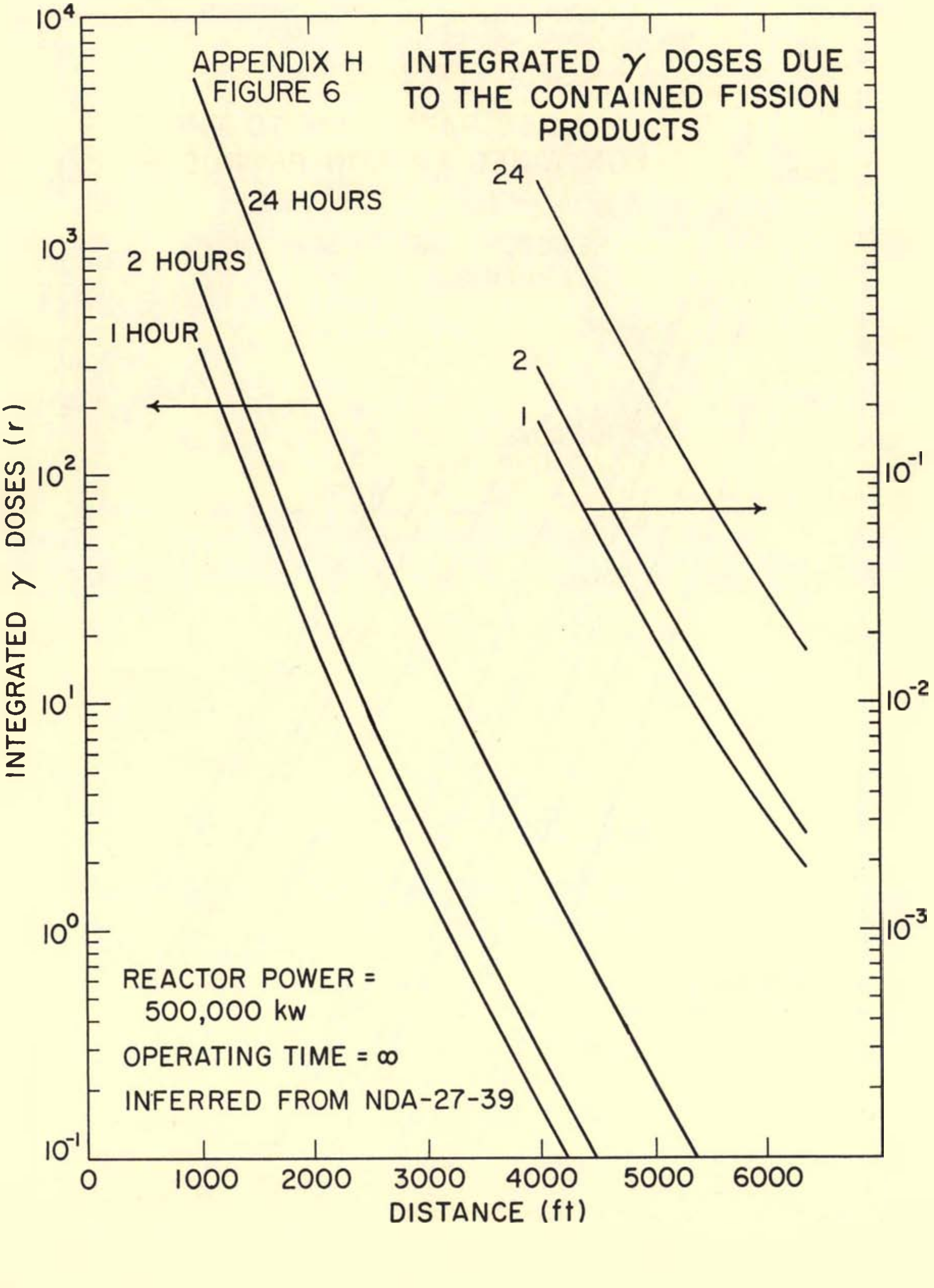

APPENDIX H – FIGURE I
γ DOSE RATES I HOUR AFTER SHUTDOWN FOR DIFFERENT REACTOR OPERATING TIMES (τ₀)
τ₀ = ∞
τ₀ = 1000 hrs
REACTOR POWER = 500,000 kw
INFERRED FROM NDA-27-39
γ DOSE RATES (r/hr)
DISTANCE (ft)
0
1000
2000
3000
4000
5000
6000
10^3
10^2
10^1
10^0
10^-1
10^-2
10^-3

