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ENVIRONMENTAL ANALYSIS OF NS "SAVANNAH" OPERATION AT CAMDEN

W. B. Cottrell
L. A. Mann
F. L. Parker
G. D. Schmidt

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REACTOR PROJECTS DIVISION

ENVIRONMENTAL ANALYSIS OF NS "SAVANNAH" OPERATION AT CAMDEN

W. B. Cottrell F. L. Parker
L. A. Mann G. D. Schmidt

Prepared for
Nuclear Merchant Ship Reactor Project
Maritime Reactors Branch
U.S. Atomic Energy Commission

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ABSTRACT

An analysis is presented of the accidental release of activity following the operation of the NS "Savannah" at the New York Shipbuilding Corporation docks in Camden, New Jersey. Although a number of accidents are considered, the report is primarily concerned with the environmental activity levels and subsequent exposures which would result from the "maximum credible accident." Two variations of the MCA are considered: one in which the activity is released to the atmosphere, and another in which the vessel sinks and releases activity to the water. In the former case, due to the exceptional containment afforded by the location of the contained pressurized-water reactor system within a ventilated ship's compartment, no person would receive more than 0.3 rem total integrated exposure, and the total population exposure would be 4060 man-rems or less. The analyses of the release of activity to the Delaware River were possible because of the existence of model data on river dispersions, and they revealed that the maximum concentrations only slightly exceeded the continuous occupational exposure levels. It is concluded from these analyses that the exposures which would ensue from potential accidents following the operation of the NS "Savannah" at Camden should not cause any undue hazard to the surrounding populace.

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ENVIRONMENTAL ANALYSIS OF NS "SAVANNAH" OPERATION AT CAMDEN

W. B. Cottrell L. A. Mann F. L. Parker[1] G. D. Schmidt[2]

1. INTRODUCTION AND SUMMARY

The NS "Savannah" was first proposed by President Eisenhower in 1955 as further evidence of this country's interest in the peaceful uses of atomic energy. In 1956, Congress authorized the program and provided funds for the design and construction of the vessel subsequently named the "Savannah."

On October 15, 1956, the President directed the Atomic Energy Commission and the Maritime Administration to proceed with its construction, and, to complement this effort, a Maritime Reactors Branch was established within the Atomic Energy Commission. The design of the vessel was contracted to the George G. Sharp Company of New York and that of the nuclear power plant and auxiliaries to the Babcock & Wilcox Company. Construction of the ship was contracted to the New York Shipbuilding Corporation, to be accomplished at their Camden, New Jersey, facility. The States Marine Corporation of Delaware has been selected as the operating agent for the ship. In the course of the program, many other contractors and subcontractors, including the Oak Ridge National Laboratory, have been involved in this effort.

It was decided that the vessel should be a combination cargo and passenger vessel with a displacement of approximately 20,000 tons which would perform as well as, if not better than, other vessels of this class. It was also intended from the start that the vessel should serve national good will, and it is expected to tour and to be displayed throughout the seaports of the world. In view of these requirements, there has been an effort to make this vessel as attractive and modern as any afloat and, in view of its nuclear power plant, to provide it with an exceptional degree of reliability and safety.

This report is not a design report, nor is it a complete hazards report. It is a vital part of a complete hazards analysis, but it is only that part of the analysis involving the consequences of the release of activity to the environment surrounding the proposed Camden, New Jersey, startup site. The sources of activity and, in some cases, particularly in the case of the maximum credible accident (MCA), the presumed mechanism for activity release have been defined by the Babcock & Wilcox Company.[3,4]

The NS "Savannah" is subject to most of the "conventional" reactor accidents and failures, and in addition is subject to all the hazards of a ship at sea. The designers of the vessel have been quite successful in an attempt to preclude the possibility that the reactor and ship hazards would be additive. The NS "Savannah" has been designed so that no ship accident in confined waters can induce the maximum credible reactor accident; however, it is still conceivable that such an accident could occur on the high seas.

This analysis of the consequences of release of activity to the environment surrounding the Camden site is unique in that the possibility of release to the hydrosphere has been as important a consideration as release to the atmosphere. The most significant information which permits the confident evaluation of the activity concentrations in the Delaware River following assumed releases at the site and elsewhere is provided by model tests of the dispersion of dye. Some model data were available from earlier tests by the U.S. Army Corps of Engineers on the model of the Delaware River at Vicksburg, and these have subsequently been extended through the joint efforts of D. W. Pritchard of Johns Hopkins University and the Corps of Engineers.

The ability to contain activity which might be released from the fuel in the event of a reactor accident is one of the most important features of any reactor system. The proposed design of the

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[1]Health Physics Division.

[2]On loan from U.S. Public Health Service.

[3]J. H. MacMillan (ed.), *Nuclear Merchant Ship Reactor Project Preliminary Safeguards Report*, BAW-1117, vol I (rev) (Dec. 22, 1958); vol II (Nov. 3, 1958).

[4]J. H. MacMillan (ed.), *Nuclear Merchant Ship Reactor Project Supplementary Information on Reactor Safeguards*, BAW-1150 (June 1, 1959).

nuclear plant aboard the NS "Savannah" will provide a degree of containment which is unexcelled by any power reactor in existence. In addition to the containment barriers inherently provided by the fuel cladding and the primary system, the plant is enclosed in a steel pressure-containment vessel, and this vessel in turn is located in an isolated hold of the ship (designated the reactor compartment) which is maintained at a negative pressure; the air in this hold is continuously filtered and discharged to the ship's stack. Thus the NS "Savannah" employs, in series, the two most effective "containment techniques" yet devised.

In undertaking this environmental analysis, the various possible accidents were first examined to be certain that the important or controlling hazards were considered. The resulting activity concentrations and the potential exposure as a consequence of the release of the activity to either the air or river water were estimated. The exposure information was then evaluated and related to the area and the persons affected in order to arrive at a comprehensive evaluation of the hazards associated with the release of activity.

The atmospheric releases following the MCA were evaluated for typical lapse and inversion conditions. The consequences of deposition and rainout, as well as release at ground level and stack height, both with and without the stack filter, were considered. While the resulting exposure data were evaluated both in terms of continuous exposure at the calculated concentration and in terms of the total integrated dose from continuous exposure over a 24-hr period, the latter is the more meaningful.

As previously noted, appropriate model data existed from which it was possible to determine the concentration of activity in the river as a function of both time and position for both a continuous and an instantaneous release. In view of the long half life for the residence of any contamination in a tidal estuary, it is fortunate that the activity concentrations that would be found in the water following the accidental release of activity would be low. As a consequence of the design and environmental safety features, it is not surprising that the off-site exposure following even the maximum credible reactor accident would also be very low. The total integrated dose from atmospheric contamination following this accident at the point of maximum ground concentration during the inversion condition is 200 mr, the maximum total exposure to the populace from such an incident is 4000 man-rems, and the consequent genetic dose to the populace of the United States is 2×10^{-5} rem. Were this same accident to release the activity to the river rather than to the atmosphere, the resulting maximum concentration (which would be temporary) would be less than a factor of 2 above the maximum permissible concentration (MPC) for continuous occupational exposure. This concentration level above MPC may persist for several days, but this peak does not occur near the intake of any municipal water supply.

These analyses are not without some uncertainties, such as the rate and the total fraction of activity release from the fuel, the fraction deposited before reaching the filter, the fraction removed by the filter, and the assumed meteorological conditions. The calculated exposures are so low, however, that increases by an order of magnitude would not significantly alter the argument. The reason for this is simple; the NS "Savannah" containment was not designed so as to preclude the possibility of any certain exposure as a result of its MCA, but rather to assure that the exposure would be as low as practical. The result, which is principally due to the location of the containment vessel in a volume from which the release of activity is directed through the ship's stack, has been the reduction of the possibilities of accidental exposures to exceptionally low values. This is extremely desirable for a vessel with the mission of the NS "Savannah," since it eliminates any technical basis for denying the NS "Savannah" access to the ports of the world.

While most of the foregoing conclusions have been based upon consideration of the MCA, the various accidents considered in this report include many that are less serious, all of which could result in the loss of some activity to the environment. No attempt has been made to consider all possible accidents individually; however, a variety of accidents representative of a number of different situations have been studied. In all instances the amount of activity release vs time for a particular accident was that given in Babcock & Wilcox Company reports.[3] Although in the initial stages of testing and operation the activity buildup in each of the various systems and components

will be far from the maximum design value, all analyses have been carried out by using the maximum activity levels except where otherwise stated. The accidents considered include the following: (1) inadvertent release of gaseous activity, (2) rupture of the double-bottom tanks, (3) spill of the ion exchange resin, (4) damage to a fuel element during refueling, (5) the MCA with the ship afloat, (6) the MCA with the ship sunk, and (7) variations of the MCA in which the containment vessel is voided.

The Babcock & Wilcox Company analysis[3] demonstrated that no accident occurring within the container could cause its rupture, while the George G. Sharp study[4] showed that no ship accident in confined waters could either rupture the containment vessel or initiate the MCA. Examination of the presumed course of the MCA reveals that a more serious accident is conceivable; that is, the containment vessel might be voided at the time of the MCA, either as a consequence of the same accident or otherwise. There are two instances in which this might happen, namely, (1) a ship collision on the high seas and (2) the containment vessel being opened too soon after shutdown.

The consequences of a collision on the high seas are beyond the scope of this report, but the consequences of such an incident may be evaluated from the data given herein. Since less than 2% of the world's merchant fleet is capable of causing such an accident, and could cause it only if the colliding ship were to strike the NS "Savannah" in the reactor compartment, the probability of such an accident is very small. The area seriously contaminated would be large but, in general, would be confined to the open sea.

On the other hand, if the reactor was shut down in port and the containment vessel was opened for maintenance, it is conceivable that the primary system might rupture and release activity directly from the open containment vessel to the atmosphere. The occurrence of such an accident must be precluded by an administrative procedure which would not permit the containment vessel to be opened until the reactor had been allowed to cool for a sufficient time so that in the subsequent event of a primary system rupture there would be time to reseal the containment vessel before fuel-element melting began to occur. This waiting time is a function of both reactor power and operating time, but fortunately it is sufficiently short in any case to not impose a serious restriction on ship maintenance.

In view of the extremely low exposures that would result following the MCA in which the activity might be released to either the atmosphere or the water, it is concluded that the operation of the NS "Savannah" in even as populous surroundings as the New York shipyard at Camden, New Jersey, should not cause any undue hazard to the public.

2. SITE DESCRIPTION

The NS "Savannah" is being built at the New York Shipbuilding Corporation shipyards in Camden, New Jersey. It is anticipated that the reactor critical experiments and dockside tests up to and including operation at full power will be conducted at this site.

As shown in Fig. 2.1, the city of Camden is located on the New Jersey shore of the Delaware River directly opposite Philadelphia, Pennsylvania, which is on the west bank of the river. The Delaware Estuary opposite the New York Shipbuilding shipyard is about 2200 ft wide and has an average depth of 25 ft at mean low water. Camden is upriver approximately 101 miles from the Atlantic Ocean and is approximately 120 miles northeast of Washington, 75 miles southwest of New York City, and 55 miles west across the state of New Jersey from the Atlantic Ocean. Although the river has some effect on the local meteorology, the Philadelphia-Camden area lies far enough inland from the Atlantic Ocean that diurnal land-sea breeze effects are not of consideration. Additional information on the meteorology of the site is given in Appendix B.