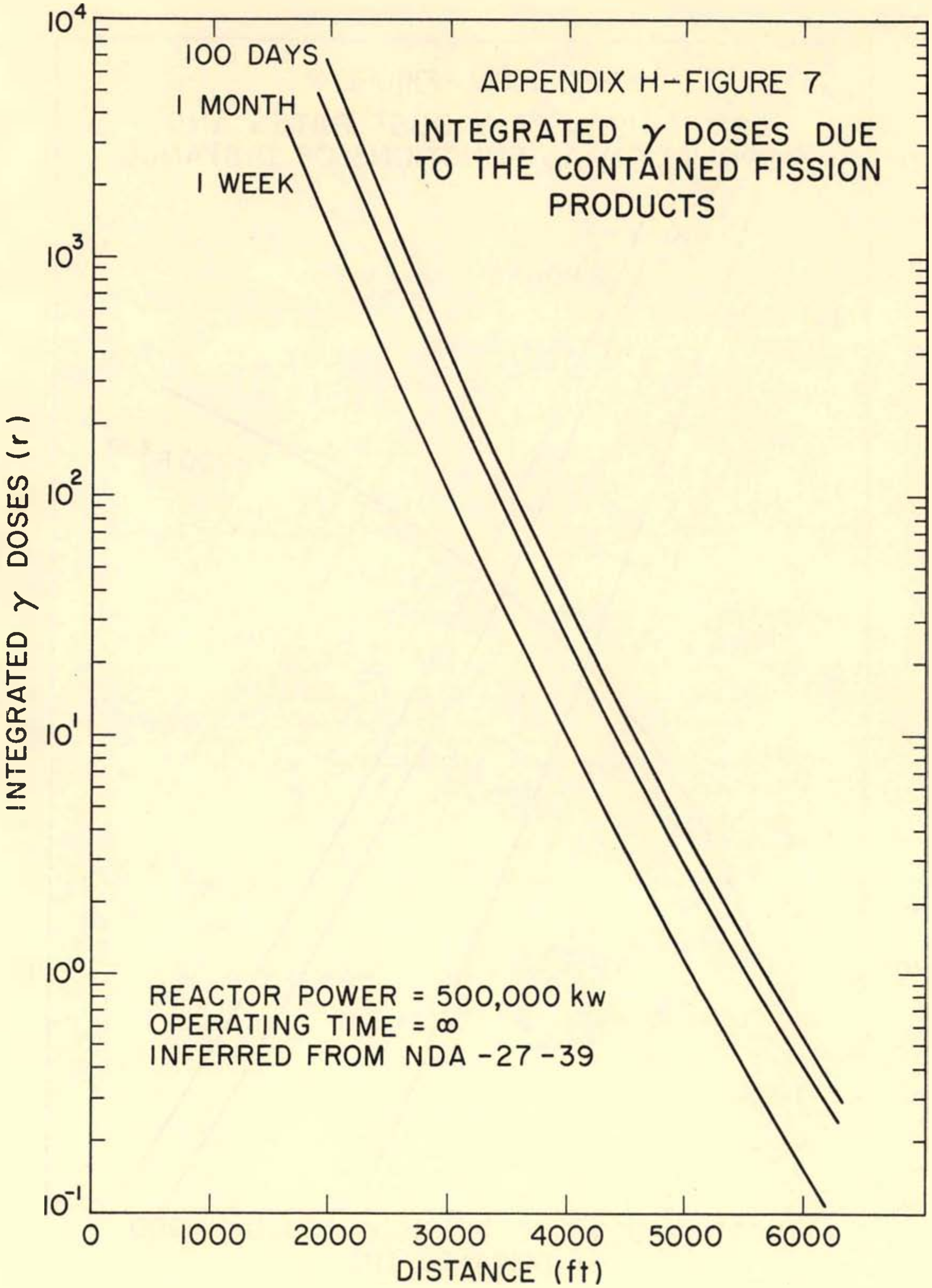

APPENDIX H
FIGURE 2
γ DOSE RATES 1 DAY AFTER SHUTDOWN FOR DIFFERENT REACTOR OPERATING TIMES (τ0)
τ0 = ∞
τ0 = 1000 hrs
REACTOR POWER = 500,000 kw
INFERRED FROM NDA-27-39
γ DOSE RATES (r/hr)
DISTANCE (ft)
0
1000
2000
3000
4000
5000
6000
10^3
10^2
10^1
10^0
10^-1
10^-2
10^0
10^-1
10^-2
10^-3
10^-4


APPENDIX H-FIGURE 3
γ DOSE RATES 30 DAYS AFTER SHUTDOWN FOR DIFFERENT REACTOR OPERATING TIMES (τ0)
τ0 = ∞
τ0 = 1000 hr
REACTOR POWER = 500,000 kw
INFERRED FROM NDA-27-39
γ DOSE RATES (r/hr)
DISTANCE (ft)
0
1000
2000
3000
4000
5000
6000
10^2
10^1
10^0
10^-1
10^-2
10^-3
10^-4