The location of the site on a tidal estuary poses a number of problems in environmental analysis with regard to the dispersion of activity accidentally released to the water. The potential area for water-borne contamination extends along the entire tidal reach of the river from Trenton, which is 35 miles upriver from Camden, to Delaware Bay, including areas adjacent to tidal tributaries. Detailed information on the hydrology of the surrounding area is given in Appendix E.

The general Philadelphia-Camden area is shown in more detail in Fig. 2.2. All cities with a population greater than 5000 and within a radius of approximately 30 miles of the site are shown, in addition to the county boundaries. The county population density varies from 17,700 per square mile for Philadelphia to 165 per square mile for Salem, averaging ~1125 per square mile for the entire area. Additional information on the cities of Camden and Philadelphia and the surrounding area is presented in Chap. 4, p 55.

An aerial photograph of the New York Shipbuilding Corporation yards at Camden and the surrounding area is shown in Fig. 2.3. The shipyards comprise approximately 160 acres of waterfront along Broadway in the southernmost part of Camden, New Jersey, at the confluence of the Delaware River and Newton Creek. The southern part of the yard, between Whitman Bridge and Newton Creek, is in Gloucester City. A site plan of the yards is shown in Fig. 2.4. The NS "Savannah" is being built in the southernmost covered shipway, designated as the "O" way.

Following launching in July 1959, the ship was floated into wet slip "H" at the northern end of the covered way. Prior to initial startup, it is expected that the ship will be moved to the outfitting basin, piers 1 and 2, approximately 450 ft south of the northernmost boundary of the yards.

Approximate distances of significant points, measured from the outfitting basin, are as follows:

	Site Boundary (ft)	Nearest Residential Area (ft)
North	450	1500
East	1000	1100
South	3400	3600
West		2100[1]

[1]Pennsylvania shore of Delaware River.

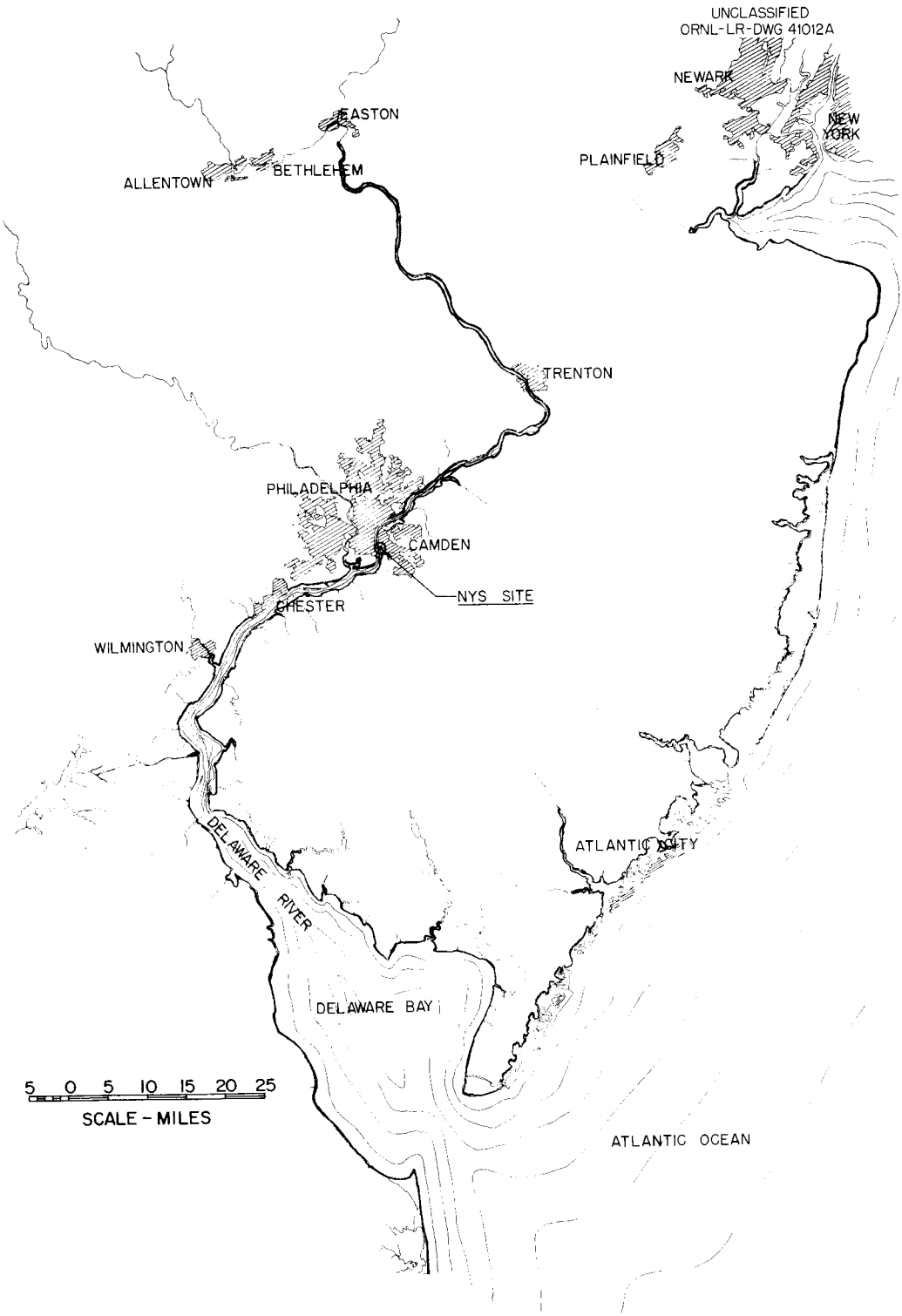

Fig. 2.1. Map of Lower Delaware River Valley.

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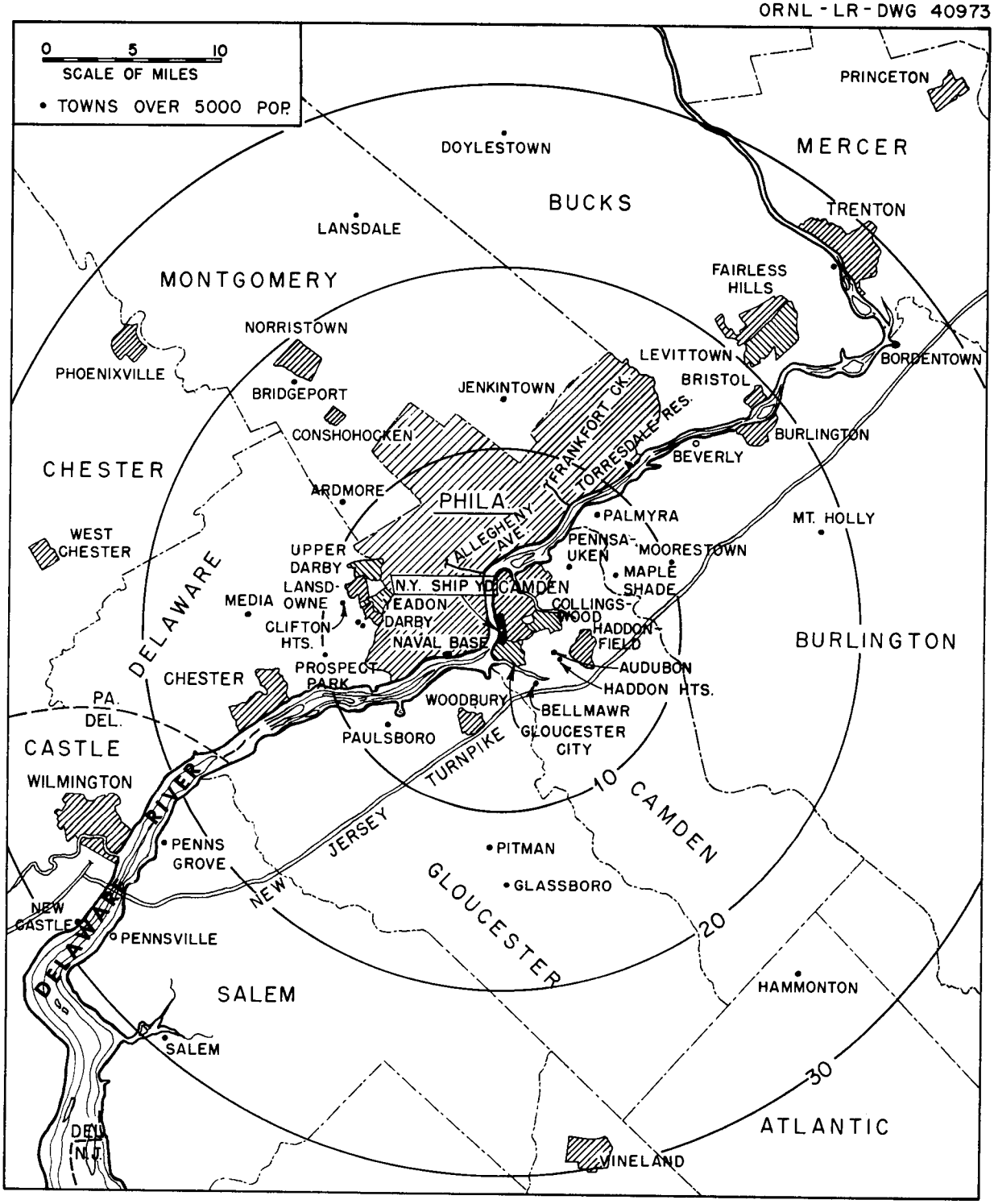

Fig. 2.2. Map of Philodelphio-Camden Area.

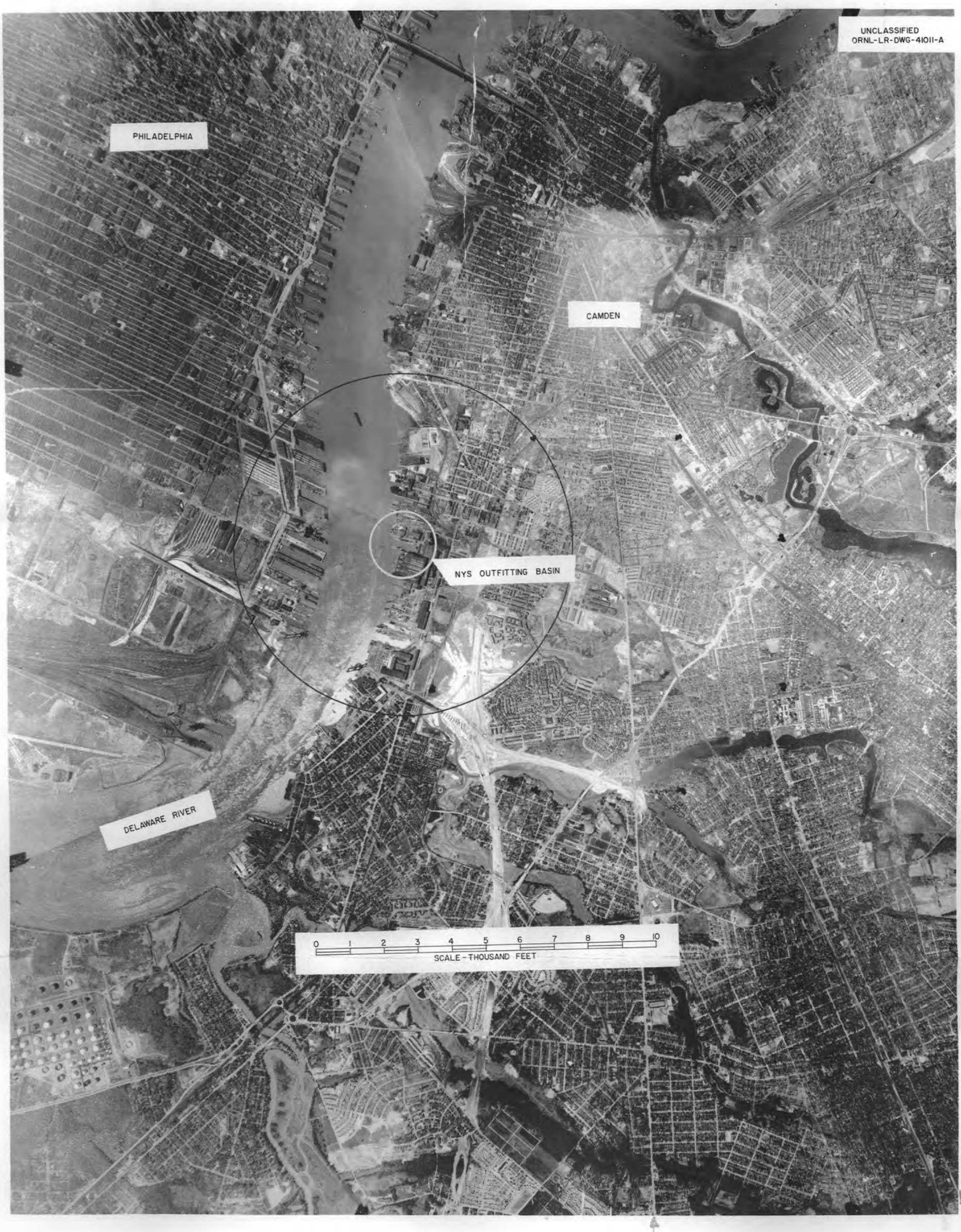

Fig. 2.3. Aerial View of Site and Surroundings.

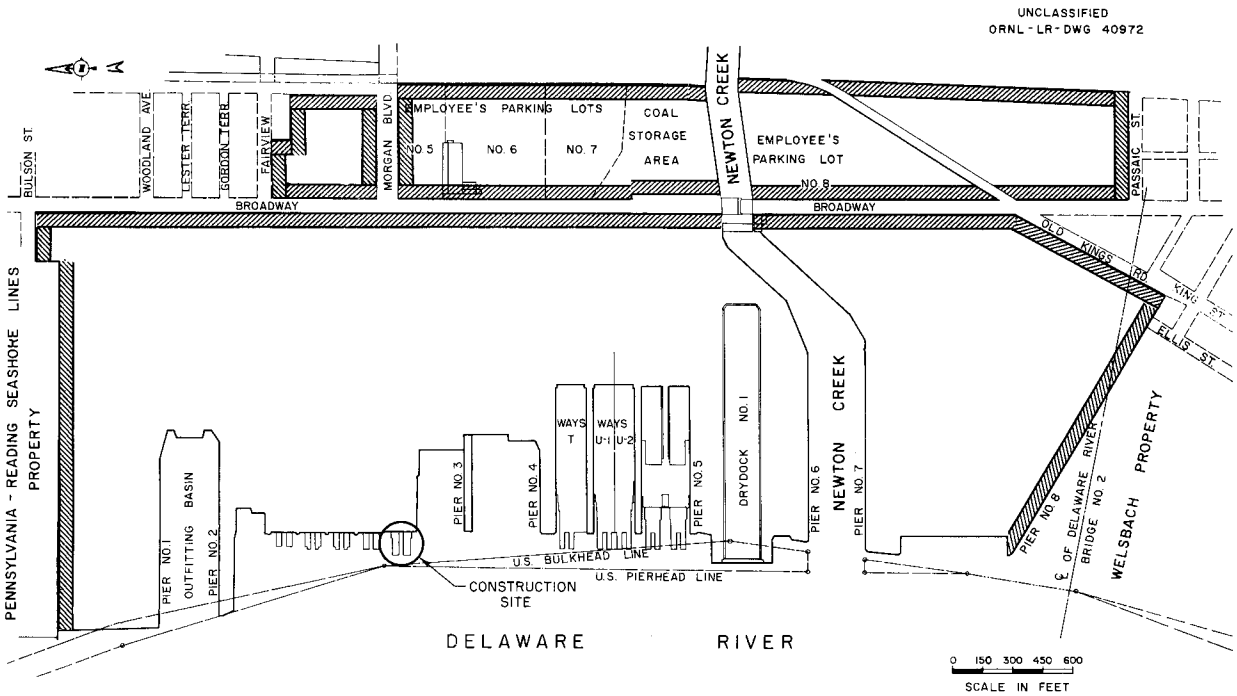

Fig. 2.4. Site Plan of New York Shipbuilding Corporation Yard.

3. SHIP DESIGN FOR ACTIVITY CONTROL[1]

REACTOR COMPARTMENT

The power plant is made up of a reactor system and a propulsion system. The propulsion system consists of the conventional components, such as the main turbines, reduction gear, main condensers, and the feedwater system, and is located in the machinery space forward of hold No. 5. The reactor system, comprised of the nuclear core, primary coolant system, heat exchangers, and related components, is located in the reactor space forward of the machinery space and aft of hold No. 4. The hull is divided into holds and spaces by watertight transverse bulkheads which provide barriers to the spread of radioactivity.

The containment vessel is located in the reactor compartment. The reactor core, heat exchangers, and other main components of the reactor system are located within the containment vessel. The remaining space inside the reactor compartment but outside the containment vessel is further subdivided into an upper and a lower void by the secondary concrete shield, which shields the lower half of the containment vessel but is not integral with it. The shielding for the upper half of the containment vessel is lead and polyethylene and is integral with the containment vessel. The reactor compartment is thus divided into an upper void that is outside the containment vessel and the secondary shielding, and a lower void that is inside the secondary shielding but outside the containment vessel.

[1]The system descriptions given in this chapter are based on the following reports: F. R. Thomasson and F. W. Davis, *NS Savannah, Analysis of Operation with Regard to Waste Collection and Disposal*, BAW-1109 (September 1958); J. H. MacMillan (ed.), *Nuclear Merchant Ship Reactor Project; Supplementary Information on Reactor Safeguards*, BAW-1150 (June 1, 1959); and J. H. MacMillan (ed.), *Nuclear Merchant Ship Reactor Project Preliminary Safeguards Report*, BAW-1117, vol I (rev) (Dec. 22, 1958) and vol II (Nov. 3, 1958).

VENTILATION AND FILTERS

The design of the reactor compartment ventilation system is not yet complete in detail, and therefore the system described here may differ somewhat from that of the as-built vessel. In this report it is assumed that the essential features of this system which pertain to the restriction and control of radioactivity during normal and emergency operation will be retained.

The normal air flow through the reactor compartment will be from the upper void to the lower void and then through the filter to the blower, which will discharge the activity up through the 90-ft forward stack. Since the lower void contains the gaseous purification system, ion exchange units, buffer seal system, waste tanks, etc., the above-described flow of air is consistent with the preferred technique of directing the flow of air from areas of low anticipated activity level to areas of increasing activity level.

The ventilation system has the following additional features:

1. A 4000-cfm exhaust fan maintains a negative pressure on the compartment to prevent outward seepage of air-borne contamination.
2. Filters (CWS No. 6 and silver-plated copper mesh for iodine) are provided upstream of the fan for the removal of particulate material and radioactive gases, except the noble gases.
3. Radioactivity monitors are located before and after the filters to provide information on the efficiency of the filters and on the concentration of the activity that is being released to the atmosphere.
4. Discharge is at the top of the forward mast, which is about 90 ft above the water line.
5. Provisions are included for discharge just above the water line at either side of the ship if the stack release is being downwashed to the deck. Administrative control is required to prevent use of this feature when near land.

A standby motor-and-fan unit is provided which can be placed on stream within a few minutes in the event of the failure of the operating blower. Thus, in the event of the failure of one blower during an emergency, the essential removal and filtration of the air from this region would be continued. This would be necessary not only in the event of the maximum credible accident during which activity from melted fuel elements could leak out of the containment vessel into the compartment but also in the event of any one of a number of lesser accidents involving any of the equipment located in the lower void which contained activity. In addition to the safety features inherent in the existence of a standby as well as an operating blower, the electrical supply to either blower will automatically be switched to the emergency power supply in the event of the loss of reactor-generated power.

The filters specified for this ventilation system, as mentioned above, include a series arrangement consisting of a modified CWS No. 6 filter for particulate matter, followed by a silver-plated copper mesh filter for iodine.[2] The principal contributors to the inhalation exposure from the release of activity from the stack are strontium (a particulate) and iodine. The modified CWS No. 6 filter with a Fiberglas filter assembly is 99.95% efficient in the removal of 0.3-μ particles. The actual size of the strontium particles that would reach the filter is not known, but in view of the nature of the MCA, which involves both the release of the primary and secondary water, as well as the melting of the fuel elements, most of the strontium would have ample time to agglomerate.

Silver-plated copper mesh filters have been tested under conditions which have resulted in greater than 99.9% removal of iodine. Whether this high efficiency may be realized under the operating conditions of the NS "Savannah" has not been established. There is, however, a factor which largely compensates for the uncertainty with regard to filter efficiencies, that is, the likelihood of deposition of air-borne fission product activity. Preliminary results[3] in an experiment in which fresh air was passed continuously over a fission product source indicate that 85% of the iodine, 99% of the tellurium, 100% of the barium, and 16% of the strontium were adsorbed on the surface of the ducting system immediately downstream of the source.

In the analysis of reactor accidents considered in this report, it is assumed that the filter combination will effect a reduction by a factor of 1000

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[2] L. Silverman *et al.*, "Iodine Collection Studies," paper presented at the Air Cleaning Conference in Idaho, July 1959.

[3] P. K. Conn, E. S. Collins, and J. B. Trice, *Trans. Am. Nuclear Soc.* 2(1), 210 (1959).

in the strontium and iodine concentrations. It would appear, in view of the combination of the filters, the deposition, and other natural processes, that the actual reduction of the strontium and iodine concentrations may be much greater than the specified factor of 1000.

CONTAINMENT VESSEL

The containment vessel, a cylinder with hemispherical heads, has an inside diameter of 35 ft and is 50 ft 6 in. in length; it is fabricated of $1\frac{1}{4}$-in.-thick steel plates. It is situated fore and aft of the ship centerline and 18 in. above the inner bottom tank top. A cupola (13 ft 6 in. ID, 16 ft 6 in. high) on the centerline of the vessel houses the control-rod drives. A hatch at the top of the cupola is provided for refueling and general servicing of the reactor, and two 42-in.-ID access hatches are located 13 ft 4 in. fore and aft of the cupola for replacing or servicing components such as pumps, valves, etc. One of these access hatches is an air-lock entrance, which will be the normal means of entry into the containment vessel. The air lock is necessary to maintain the integrity of the containment vessel atmosphere.

The containment vessel will be sealed at all times during plant operation and will be opened only following a prescribed waiting time after shutdown and then only when the radiation monitors indicate that it is safe to do so. The containment vessel has an air-conditioning system that will maintain a relatively constant ambient temperature of less than 140°F and a maximum relative humidity of 73%. This is a self-contained system and does not provide for any intake of fresh air or exhaust external to the containment vessel. To purge the vessel air or ventilate with fresh air, approximately 1500 cfm of reactor compartment ventilation flow can be diverted through the containment vessel. This would leave about a 2500-cfm flow from the upper void directly to the lower void, which would be used to dilute the containment vessel discharge flow, including any accumulated activity. The purged gas would be handled as the normal flow from the reactor compartment; that is, it would be filtered, monitored, and discharged at the top of the forward mast.