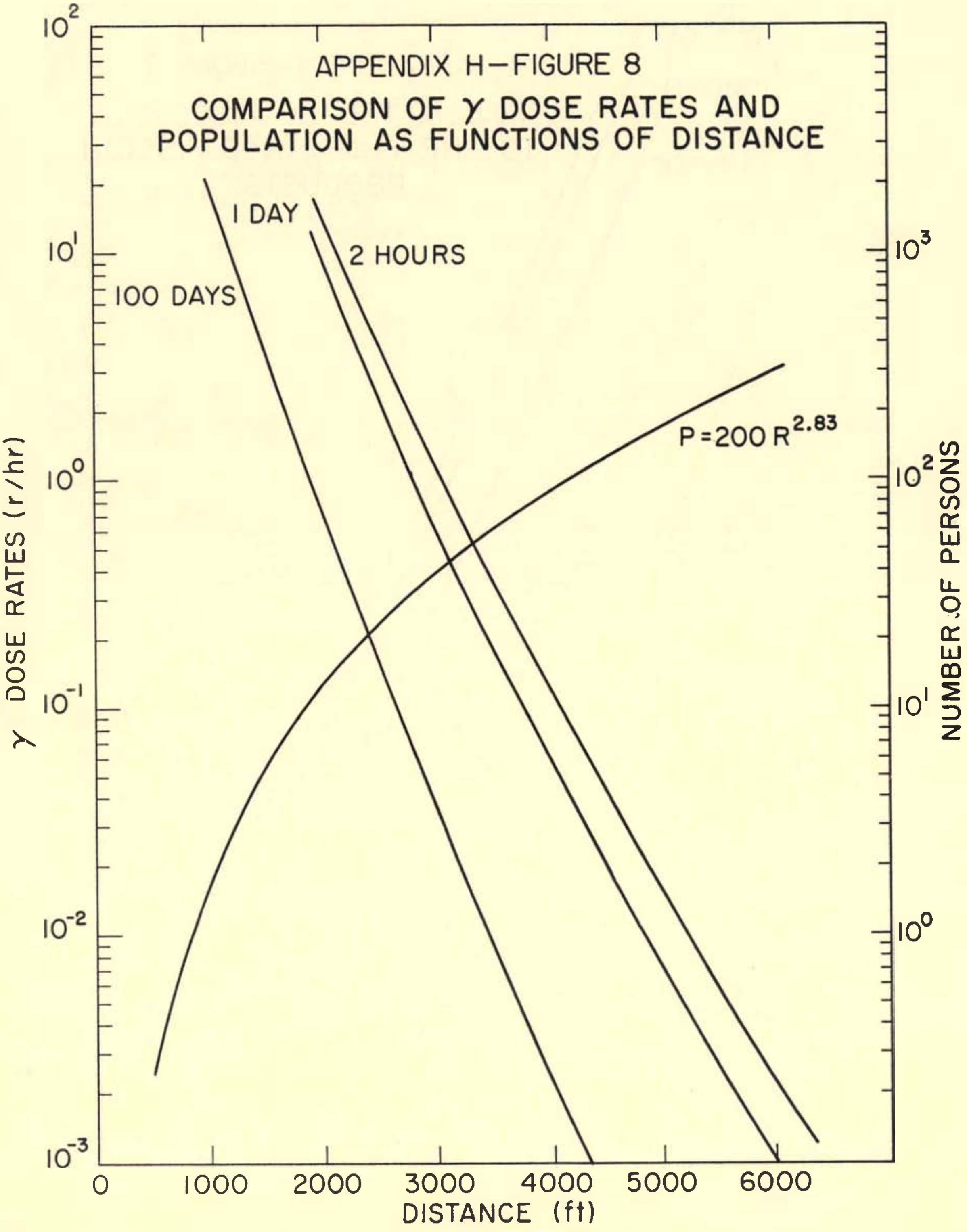

APPENDIX H-FIGURE 4
γ DOSE RATES 100 DAYS AFTER SHUTDOWN FOR DIFFERENT REACTOR OPERATING TIMES (τ_0)
REACTOR POWER = 500,000 kw
INFERRED FROM NDA-27-39
$\tau_0 = \infty$
$\tau_0 =$ 1000 hrs
γ DOSE RATES (r/hr)
DISTANCE (ft)
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
0
1000
2000
3000
4000
5000
6000