The containment vessel has been designed to contain the instantaneous release and expansion of the entire contents of the primary system and one secondary system.[1] Accordingly, the vessel is designed for a maximum internal pressure of 186 psig. After completion of assembly and x ray of welds, the containment vessel was hydrostatically tested to 100% of the pressure calculated for the MCA.

The containment vessel and penetrations were designed and constructed to minimize leakage, since it was realized that a completely leak-tight vessel could not be built. Accordingly, a leak test is being developed that will determine whether the vessel meets the design leakage criterion of not more than 0.2% of the free volume of the vessel per day for the average calculated pressure of 60 psig during the first day following the MCA. The leakage from the containment vessel in the event of the MCA would be into either or both of the upper and the lower voids, which are ventilated as a unit. The activity would then be filtered and discharged at the top of the radioactive discharge stack (90 ft in height).

SHIELDING

The primary shield consists of a 33-in. annulus of light water that surrounds the reactor pressure vessel and extends 17 ft $2\frac{1}{2}$ in. from a point well below the active core to well above it. The water annulus is supplemented by a lead shield 1 to 3 in. thick at the tank wall and local applications of lead to optimize the shield design. The primary shield is more than sufficient to limit the dose rate to 200 mrems/hr inside the containment vessel $\frac{1}{2}$ hr after shutdown, except at possible local concentrations of fission and corrosion products in the primary system piping.

The secondary shield will consist of lead, polyethylene, and concrete of sufficient thickness to reduce reactor and coolant radiation doses to continuous allowable levels. The lead and polyethylene will be used for secondary shielding on the upper half of the containment vessel, that is, within the upper void. Approximately 6 in. of lead will be applied directly to the containment shell, followed by about 6 in. of polyethylene. Up to 33 in. of concrete will be used for shielding the lower half of the vessel and will be integral with the containment shell only where it joins the lead and polyethylene shielding of the upper half. The concrete shielding thus forms the lower void, which is inside this secondary shielding but outside the containment vessel. Entry into this area will not be permitted when the reactor is operating because of the high dose rate.

WASTE DISPOSAL

The waste disposal system of the NS "Savannah" has been designed to contain all liquid and solid wastes for disposal by removal at dockside. While the gaseous activity may also be contained, provisions exist to permit the controlled release of the gaseous activity at concentrations below those deemed acceptable for release to the environment.

Liquid Wastes

The principal source of radioactive liquid wastes is the primary coolant in the primary system and auxiliary systems, such as the buffer seal, the primary pressurizing system, and the primary purification system. The quantity of these wastes has been estimated for the following operating conditions:

Expansion drainage during the startup	317 ft^3
Drainage from pressurizer, surge tank, and effluent condensing tank down to operating level after complete fill	150 ft^3
Maximum operational leakage and drainage for 100 days	490 ft^3
Total	957 ft^3

The total storage capacity on the ship is 1353.5 ft^3, and it is made up of the following:

1. Containment vessel drain tank (33.5 ft^3). The stainless steel tank is located inside the containment vessel, accumulates leakage wastes, and is periodically emptied into the upper waste storage tanks.
2. Laboratory waste tank (70 ft^3). The stainless steel tank is located in the lower void and is reserved for wastes containing reagents and high-solid-content fluids. The tank is equipped with a stirrer.
3. Upper waste storage tanks (2 units, 275 ft^3 each). The stainless steel tanks are located in the lower void for storage of startup drainage and general wastes.
4. Inner bottom tanks (2 units, 350 ft^3 each). The carbon-steel plastic-lined tanks are located in the inner bottom of the ship. The ship's hull forms part of the tank. These tanks will be used for storage of low-level waste.

The primary coolant purification system removes impurities from the primary cooling water. The impurities consist of dissolved and undissolved corrosion products, fuel and fission products from defective fuel rods, and residual impurities in the makeup water. Certain inert gases, such as argon, xenon, krypton, radon, helium, and neon, will not be removed by the purification system. These gases are stripped from the primary cooling water by a gas-removal system at the buffer seal surge tank.

The purification system is a low-pressure system consisting of two letdown coolers, three demineralizers, and two filters. During reactor operation, the water to be purified is drawn from the primary system, cooled in the letdown coolers, and depressurized by a flow control valve and block orifice. Following pressure and temperature reduction, the water flows to the demineralizers and filters located in the lower void. The purified water returns to the primary loop through the buffer seal system. The ion exchange resins in the demineralizers constitute the major source of solid activity. The effluent filters will be backwashed. The backwash is part of the 100-day operational liquid waste volume noted above.

Solid Wastes

The spent demineralizers of the primary purification system, as mentioned above, are the major source of solid wastes. Each unit has been designed for 50 days of service under the maximum corrosion rate of 10 mg/dm^2 per month. At the end of its lifetime, each unit is predicted to contain 407 curies of corrosion products. (The value of 407 curies of activated corrosion products is conservative; it was calculated on the basis of the arbitrary concentration of impurities that may be expected to be found in the fuel cladding.) In 100 days the two units used would contain 4.5 curies of fission products per 1530 g of fuel exposed (1530 g is the amount of fuel in one pin). The spent resin will not be sluiced out and the demineralizers recharged on board ship, but, rather, the demineralizers will be transferred to dockside facilities equipped to handle them. The units will be transferred within shielding casks to limit exposure to personnel.

The charcoal adsorption beds of the gaseous purification system are the second major source of solid wastes. It is estimated that these units will accumulate 8.1 curies of activity during 100 days of operation with 1530 g of fuel exposed. The stack filters of the reactor compartment ventilation system are another source of solid wastes. Estimates

of the activity that may be accumulated in these units are presented in Chap. 4, p 22.

Other types of solid wastes that will be accumulated on board ship will consist of contaminated tools, equipment, laboratory articles, clothing, blotting paper, etc. These miscellaneous solid wastes will be stored in properly constructed, sealed, and shielded (if necessary) containers and disposed of by transfer to dockside facilities. It is assumed that ultimate disposal will be carried out by a licensed and adequately equipped contractor, who will receive these wastes at the dock.

Gaseous Wastes

As in the case of the liquid wastes, the primary coolant system is the main source of gaseous wastes. The gaseous activity is that due to activation of the primary coolant, its contaminants, and the fission products that leak into it from fuel elements. The gaseous wastes that must be controlled are due to (1) leakage from primary components such as valves; (2) the gases vented from components such as waste tanks, the buffer seal surge tonk, and effluent condensing tanks; and (3) the saturation activity of Ar^{41} inside the containment vessel as a result of direct activation. The gaseous waste collection system is designed to (1) concentrate and accumulate both argon and the fission gases that could be released if a fuel cladding defect developed and (2) provide for decay and dilution of gaseous activity to tolerable levels before release to the atmosphere.

The controlled release of activity to the atmosphere after filtration is the normal means of disposal where fuel defects have not developed (only as long as insignificant quantities of fission products have been detected). In order to accomplish controlled release, a manifold collects gases vented from the waste tanks, buffer seal surge tank, effluent condensing tank, and primary coolant purification system. This manifold exhausts to the lower void ventilation discharge, which provides for dilution by 4000 cfm of air, filtration, and subsequent discharge at the top of the forward mast (90 ft high). If the stack discharge monitors indicate that the activity being released exceeds the acceptable concentration level, the gas manifold discharge may be released into the containment vessel for dilution and holdup for decay. The containment vessel will be closed during normal operation, but any accumulated activity may be purged by ventilating with part of the lower void flow, as noted above.

In the event defects develop in the fuel rod cladding, a gas purification system will be placed in operation. The adsorption equipment of this system operates on the vent gas from a stripping column located on the buffer seal surge tank. The vent gas is purified by combining any oxygen present with a portion of the hydrogen flow and by adsorbing the fission product gases on charcoal maintained at a reduced temperature. The vent gas, after being purified, returns to the surge tank for another stripping cycle. It is expected that the majority of the fission product gases will be removed from the coolant and concentrated in this manner.

Another point of degasification of the primary system will be a vent line from the pressurizer void to the purification blowdown stream between the coolers and the block orifices. The vent line will function to suppress radioactive gas buildup in the pressurizer by providing for complete change of the gas in the pressurizer when it becomes necessary. The gases vented from this source will increase the gas content of the buffer seal surge tank, from which gas will be continuously bypassed to the gas purification system.

MONITORING

General System Description

The radiation monitoring system is designed to provide protection for the nuclear power plant and operating personnel and to include the flexibility which may be required for future technical investigation. The system functions and components are listed below:

Functions	Components
Fixed health physics monitoring	3 channels, 14 detectors
Plant functional monitoring	5 channels, 9 detectors
Waste disposal monitoring	3 channels, 3 detectors[4]

The main radiation indicator panel will be located within the ship's main control room. Each channel will transmit the radiation level seen by

[4]One channel and one detector are in common with plant functional systems.

its detector to an indicator that shows the set alarm conditions. An alarm is given by an audible and a visible signal at the control console, as well as at the monitoring point, when the detected radiation level exceeds the set level. The reactor operator will be able to silence the audible alarm without impeding the reception of additional alarm signals from other points. The visible signal, however, will remain lighted while the overtolerance radiation condition persists. An auxiliary annunciator panel containing indicator lights for each channel will be located in the health physics office for convenient over-all survey of the radiation situation.

Fixed Health Physics Monitoring

The purpose of the fixed health physics monitoring system is to provide protection for plant operating personnel and passengers. This system will consist of 12 area detectors operating on two channels plus two containment access detectors on a third channel. Through an automatic scanning mechanism, six detectors can be sequentially switched into each channel and the radiation levels at these locations measured.

In the selection of monitoring points, the locations chosen were those of greatest proximity to the reactor containment accessible to personnel during normal operation. The monitoring points, as well as the detector sensitivities required, are listed in Table 3.1.

The containment access detectors will be located near the points of containment entry, probably at the lower manway and the upper air lock. The detectors will be calibrated and maintained on a periodic basis, and a permanent record of the radiation levels detected will be kept.

Plant Functional Monitoring

The objectives of the plant functional monitoring system will be to (1) detect leakage in the boilers from primary to secondary side, (2) detect leakage into the intermediate system from the primary system, (3) detect depletion of the ion exchange resins by effluent activity from the primary system demineralizers, and (4) detect the presence of gross fission products in the primary system due to possible defective fuel elements.

Waste Disposal Monitoring

This system serves to monitor the liquid waste collection tanks (using a plant functional detector) and the gaseous wastes discharged to the stack (two channels, two detectors) as necessary for disposal. Since it will not be necessary to monitor the waste tanks continuously, a waste transfer pump is used for sampling each tank through a loop at the sample station of the plant functional system.

As noted previously, the gas manifold will vent radioactivity to the lower void ventilation system for discharge to the environment at acceptable concentrations. In order to ensure that the concentration of activity released is of an acceptable level and to provide a permanent record of all activity discharged, appropriate monitors will be located in the discharge stack. The monitors must have sensitivities and selectivities adequate to dependably signal concentrations of activities in excess of those calculated or assumed in this report. The efficiency of stack filtration will be determined by locating monitors both upstream and downstream of the filters.

Portable Monitoring Equipment

In addition to the fixed monitoring system described above, portable instruments will be used for on-the-spot detection of radioactivity. The portable instruments will measure alpha, beta, gamma, and neutron radiation. Air-sampling devices will also be provided. These instruments have a range of sensitivities from essentially background to the highest dose rates from inside the containment vessel and the MCA. Adequate laboratory equipment is available for counting air, water, and smear samples. Personnel monitors such as film badges and self-reading dosimeters are also an essential part of the radiation monitoring equipment.

Sources of Activity Outside the Containment Vessel

Most of the auxiliary equipment is located outside the containment vessel in the lower void or machinery space. These components do not contain primary coolant under high temperatures and pressures; however, several components will handle the primary coolant. Other sources of activity

Table 3.1. Fixed Health Physics Monitoring

Channel	Monitor Numbers	Location	Sensitivities (mrems/hr)
1	1	Deck A, outside doctor's office	0.01–10
	2–3	Deck B, port and after passageways	0.01–10
	4–5	Deck C, port and after passageways	0.01–10
	6	Deck D, starboard passageway	0.01–10
2	7–8	Deck D, fore and aft bulkhead	0.1–100
	9–12	Tank top (port, starboard, fore, and aft passageways)	0.1–100

Table 3.2. Sources and Locations of Activity

Source	Location	Volume (ft^3)	Type of Activity	Corrosion Product Activity		Fission Product Activity	
				Concentration ($\mu c/cm^3$)	Total Curies	Concentration ($\mu c/cm^3$)	Total Curies
Intermediate cooling water system	Machinery space	218	Liquid	0.0084	0.0518	0.0014	0.0086
			Gaseous	0.0019	0.0117	0.00056	0.0345
Secondary side of boilers (two units)	Machinery space	454	Liquid	0.045	0.579	0.0075	0.096
			Gaseous	0.0010	0.0129	0.0003	0.0039
Inner bottom waste tanks (two units, 350 ft^3)	Inner bottom	700	Liquid	0.145	2.87	0.0245	0.486
			Gaseous	0.0010	0.020	0.00261	0.052
Waste tanks (two units, 260 ft^3; one unit, 67 ft^3)	Lower void	587	Liquid	0.145	2.41	0.0245	0.407
			Gaseous	0.0010	0.016	0.00261	0.0434
Buffer seal surge tank							
Liquid space	Lower void	46.4	Liquid	0.145	0.191	0.0245	0.0322
			Gaseous	0.0010	0.0013	0.00261	0.0034
Void space	Lower void	40.6	Gaseous	0.042	0.0483	0.112	0.129
Ion exchange resins (three units)	Lower void	17.5[a]	Solid		702[b]		9.0[b]
Charcoal beds (three units)	Lower void						8.1[c]
Effluent filters[d] (two units)	Lower void						
Stack filter[d]	Deck A						
Sampling system[d]	Lower void						

[a]Volume per unit.
[b]Total for two units operated for 100 days after failure of one fuel pin.
[c]For each unit.
[d]Activity buildup indeterminate (see Chap. 5).

outside the containment vessel include the intermediate cooling water system, the secondary side of the boiler, waste tanks, etc. These sources, their location, the volumes involved, and the maximum activity expected[5] are described in Table 3.2. The activities listed are those given in reports BAW-1109 and BAW-1150.[6] It was assumed that the waste storage tanks were filled with primary coolant and that no decay had occurred.

[5]After operation for 300 days at full power followed by failure of one fuel pin (1530 g) and subsequent operation for another 100 days with liquid and gaseous purification.

[6]F. R. Thomasson and F. W. Davis, *NS Savannah, Analysis of Operation with Regard to Waste Collection and Disposal*, BAW-1109 (September 1958); J. H. MacMillan (ed.), *Nuclear Merchant Ship Reactor Project; Supplementary Information on Reactor Safeguards*, BAW-1150 (June 1, 1959).

4. CONSEQUENCES OF THE MAXIMUM CREDIBLE ACCIDENT

INTRODUCTION AND CRITERIA FOR MCA EXPOSURE CALCULATIONS

The MCA considered here proceeds from a large rupture of the primary water system.[1] When the reactor is deprived of adequate cooling, afterheat will cause the core to heat up, vaporize any residual water in the core, and, if the reactor has been operating long enough at power, eventually cause the fuel-element cladding to rupture because of decreased strength at higher temperatures. There is no satisfactory means for calculating the temperature at which the cladding will fail, and two different approaches for different situations have been used.

For the first case, it was assumed that the cladding failure temperature was a direct function of the fission product gas pressure within the fuel capsule.[2] At the end of core life, 52,000 Mwd, the internal gas pressure would reach about 2000 psi (at 1600°F), and it was assumed that the cladding would fail at a temperature of 1600°F. It was further assumed that all the fission products which are volatile below 1600°F would be released at this time. Only the volatile fission product activity released during the MCA was tabulated in the previous hazards report.[1]

For the second case, not only were all fission products considered, but it was assumed that conditions existed that would cause fuel rod failure during the early stages of reactor operation when there was essentially no fission gas pressure within the fuel rods. This situation was outlined in a letter of April 8, 1959, from Babcock & Wilcox to ORNL, which is included as Appendix G. The important assumption given is that the cladding will fail because it will melt when the temperature reaches 2550°F. Appendix G also gives the results of calculations of the percentage of the total core activity that is released, which is related to the number of rods that have failed, as a function of time after the onset of the MCA for different periods of operation at various power levels.

In the accident analysis presented here, the MCA was assumed to occur after long-term operation. The fission product inventory was taken to be that for 600 days of operation at 69 Mw to show the worst possible conditions. This use of the fission product inventory for long-term operation gives conservative estimates of the exposure when considering the initial startup at Camden. The effects of short-term operation and low power levels on the fission product inventory and the resulting exposures are described in Chap. 6.

Calculations of the percentage of the total activity that would be released were based on 100% of the fuel rods having failed following the MCA. This assumption is only slightly conservative, since ref 1 and Appendix G indicate that approximately 90% of the fuel elements have failed 2 hr after onset of the MCA.

[1]J. H. MacMillan (ed.), *Nuclear Merchant Ship-Reactor Project Preliminary Safeguards Report*, BAW-1117, vol I (rev) (Dec. 22, 1958).

[2]*Ibid.*, p 204.

It was assumed that failed fuel elements would release the following percentages of the various accumulated fission products:

Element	Amount Released (%)
Xe, Kr, Rb, I, Br, Cs	100
Sr, Ba	10
Te, Se, Sb, Eu, Mo, Tc, Sm	1
Y, La, Ce, Pr, Nd, Pm, Zr, Nb, Ru, Rh	0.1

These assumed release values for both the volatile and the nonvolatile fission products are conservatively high when compared with reported measurements of the release of fission products from molten reactor fuels.[3,4]

The leakage rate of the containment vessel was taken as 0.2% of the free volume per day. This is the design maximum leakage rate given by Babcock & Wilcox for the calculated average conditions (Δp = 60 psi) during the first day following the MCA.[1,5] It was assumed that all leakage would be into the reactor compartment, which would be continuously ventilated to the top of the radioactive-effluent discharge stack (height, 90 ft). It was further assumed that the reactor-compartment discharge would be filtered with a 99.9% efficiency for all activity except the noble gases. It should be noted that leakage from systems that penetrate the containment vessel must not increase the total to greater than 0.2% per day. The meteorological conditions considered were typical daytime lapse and nighttime inversions for the Camden area (see Appendixes A and B).

The quantity of activity that is released to the containment vessel following the MCA was calculated from the expression

$$Q_{T,i} = C_i \times F \times F_{R,i} \ ,$$

where

$Q_{T,i}$ = curies of isotope i released to containment vessel following the MCA,

C_i = curies of isotope i present in the reactor core after long-term operation (see Appendix H),

F = fraction of the fuel elements that has failed, here taken as 1,

$F_{R,i}$ = fraction of isotope i present in fuel element that is released upon failure.

Values of $Q_{T,i}$ for the isotopes of interest to the exposure calculations are tabulated in a subsequent section of this chapter (see Table 4.12).

The activity released to the environment for the particular cases considered is then

$$Q_i = Q_{T,i} \times L \times F_{F,i} \ ,$$

where

Q_i = quantity of a given isotope released to the environment and may be (1) a release rate (curies/sec) or (2) the total amount (curies) when integrated over time,

$Q_{T,i}$ = same as defined above,

L = fraction of the free volume of the containment vessel that leaks per second (0.2%/day = 2.3×10^{-8} fraction/sec),

$F_{F,i}$ = fraction of the activity that is not removed by filtration (taken as 10^{-3} for all isotopes except the noble gases, for which it is 1.0).

The leakage rates of the important isotopes are tabulated in the following section (see Table 4.1).

The consequences of the MCA are considered for (1) release to the atmosphere and (2) release to the hydrosphere. For the release to the atmosphere, exposures are calculated for inhalation of activity, submersion in the radioactive cloud, and exposure from ground deposition as a result of rainout. In the case of release to the hydrosphere (Delaware River and Estuary), the exposures from submersion in the river (swimming and boating) and from drinking the water have been computed.

RELEASE TO THE ATMOSPHERE

The consequences of release of activity to the atmosphere have been calculated by utilizing the atmospheric dispersion computations of Appendix A and the quantities of activity released. Internal and external exposures have been calculated for the case where an individual is exposed to the radioactive cloud. The external (submersion and direct) exposures must be added to the inhalation exposures in order to arrive at the total exposure

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[3] S. J. Rogers and G. E. Kennedy, *Fission Product Release During a Simulated Meltdown of a PWR-Type Core*, MSA-TR-63 (Oct. 20, 1958).

[4] G. E. Creek, W. J. Martin, and G. W. Parker, *Experiments on the Release of Fission Products from Molten Reactor Fuels*, ORNL-2616 (Dec. 23, 1958).

[5] Verbal communication from J. H. MacMillan, Babcock & Wilcox Company.

to any given organ. The external whole-body exposure has been computed for the case of ground deposition of activity due to rainout and washout.

Combinations of the following types of accidents have been examined.

1. Continuous-source MCA: activity leaking into the compartment from the containment vessel and all penetrating systems at the rate of 0.2% per day.

2. Open-container MCA: the containment vessel is open and yielding essentially an instantaneous source, since activity is discharged to the environment as it is released from failed fuel elements.

3. Continuous source at 90-ft stack height: ventilation of the reactor compartment discharges activity released from the containment vessel at a height of 90 ft above the water line.

4. Ground-level source: the release of activity is considered to occur at ground level rather than at a height of 90 ft (note that the exposure of individuals located at the height of the stack, that is, in buildings, would be calculated as in the ground-level-source case).

The case of a continuous source at the 90-ft stack height is considered to be the MCA for operation in restricted areas (ports, estuaries, and adjacent coastal waters). It should be noted that the open-container MCA case is considered to be incredible for operation in restricted waters unless administrative control is lax (see Chap. 1).

The containment vessel internal pressure is assumed to remain constant at 60 psig. Since this is not strictly true, that is, the pressure will decrease greatly in one day, the 24-hr total integrated dose calculations (see p 24) based on the total exposure to activity give the most accurate, yet conservatively high, estimate of the consequences of the MCA in dosage to inhabitants of the area.

Dose Rates from Continuous Source

Inhalation Exposure. – The inhalation exposure of the internal critical organs can be calculated by expressing it as the ratio of the existing activity concentration to the maximum permissible concentration (MPC) for occupational exposure.[6] The inhalation exposure to various critical organs which corresponds to the MPC for continuous exposure is given below:

Critical Organ	Permissible Occupational Inhalation Exposure (mrems)	
	Per Week	Per Hour
Bone	560	3.3
Skin and thyroid	615	3.7
Other organs	300	1.8
Total body	100	0.6

It should be noted that the NS "Savannah" will not produce a continuous source of the long duration used to determine the MPC values, for which an exposure for many days or years is assumed. Consequently, the calculated values of inhalation exposure shown above are greater than the actual continuous exposures and are therefore conservative. The exposure caused by leakage from the containment vessel might reasonably be limited to one day on the basis that the ship could then be towed away, atmospheric conditions (wind direction) would have changed, or other control procedures could have been initiated.