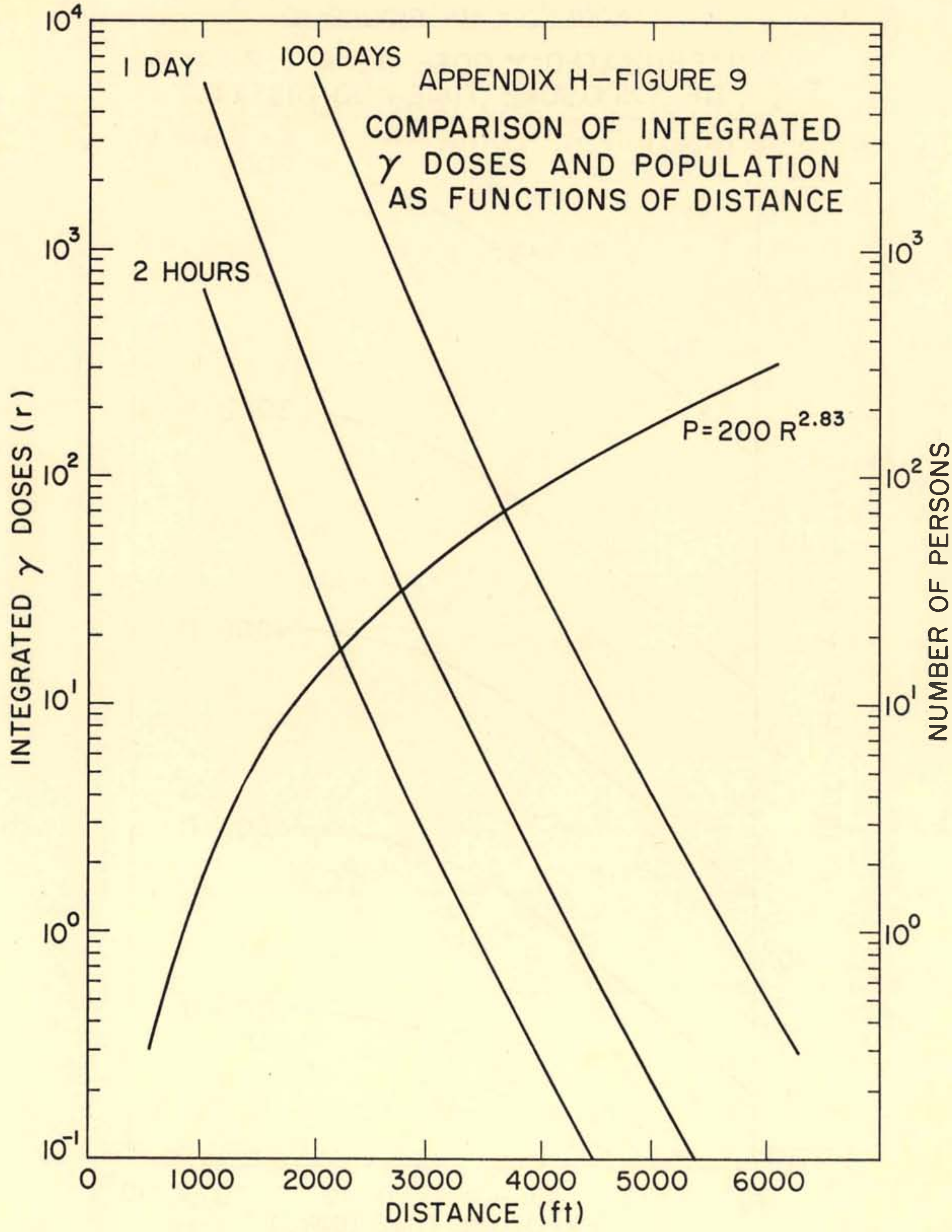

APPENDIX H-FIGURE 5
γ DOSE RATES DUE TO THE CONTAINED FISSION PRODUCTS
REACTOR POWER = 500,000 kw
OPERATING TIME = ∞
INFERRED FROM NDA-27-39
1 hr
2 hr
24 hr
1 wk
1 mo
100 days
γ DOSE RATES (r/hr)
DISTANCE (ft)
0
1000
2000
3000
4000
5000
6000
10^3
10^2
10^1
10^0
10^-1
10^-2
10^-3


APPENDIX H
FIGURE 6
INTEGRATED γ DOSES DUE TO THE CONTAINED FISSION PRODUCTS
24 HOURS
2 HOURS
1 HOUR
24
2
1
REACTOR POWER = 500,000 kw
OPERATING TIME = ∞
INFERRED FROM NDA-27-39
INTEGRATED γ DOSES (r)
DISTANCE (ft)
0
1000
2000
3000
4000
5000
6000
10^4
10^3
10^2
10^1
10^0
10^-1
10^-1
10^-2
10^-3