Calculations have been made for the activity arising from the MCA (container intact) for those isotopes which affect the bone, thyroid, kidney, and muscle. In addition to the continuous exposure, there will be an additional exposure after the air and ground activity concentrations are removed because of the presence of activity in the body. The activity in the body will decay by radioactive and biological processes. Table 4.1 lists the internal exposures from 30 important isotopes[7] and the total exposures to specific organs.

The exposure rate, D, given in the last column of Table 4.1 was calculated from

$$D_i = \frac{X_{max}}{MPC_i} D_{MPC,i} ,$$

where

D_i = critical organ dose rate from isotope i in rems/hr,

X_{max} = maximum air concentration in curies/m^3 of isotope i,

[6] *Maximum Permissible Body Burdens and Maximum Permissible Concentrations of Radionuclides in Air and in Water for Occupational Exposure*, NBS Handbook 69 (June 5, 1959).

[7] T. J. Burnett, *Nuclear Sci. and Eng.* 2, 382 (1957).

Table 4.1. Internal Dose from 90-ft-elevated Source During Nighttime Inversion for $(\chi/Q)_{max} = 6.6 \times 10^{-5}$ sec/m^3

Isotope	Q (curies/sec)	χ_{max} (curies/m^3)	MPC (curies/m^3)	Exposure Rate (mrems/hr)
		Bone		
Sr^{89}	5.9×10^{-6}	3.9×10^{-10}	10^{-8}	1.30×10^{-1}
Sr^{90}-Y^{90}	3.0×10^{-7}	1.98×10^{-11}	10^{-10}	6.6×10^{-1}
Sr^{91}-Y^{91m}	7.3×10^{-6}	4.8×10^{-10}	5×10^{-7}	3.2×10^{-3}
Y^{91}	7.5×10^{-8}	4.9×10^{-12}	10^{-8}	1.63×10^{-4}
Zr^{95}	8.6×10^{-8}	5.7×10^{-12}	6×10^{-8}	3.2×10^{-4}
Nb^{95}	8.6×10^{-8}	5.7×10^{-12}	3×10^{-7}	6.3×10^{-5}
Zr^{97}-Nb^{97m}	8.1×10^{-8}	5.3×10^{-12}	10^{-6}	1.77×10^{-5}
Nb^{97}	8.1×10^{-8}	1.70×10^{-12}	3×10^{-5}	5.9×10^{-7}
Ba^{140}-LA^{140}	8.2×10^{-6}	5.4×10^{-10}	4×10^{-8}	4.5×10^{-2}
Ce^{141}	7.8×10^{-8}	5.1×10^{-12}	2×10^{-7}	8.6×10^{-5}
Ce^{143}	8.1×10^{-8}	5.3×10^{-12}	10^{-6}	1.77×10^{-5}
Pr^{143}	8.1×10^{-8}	5.3×10^{-12}	2×10^{-7}	8.8×10^{-5}
Ce^{144}-Pr^{144}	6.0×10^{-8}	4.0×10^{-12}	3×10^{-9}	4.4×10^{-3}
Nd^{147}	3.3×10^{-8}	2.21×10^{-12}	3×10^{-7}	2.45×10^{-5}
Pm^{147}	1.17×10^{-8}	7.8×10^{-13}	2×10^{-8}	1.30×10^{-4}
Pm^{149}	1.75×10^{-8}	1.16×10^{-12}	10^{-6}	3.9×10^{-6}
			Total	0.84
		Thyroid		
I^{131}	4.5×10^{-5}	2.96×10^{-9}	3×10^{-9}	2.71×10^{0}
I^{132}	5.9×10^{-5}	3.9×10^{-9}	8×10^{-8}	1.44×10^{-1}
I^{133}	8.4×10^{-5}	5.5×10^{-9}	1×10^{-8}	1.05×10^{0}
I^{134}	9.7×10^{-5}	3.2×10^{-9}	2×10^{-7}	3.9×10^{-2}
I^{135}	7.8×10^{-5}	5.2×10^{-9}	4×10^{-8}	3.8×10^{-1}
			Total	4.3
		Kidney		
Ru^{103}-Rb^{103m}	4.2×10^{-8}	2.78×10^{-12}	3×10^{-7}	1.67×10^{-5}
Rh^{105}	1.63×10^{-8}	1.08×10^{-13}	3×10^{-6}	6.5×10^{-7}
Ru^{106}-Rh^{106}	6.2×10^{-9}	4.1×10^{-13}	5×10^{-8}	1.46×10^{-5}
Te^{127m}-Te^{127}	7.7×10^{-9}	3.7×10^{-13}	5×10^{-8}	7.4×10^{-6}
Te^{129m}-Te^{129}	4.8×10^{-8}	3.1×10^{-12}	3×10^{-8}	1.88×10^{-4}
Te^{131m}-Te^{131}	5.9×10^{-8}	3.9×10^{-12}	3×10^{-7}	2.35×10^{-5}
Te^{132}	5.9×10^{-7}	3.9×10^{-11}	10^{-7}	7.1×10^{-4}
			Total	9.6×10^{-4}
		Muscle		
Cs^{137}-Ba^{137m}	2.65×10^{-6}	1.75×10^{-10}	4×10^{-8}	7.9×10^{-3}
			Total	7.9×10^{-3}

MPC_i = maximum permissible concentration in curies/m^3 of isotope i,

$D_{MPC,i}$ = dose rate from maximum permissible concentration of isotope i in mrems·hr^{-1}.

The results given in Table 4.1 are for the point of maximum ground concentration for the nighttime inversion conditions for which $(\chi/Q)_{max} = 6.6 \times 10^{-5}$ sec/m^3, as obtained in Appendix A. In Table 4.2 and Figs. 4.1 and 4.2, the exposures to the bone and thyroid are given as functions of distance downwind (x) from the source for both nighttime inversion and daytime lapse conditions. These values were obtained by multiplying the maximum exposure by $(\chi/Q)_x/(\chi/Q)_{max}$. The exposures to the kidney and muscle are not presented, since they would be negligible for the maximum exposure case (see Table 4.1).

Under the conditions outlined above, the internal exposure rate from the MCA would be less than 5 mrems/hr at the point of maximum ground concentration based on the maximum fission product inventory in the reactor. Operation for shorter times at lower powers can be shown to reduce this maximum exposure significantly.

Submersion Exposure. – The external gamma-ray exposure rate (rems/hr) from submersion within a large cloud of radioactive material may be

Table 4.2. Internal Exposure from 90-ft-elevated Source as a Function of Distance Downwind for Typical Inversion and Lapse Conditions

Distance Downwind (m)	χ/Q (sec/m^3)	Thyroid Exposure (mrems/hr)	Bone Exposure (mrems/hr)
	Inversion		
250	2.6×10^{-13}	1.67×10^{-8}	3.3×10^{-9}
500	3.7×10^{-7}	2.41×10^{-2}	4.7×10^{-3}
1,000	2.8×10^{-5}	1.85	0.36
1,500	5.8×10^{-5}	3.8	0.73
2,000	6.6×10^{-5}	4.3	0.84
2,500	6.3×10^{-5}	4.1	0.78
5,000	3.6×10^{-5}	2.35	0.46
10,000	1.5×10^{-5}	0.98	0.190
20.000	5.7×10^{-5}	0.37	0.073
	Lapse		
100	5.65×10^{-5}	3.7	0.72
250	4×10^{-5}	2.63	0.51
350*	2.6×10^{-5}	1.68	0.33
500	1.45×10^{-5}	0.95	0.185
1,000	4.5×10^{-6}	0.291	0.056
1,500	2.2×10^{-6}	0.146	0.028
2,000	1.3×10^{-6}	0.086	0.0181
2,500	9.0×10^{-7}	0.0056	0.0112
5,000	2.6×10^{-7}	0.0168	0.0034

*Distance to street fronting on the residential area nearest to the test site.

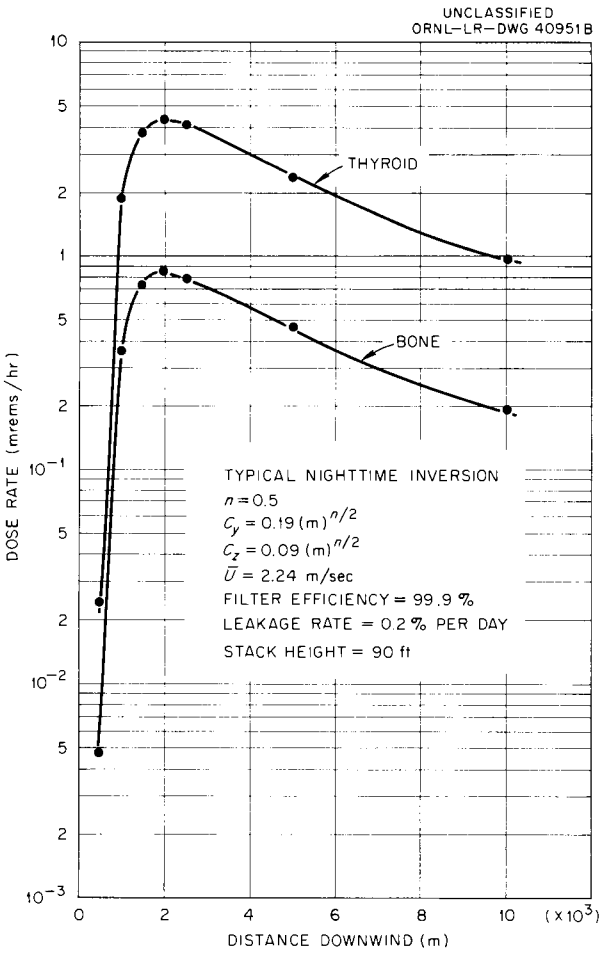

Fig. 4.1. Internal Exposure Rate from a Continuous Elevated Source During Inversion.

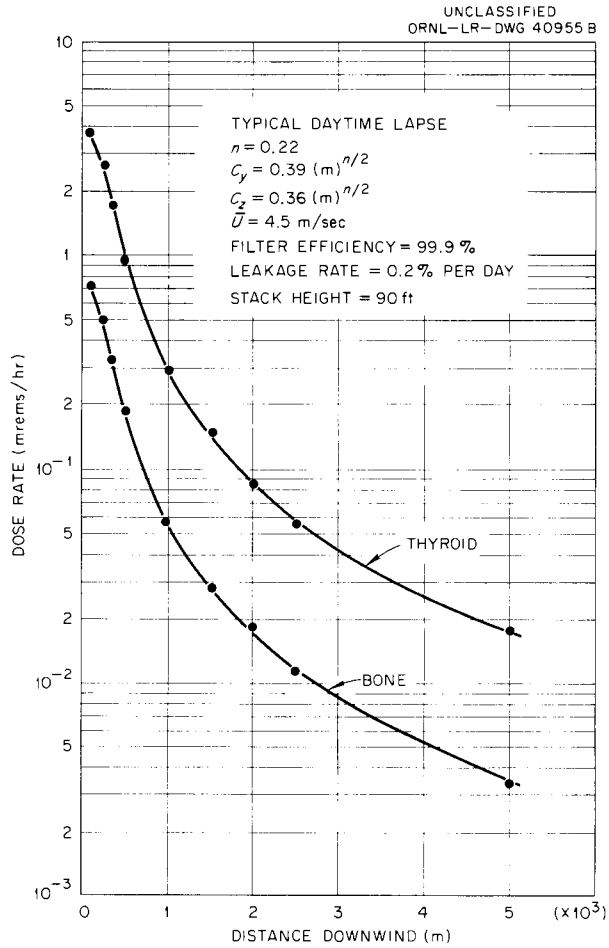

Fig. 4.2. Internal Exposure Rate from a Continuous Elevated Source During Lapse.

estimated to not exceed[7,8]

$$D_\gamma = 9.4 \times 10^{-4}\, E\chi \ , \qquad (1)$$

where E is the effective energy in Mev per disintegration, χ is the concentration in $\mu c/m^3$, and 9.4×10^{-4} is a conversion factor to give the results in rems/hr. For the case of continuous release following the MCA, the exposure (rems/hr) from a cloud of mixed fission products at a distance x downwind is

$$D_\gamma = 9.4 \times 10^{-4} \sum_i E_i Q_i \left(\frac{\chi}{Q}\right)_x \ , \qquad (2)$$

where

E_i = effective gamma-ray energy (Mev/dis) of isotope i,

Q_i = release rate (μc/sec) of isotope i,

$(\chi/Q)_x$ = dilution at x meters downwind of the source (sec/m^3).