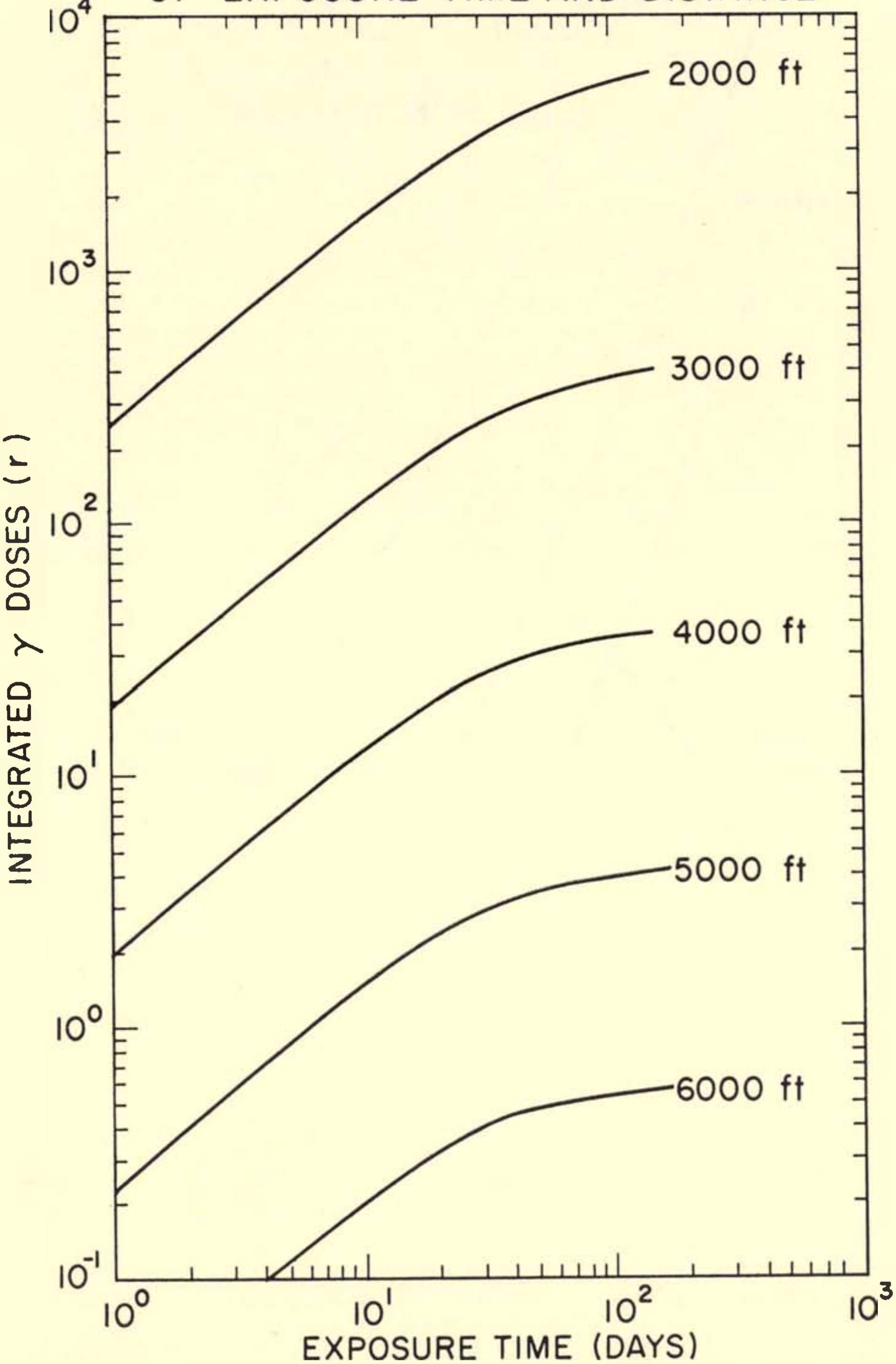
APPENDIX H-FIGURE 7
INTEGRATED γ DOSES DUE TO THE CONTAINED FISSION PRODUCTS
100 DAYS
1 MONTH
1 WEEK
REACTOR POWER = 500,000 kw
OPERATING TIME = ∞
INFERRED FROM NDA-27-39
INTEGRATED γ DOSES (r)
10^4
10^3
10^2
10^1
10^0
10^{-1}
0
1000
2000
3000
4000
5000
6000
DISTANCE (ft)


APPENDIX H—FIGURE 8
COMPARISON OF γ DOSE RATES AND POPULATION AS FUNCTIONS OF DISTANCE
1 DAY
2 HOURS
100 DAYS
P=200 R^2.83
γ DOSE RATES (r/hr)
NUMBER OF PERSONS
DISTANCE (ft)
0
1000
2000
3000
4000
5000
6000
10^2
10^1
10^0
10^-1
10^-2
10^-3
10^3
10^2
10^1
10^0


APPENDIX H–FIGURE 9
COMPARISON OF INTEGRATED γ DOSES AND POPULATION AS FUNCTIONS OF DISTANCE
1 DAY
100 DAYS
2 HOURS
P=200 R^2.83
INTEGRATED γ DOSES (r)
NUMBER OF PERSONS
DISTANCE (ft)
10^4
10^3
10^2
10^1
10^0
10^-1
0
1000
2000
3000
4000
5000
6000

APPENDIX H - FIGURE 10

INTERGRATED γ DOSE AS A FUNCTION OF EXPOSURE TIME AND DISTANCE



Appendix I

Personal and Property Damage Resulting from Release of Fission Products from a 500,000—tkw Reactor

The estimates of personal injury to the public and other off-site losses resulting from a maximum accident contained within the reactor shell are discussed in the previous section. Here, the non-contained case is considered. Many more variables must be considered; therefore, the results cannot be simply stated nor presented in terms of a few figures.

The reactor considered is the 500,000-kw (thermal) power reactor which has operated for 180 days previous to the occurrence of the accident.

Two cases of fission product release are considered:

1. Volatile—All of the noble gases and iodines plus 1 percent of the strontium-90
2. Major—50 percent of the gross fission product content of the reactor

Two release temperatures are considered:

1. Cold—Normal atmospheric temperatures
2. Hot—Approximately 3,000° F.

Two typical distributions of released particle size are considered. They are described by their median diameters:

1. 1μ—Characteristic of a fume
2. 7μ—Characteristic of industrial dust

Combinations of two different meteorological variations are considered:

1. Day or Night
   a. Day—Normal lapse conditions
   b. Night—Temperature inversion conditions
2. Dry or Wet
   a. Dry—No rain
   b. Rain—Light (0.02 in./hr)

Justification for selection of these several factors is found in preceding Appendices.

The evaulation of personal injury and other loss is summarized in the following tables. The symbols used are explained as follows:

Major release = 50 percent of all fission products released

Volatile release = Xe + Kr + I + Br released

Cold = Cloud emerges at ambient temperature

Hot = Cloud emerges at 3,000° F.

Day = Cloud released during lapse

Night = Cloud released during inversion

Rain = 0.02 in./hr rainfall rate

7μ = Cloud composed of a log normal particle distribution with a 7μ mass median

1μ = Cloud composed of a log normal particle distribution with a 1μ mass median

R = Distance of furthest boundary of category or range from reactor (miles)

P = Number of people in category or range

$ = Liability in category or range (liability per person times number of people), in millions of dollars

W = Width of cloud at city (miles)

A = Lethal exposure category

B = Sickness category

C = Some liability category

I = Urgent evacuation range

II = Evacuation range

III = Living restriction range

IV = Farming restriction range

a = Area in square miles in range IV

% = Meteorological probability of occurrence

TABLE 1

MAJOR RELEASE: COLD—1μ MASS MEDIAN PARTICLE SIZE

Personal Damage

		Day		Night	
		Rain	*Dry*	*Rain*	*Dry*
A — Lethal exposure	R(mi)	0.93	1.0	15.5	15.5
	Persons	5.0	6	3,400	3,400
B — Injury likely	R(mi)	2.2	2.3	40	44
	Persons	53	57	34,000	42,500
C — Injury unlikely	R(mi)	7.8	8.1	124	205
Observation likely	Persons	1,500	1,680	120,000	182,000
City — Interaction in category		....	....	C	B
	Persons	....	....	20,000	165,000

Property Damage and Dislocating Expense

		Day Rain	Day Dry	Night Rain	Night Dry
I. Urgent evacuation	R(mi)	15.5	0.9	100	16
	A(sq.mi)	15.8	....	92	3.4
	Persons	9,500	.3	66,000	3,700
II. Total evacuation	R(mi)	118	2.5	320	72
	A(sq.mi)	700	.54	760	54
	Persons	365,000	260	460,000	48,000
	$ Million	1,800	1.3	2,300	240
III. Restrictions on land and outdoor activity	R(mi)	410	9.1	620	340
	A(sq.mi)	7,700	6.2	2,180	790
	Persons	3,300,000	2,900	1,200,000	410,000
	$ Million	2,500	2.3	800	310
IV. Restrictions on farming, use of crops.	R(mi)	1,060	34	870	1,500
	A(sq.mi)	45,000	69	3,800	10,200
	$ Million	1,100	1.7	97	255
Total loss (II+III+IV)	$ Million	5,400	5.3	3,200	805
Percent of time for particular meteorological cond't.		13	37	2	48
City — Interaction in range		III	....	II	II
	Persons	580,000	....	25,000	100,000
	$ Million	58	....	125	500
Percent of time for particular meteorological cond't.		1	3	1	11

TABLE 2

MAJOR RELEASE: COLD—7μ MASS MEDIAN PARTICLE SIZE

Personal Damage

		Day		*Night*	
		Rain	*Dry*	*Rain*	*Dry*
A — Lethal exposure	R(mi)	0.9	1.0	8.1	5.9
	Persons	5	6	600	275
B — Injury likely	R(mi)	1.9	2.0	18.	14.3
	Persons	35	36	4,500	2,700
C — Injury unlikely	R(mi)	5.1	7.1	37	50
Observation likely	Persons	490	1,000	32,000	35,000
City — Interaction in category		...	...	C	C
	Persons	.0	.0	40,000	92,000