Equation (1) assumed submersion in a uniform, mixed, semi-infinite cloud of radioactive material. Neglecting back-scattering from the ground, the dose rate is just one-half that from an infinite medium. This equation is derived on the assumption that, in an infinite medium in equilibrium, as much energy will be absorbed in each cubic centimeter of air as is generated in it.

The gamma-ray dose during the passage of a cloud from an elevated stack is proportional to the ground concentration (χ) only at distances from the stack where the spatial variation of the

[8] *Theoretical Possibilities and Consequences of Major Accidents in Large Nuclear Power Plants*, WASH-740 (March 1957).

concentration is small. At distances close to the stack the actual dose rate is greater than that due to the ground concentration because of a contribution from the more concentrated cloud at some distance above the ground. The actual dosage calculations involve a complicated integration over the spatial concentrations of the cloud.[9] The gamma-ray dose rates close to the stack may be roughly approximated by using the maximum dose rate (based on the maximum ground concentration) for all distances closer to the stack than that at which the maximum ground concentration occurs. This method will be used here, as, for example, in Fig. 4.3.

It is conservatively assumed that the radioactive atoms do not deposit on container walls but do leak from the containment vessel and are carried in suspension by the ventilation air. The activity that leaks from the containment vessel passes through a stack filter that is assumed, on the basis of the discussion in Chap. 3, "Ventilation and Filters," to be 99.9% efficient for the removal of all isotopes except the noble gases. Accordingly, the submersion exposure has been calculated in two parts: (1) that from the noble gases krypton and xenon and (2) that from all other isotopes, both with and without the filter, to show the importance of filtration efficiency.

Table 4.3 lists the krypton and xenon isotopes of interest and the associated $\sum_i E_i Q_i$ values for both the gamma and beta energies. A similar summation was carried out for the other isotopes

[9] *Meteorology and Atomic Energy*, AECU-3066 (July 1955).

Table 4.3. The $\sum_i E_i Q_i$ Values for the Gamma and Beta Energies of the Krypton and Xenon Isotopes of Interest

Isotope	Q (curies/sec)	E_γ (Mev/dis)	E_β (Mev/dis)	$E_\gamma Q^*$	$E_\beta Q^*$
Kr^{83m}	0.0059	0.0415	0	0.000246	0
Kr^{85m}	0.0179	0.181	0.233	0.0032	0.0041
Kr^{85}	0.00040	0	0.232	0	0.00009
Kr^{87}**	0.0115	0.56	1.01	0.0064	0.0116
Kr^{88}	0.045	2.07	0.331	0.093	0.0149
Xe^{133m}	0.00168	0.233	0	0.00039	0
Xe^{133}	0.084	0.081	0.115	0.0068	0.0097
Xe^{135m}**	0.0086	0.52	0	0.0045	0
Xe^{135}	0.082	0.268	0.302	0.0219	0.0247
Xe^{137}**	$<10^{-5}$	0	1.33	0	0
Xe^{138}**	0.0053	0	1.0	0	0.0053
Total, Q_T	0.2623		Total, $\sum_i E_i Q_i$	0.136	0.070

$$\text{Mean } E_\gamma = \frac{\sum_i (E_i Q_i)_\gamma}{Q_T} = 0.518$$

$$\text{Mean } E_\beta = \frac{\sum_i (E_i Q_i)_\beta}{Q_T} = 0.267$$

*The small contributions by the daughters were neglected.

**Attenuation from decay included.

having substantial yields and half lives greater than 2 min. Over 100 isotopes were included in this group, and the $\sum_i E_i Q_i$ value was 0.45. Decay was considered only for I^{134}, Cs^{138}, Cs^{139}, and the isotopes noted in Table 4.3.

For the maximum $(\chi/Q)_x$, which is 6.6×10^{-5} sec/m^3 at 2050 m for nighttime inversion conditions, the following gamma-ray dose rates were obtained for the fission products:

$$D_\gamma\,[\text{Kr} + \text{Xe}] = 8.4 \text{ mrems/hr} ,$$
$$D_\gamma\,[\text{all isotopes}] = 36.4 \text{ mrems/hr, no filter} ,$$
$$D_\gamma\,[\text{all} - (\text{Kr} + \text{Xe})] = 28.0 \text{ mrems/hr, no filter} ,$$
$$D_\gamma\,[\text{all} - (\text{Kr} + \text{Xe})] = 0.028 \text{ mrem/hr, filter 99.9\% efficient} .$$

With stack filtration of the released activity, the controlling dose here is from krypton and xenon.

Whole-body beta exposure from submersion in a radioactive cloud should be somewhat less than the gamma-ray exposure and, since it affects principally the skin, should not contribute significantly to the acceptable emergency dose. The beta submersion dose rate (rems/hr) may be calculated[9] from

$$D_\beta = 0.32 \times \frac{3600}{6.8 \times 10^{10}} R_\beta ,$$

where R_β is in Mev·sec^{-1}·m^{-3}. For the NS "Savannah,"

$$R_\beta = 3.7 \times 10^{10} \sum_i (E_i Q_i)_\beta \left(\frac{\chi}{Q}\right)_x F_{F,i} ,$$

where

E_i = effective beta energy (Mev/dis) of isotope i,
Q_i = release rate (curies/sec) of isotope i from the containment vessel,
$(\chi/Q)_x$ = dilution at x meters downwind of the source (sec/m^3),
$F_{F,i}$ = fraction of isotope i not filtered out (1.00 for noble gases),

and 3.7×10^{10} is a conversion factor to give the $\sum_i E_i Q_i$ values in Mev/sec. Substituting for R_β and simplifying gives

$$D_\beta = 6.37 \times 10^2 \sum_i (E_i Q_i)_\beta \left(\frac{\chi}{Q}\right)_x F_{F,i} .$$

The beta dose is then handled in the same manner as was the gamma dose rate. Table 4.3 shows the $\sum_i (E_i Q_i)_\beta$ for xenon and krypton to be 0.070. For all isotopes except xenon and krypton, $\sum_i (E_i Q_i)_\beta$ = 0.64, where the same isotopes and decay are included as in the gamma exposure case.

For the maximum case, $(\chi/Q)_{max} = 6.6 \times 10^{-5}$ sec/m^3 at 2050 m, and the beta dose rates are

$$D_\beta\,[\text{Kr} + \text{Xe}] = 2.94 \text{ mrems/hr} ,$$
$$D_\beta\,[\text{all isotopes}] = 29.84 \text{ mrems/hr, no filter} ,$$
$$D_\beta\,[\text{all} - (\text{Kr} + \text{Xe})] = 26.9 \text{ mrems/hr, no filter} ,$$
$$D_\beta\,[\text{all} - (\text{Kr} + \text{Xe})] = 0.027 \text{ mrem/hr, filter 99.9\% efficient} .$$

Thus krypton and xenon control the beta submersion exposure rate, which is about one-third the whole-body external gamma exposure rate.

The whole-body external beta and gamma exposures from the krypton and xenon isotopes are shown in Table 4.4 and Figs. 4.3 and 4.4, as a function of the distance downwind of the source for typical lapse and inversion conditions. The dotted portion of the gamma submersion curve for inversion (Fig. 4.3) is an extrapolation of the

Table 4.4. Submersion Dose vs Distance Downwind for Exposure Calculated on Basis of the Ground Concentration

Distance Downwind (m)	Krypton and Xenon Submersion Exposure (mrems/hr)			
	Inversion		Lapse	
	Gamma	Beta	Gamma	Beta
100			7.2	2.57
250	3.3	1.16×10^{-8}	5.1	1.82
350			3.3	1.16
500	0.047	0.0165	1.82	0.65
1,000	3.5	1.25	0.56	0.200
1,500	7.4	2.62	0.279	0.097
2,000	8.4	2.94	0.166	0.058
2,500	8.0	2.85	0.114	0.040
5,000	4.6	1.60	0.034	0.0114
10,000	1.88	0.67		
20,000	0.72	0.257		

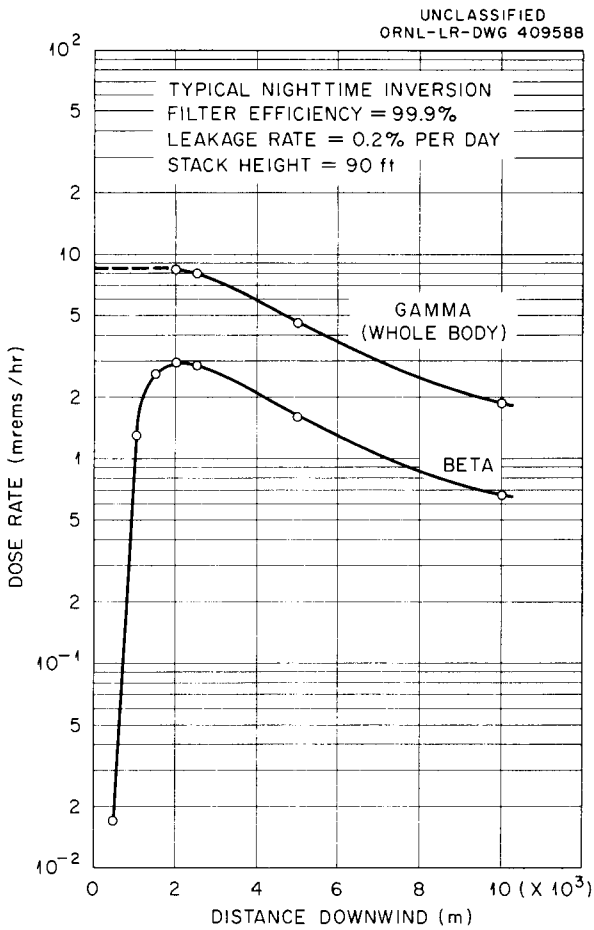

Fig. 4.3. Submersion Exposure Rate from a Continuous Elevoted Source During Inversion.