Property Damage and Dislocating Expense

		Day Rain	*Day Dry*	*Night Rain*	*Night Dry*
I. Urgent evacuation	R(mi)	35	6.8	50	30
	A(sq.mi)	80	3.8	28	12.1
	Persons	80,000	300	35,000	19,000
II. Total evacuation	R(mi)	75	23.6	93	100
	A(sq.mi)	300	37	81	91
	Persons	170,000	29,500	80,000	68,000
	$ Million	850	147	400	340
III. Restrictions on land and outdoor activity.	R(mi)	140	81	170	310
	A(sq.mi)	1,000	360	230	680
	Persons	450,000	203,000	175,000	350,000
	$ Million	330	152	131	260
IV. Restrictions on farming, use of crops.	R(mi)	224	280	330	1,100
	A(sq.mi)	2,300	3,700	745	5,800
	$ Million	57	93	18.6	145
Total loss (II+III+IV)	$ Million	1,240	390	550	750
Percent of time for particular meteorological cond't.		13	37	2	48
City — Interaction in range		III	III	III	II
	Persons	715,000	590,000	84,000	160,000
	$ Million	71	59	8.4	800
Percent of time for particular meteorological cond't.		1	3	1	11

TABLE 3

MAJOR RELEASE: HOT—1μ MASS MEDIAN PARTICLE SIZE

Property Damage and Dislocating Expense

		Day		Night	
		Rain	*Dry*	*Rain*	*Dry*
I. Urgent evacuation	R(mi)	4.5	0	27	0
	A(sq.mi)	1.6	0	9.5	0
	Persons	370	0	13,500	0
II. Total evacuation	R(mi)	58	0	335	0
	A(sq.mi)	190	0	750	0
	Persons	132,000	0	400,000	0
	$ Million	660	0	2,000	0
III. Restrictions on land and outdoor activity.	R(mi)	450	0	1,200	0
	A(sq.mi)	8,200	0	7,000	0
	Persons	3,800,000	0	3,600,000	0
	$ Million	2,850	0	2,700	0
IV. Restrictions on farming, use of crops.	R(mi)	2,200	1.8→16.8	3,100	69→550
	A(sq.mi)	150,000	18	38,000	1,800
	$ Million	3,750	.45	960	45
Total Loss (II+III+IV)	$ Million	7,200	.45	5,700	45
Percent of time for particular meteorological cond't.		13	37	2	48
City — Interaction in range		III	...	III	...
	Persons	400,000	0	195,000	0
	$ Million	40	0	20	0
Percent of time for particular meteorological cond't.		1	3	1	11

NOTE: There is no personal damage for this case.

TABLE 4

MAJOR RELEASE: HOT—7μ MASS MEDIAN PARTICLE SIZE

Property Damage and Dislocating Expense

		Day		Night	
		Rain	*Dry*	*Rain*	*Dry*
I. Urgent evacuation	R(mi)	37	0	93	0
	A(sq.mi)	82	....	82	....
	Persons	85,000	0	63,000	0
II. Total evacuation	R(mi)	118	1.9→14	220	0
	A(sq.mi)	680	14	370	0
	Persons	365,000	7,600	200,000	0
	$ Million	1,825	38	1,000	0
III. Restrictions on land and outdoor activity.	R(mi)	230	1.4→55	360	60→450
	A(sq.mi)	2,400	170	900	1,300
	Persons	1,150,000	122,000	450,000	580,000
	$ Million	864	92	340	435
IV. Restrictions on farming, use of crops.	R(mi)	420	10.5→192	590	45→1,800
	A(sq.mi)	7,920	1,800	2,000	15,000
	$ Million	200	45	50	375
Total loss (II+III+IV)	$ Million	2,900	175	1,390	810
Percent of time for particular meteorological cond't.		13	37	2	48
City — Interaction in range		II	III	II	
	Persons	55,000	435,000	120,000	0
	$ Million	265	43.5	600	0
Percent of time for particular meteorological cond't.		1	3	1	11

NOTE: There is no personal damage for this case.

TABLE 5

VOLATILE RELEASE: NO Sr.—1μ MASS MEDIAN PARTICLE SIZE

Personal Damage

		Day		Night	
		Rain	*Dry*	*Rain*	*Dry*
A — Lethal exposure	R(mi)	.62	.62	9.3	9.3
	Persons	1.6	1.6	880	880
B — Injury likely	R(mi)	1.5	1.5	24.8	26
	Persons	18.5	18.5	11,300	13,000
C — Injury unlikely	R(mi)	4.9	4.9	84	109
Observation likely	Persons	420	420	71,000	96,000
City — Interaction in category		....	....	C	C
	Persons	0	0	11,000	58,000

Property Damage and Dislocating Expense

		Day Rain	Day Dry	Night Rain	Night Dry
I. Urgent evacuation	R(mi)	5.9	.4	49	8.7
	A(sq.mi)	2.9	.03	27.5	1.2
	Persons	710	.8	41,000	730
	$ Million	3.5	....	205	3.6
Percent of time for particular weather conditions.		13	37	2	48

NOTE: No interaction for Ranges II, III, IV, nor in city for any Range.

TABLE 6

VOLATILE RELEASE: NO Sr—7μ MASS MEDIAN PARTICLE SIZE

Personal Damage

		Day		Night	
		Rain	*Dry*	*Rain*	*Dry*
A — Lethal exposure	R(mi)	.57	.59	6.2	4.3
	Persons	1.3	1.4	305	120
B — Injury likely	R(mi)	1.24	1.3	11.8	8.7
	Persons	10.6	12.2	1,600	800
C — Injury unlikely	R(mi)	3.5	4.5	28	30.4
Observation likely	Persons	170	340	15,300	18,000

Property Damage and Dislocating Expense

I. Urgent evacuation	R(mi)	26	4.2	37	19.2
	A(sq.mi)	43	1.6	16	5.0
	Persons	28,000	290	31,500	5,600
	$ Million	140	1.4	160	28
Percent of time for particular meteorological cond't.		13	37	2	48

NOTE: No interaction in Ranges II, III, IV, nor in city.

TABLE 7

VOLATILE RELEASE: WITH 1% Sr—1μ MASS MEDIAN PARTICLE SIZE

Personal Damage

		Day		*Night*	
		Rain	*Dry*	*Rain*	*Dry*
A — Lethal exposure	R(mi)	.62	.62	9.3	9.3
	Persons	1.6	1.6	880	880
B — Injury likely	R(mi)	1.5	1.5	24.8	26
	Persons	18.5	18.5	11,300	13,000
C — Injury unlikely	R(mi)	4.9	4.9	84	109
Observation likely	Persons	420	420	71,000	96,000
City — Interaction in category		...	...	C	C
	Persons	...	...	11,000	58,000

Property Damage and Dislocating Expense

		Day Rain	*Day Dry*	*Night Rain*	*Night Dry*
I. Urgent evacuation	R(mi)	5.9	.4	49	8.7
	A(sq.mi)	2.9	.03	27.5	1.2
	Persons	710	.8	41,000	730
	$ Million	3.5	0	205	3.6
III. Restrictions on land and outdoor activity.	R(mi)	60	1.5	211	43
	A(sq.mi)	200	.24	350	22
	Persons	182,000	19.5	235,000	36,000
	$ Million	137	.01	177	27
IV. Restrictions on farming, use of crops.	R(mi)	280	5.6	510	198
	A(sq.mi)	3,500	2.3	1,560	310
	$ Million	89	.06	39	7.7
Total loss	$ Million	230	.07	421	38.3
Percent of time for particular meteorological cond't.		13	37	2	48
City — Interaction in range		...	...	III	III
	Persons	0	0	20,000	24,000
	$ Million	0	0	2	2.4
Percent of time for particular meteorological cond't.		1	3	1	11

TABLE 8

VOLATILE RELEASE: WITH 1% Sr—7μ MASS MEDIAN PARTICLE SIZE

Personal Damage

		Day		Night	
		Rain	Dry	*Rain*	*Dry*
A — Lethal exposure	R(mi)	.57	.59	6.2	4.3
	Persons	1.3	1.4	305	120
B — Injury likely	R(mi)	1.24	1.3	11.8	8.7
	Persons	10.6	12.2	1,600	800
C — Injury unlikely	R(mi)	3.5	4.5	28	30.4
Observation likely	Persons	170	340	15,300	18,000

Property Damage and Dislocating Expense

		Day Rain	Day Dry	Night Rain	Night Dry
I. Urgent evacuation	R(mi)	26	4.2	37	19.2
	A(sq.mi)	43	1.6	16	5.0
	Persons	28,000	290	31,500	5,600
	$ Million	140	1.4	160	28
III. Restrictions on land and outdoor activity.	R(mi)	53	14.4	75	61
	A(sq.mi)	160	15	56	39
	Persons	155,000	8,000	63,000	51,000
	$ Million	116	6.0	47	38
IV. Restrictions on farming, use of crops.	R(mi)	100	49	137	198
	A(sq.mi)	520	140	164	310
	$ Million	13	3.5	4.1	7.7
Total loss	$ Million	269	10.9	211	73.7
Percent of time for particular meteorological cond't.		13	37	2	48
City — Interaction in range				III	III
	Persons	0	0	8,000	50,000
	$ Million	0	0	.8	5.0
Percent of time for particular meteorological cond't.		1	3	1	11

NOTE: No interaction in city for categories A, B, or C.