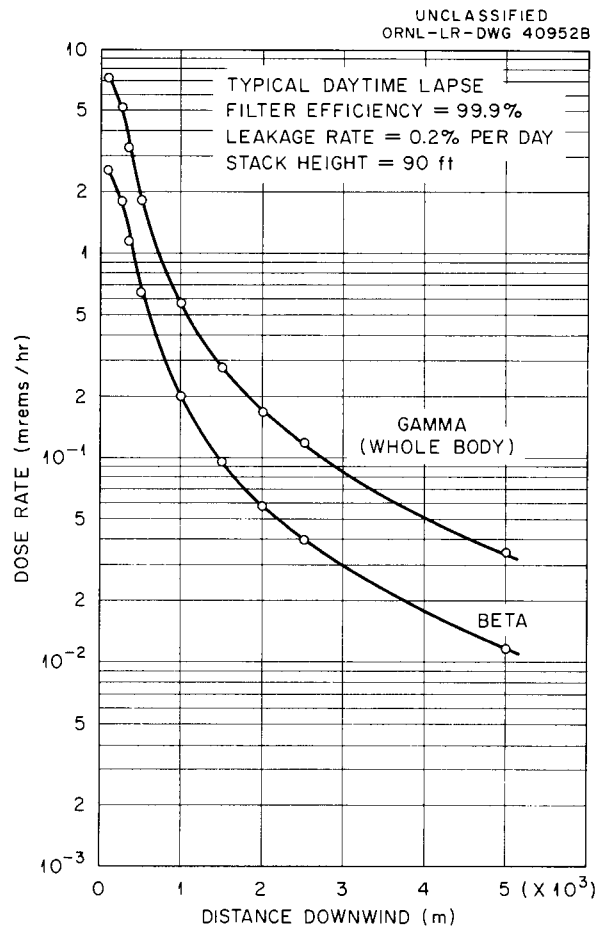

Fig. 4.4. Submersion Exposure Rate from a Continuous Elevated Source During Lapse.

maximum dose rate due to ground concentration, as noted above (see p 21).

Ground-Level Source or Looping Meteorological Condition. – If the recipient of air-borne activity is at the center of the cloud or plume emitted from the source, the concentration to which he is exposed will be greater than for the conditions described above. Either of two mechanisms can cause this situation for a ground-level receiver: (1) the emission point is at ground level with typical meteorological conditions prevailing, or (2) the emission point is elevated but the center of the plume "loops" or wanders down to ground level. In either case, attenuation of the activity concentration because of the vertical diffusion gradient does not exist for the recipient. The equation for dispersion of activity for these conditions is (see Appendix A)

$$\frac{\chi}{Q} = \frac{2}{\pi C_y C_z \bar{U} x^{2-n}} \exp - \frac{y^2}{C_y^2 x^{2-n}} ,$$

or, directly downwind ($y = 0$),

$$\frac{\chi}{Q} = \frac{2}{\pi C_y C_z \bar{U} x^{2-n}} .$$

The resulting $(\chi/Q)_x$ for the typical inversion and lapse conditions are presented in Table 4.5, as well as the ratio of $(\chi/Q)_x$ to $(\chi/Q)_{max}$, where $(\chi/Q)_{max}$ is the maximum downwind concentration for unit release at a height of 90 ft under typical

Table 4.5. Fraction of Maximum Concentration vs Distance Downwind for a Ground-Level Source

x, Distance Downwind (m)	Inversion Conditions		Lapse Conditions	
	$(\chi/Q)_x$ (sec/m^3)	$\frac{(\chi/Q)_x}{(\chi/Q)_{max}}$ *	$(\chi/Q)_x$ (sec/m^3)	$\frac{(\chi/Q)_x}{(\chi/Q)_{max}}$ *
100			2.8×10^{-4}	4.2×10^{0}
250	4.2×10^{-3}	6.4×10^{1}		
500	1.49×10^{-3}	2.26×10^{1}	1.59×10^{-5}	2.42×10^{-1}
800	7.4×10^{-4}	1.12×10^{1}		
1,000	5.3×10^{-4}	8.0×10^{0}	4.6×10^{-6}	6.9×10^{-2}
1,500	2.87×10^{-4}	4.3×10^{0}	2.26×10^{-6}	3.4×10^{-2}
2,000	1.87×10^{-4}	2.83×10^{0}		
2,500	1.33×10^{-4}	2.02×10^{0}	1.03×10^{-6}	1.5×10^{-2}
5,000	4.7×10^{-5}	7.1×10^{-1}	2.64×10^{-7}	4.0×10^{-3}
10,000	1.67×10^{-5}	2.53×10^{-1}	7.7×10^{-8}	1.16×10^{-3}
20,000	5.9×10^{-6}	8.9×10^{-2}		
50,000	9.4×10^{-7}	1.42×10^{-2}	4.4×10^{-9}	6.7×10^{-5}
100,000	5.3×10^{-7}	8.0×10^{-3}	1.28×10^{-9}	1.94×10^{-5}

*$(\chi/Q)_{max} = 6.6 \times 10^{-5}$ sec/m^3 at 2050 m with a 90-ft-elevated source.

inversion conditions. The dispersion from a ground-level source is a minimum at the point of release and increases with distance downwind from the source. The resulting air concentration is greater at the closer distances, and beyond 5000 m is essentially the same as for the 90-ft-elevated source.

The conditions of the continuous MCA are the same as those used earlier, with the exception that the release point is assumed to be a ground-level source. The resulting exposures, which are a function of the dispersion, $(\chi/Q)_x$, can then readily be calculated from the data presented above. For $(\chi/Q)_{max} = 6.6 \times 10^{-5}$ sec/m^3 the exposure to the thyroid is 4.3 mrems/hr; the exposure to the bone is 0.84 mrem/hr; and the gamma-ray submersion dose is 8.4 mrems/hr (Tables 4.2 and 4.4). The exposures for any other dispersion, $(\chi/Q)_x$, are then

$$D_{thyroid} = 4.3 \frac{(\chi/Q)_x}{(\chi/Q)_{max}} ,$$

$$D_{bone} = 0.84 \frac{(\chi/Q)_x}{(\chi/Q)_{max}} ,$$

$$D_{\gamma\ submersion} = 8.4 \frac{(\chi/Q)_x}{(\chi/Q)_{max}} .$$

The exposures to the kidney and muscle have not been included here, since, as mentioned above, they were seen to be insignificant. Figures 4.5 and 4.6 give the dose rates for the typical inversion and lapse conditions. It should be noted that filtration with an efficiency of 99.9% is assumed for all isotopes except the noble gases.

The maximum exposure in the nearest residential area (350 m from the site) is seen to be the 0.42-rem/hr gamma-ray submersion dose rate during inversion conditions. Such conditions would have to be maintained for approximately 60 hr to give an exposure of 25 rems to the whole body.

Twenty-Four-Hour Total Integrated Dose from Continuous Source

In order to evaluate more accurately the exposures resulting from containment vessel leakage as a continuous source, the total integrated dose (TID) due to 24-hr leakage exposure has been calculated. It was assumed that a leakage rate of

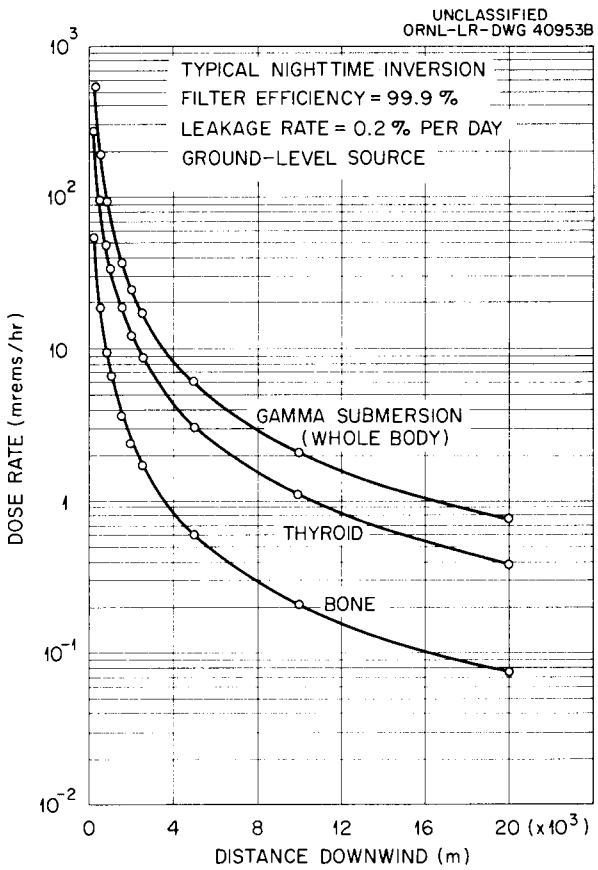

Fig. 4.5. Exposure Rate from a Continuous Ground-Level Source During Inversion.

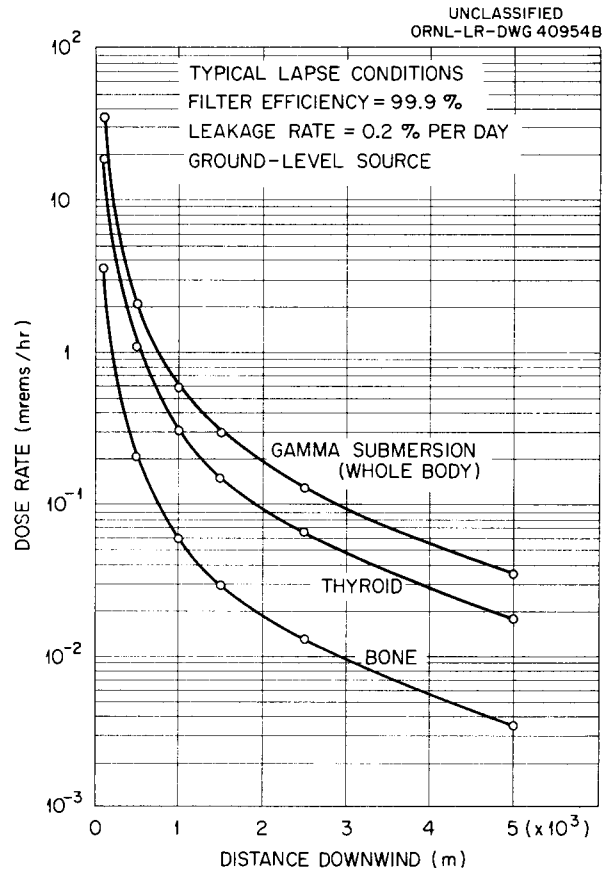

Fig. 4.6. Exposure Rate from a Continuous Ground-Level Source During Lopse.

0.2% per day and failure of 100% of the fuel elements represented the first-day conditions. The TID exposures were calculated for the 30 isotopes listed in Table 4.1; decay was not considered, since most of the isotopes have relatively long half lives.

90-ft-elevated Source. – The TID in mrems to internal organs is given by

$$\text{TID} = Q \times t \times D \times BR \times \left(\frac{\chi}{Q}\right)_x , \qquad (3)$$

where

Q = continuous source strength in curies/sec $= Q_L \times F_F$ ($F_F = 10^{-3}$, and Q_L = containment vessel leakage rate),

t = time of exposure, 24 hr, or 8.64×10^4 sec,

D = exposure from intake of 1 μc of isotope in mrems/μc (ref 10),

$(\chi/Q)_x$ = dispersion in sec/m^3,

BR = breathing rate in cm^3/sec = 500 cm^3/sec.

The TID's for the 30 isotopes listed in Table 4.1 have been calculated for the critical organs of reference. The 24-hr critical-organ TID's are tabulated below for the point of maximum ground concentration [$(\chi/Q)_{max} = 6.6 \times 10^{-5}$ sec/m^3, nighttime inversion]:

Critical Organ	24-hr TID (mrems)
Thyroid	202
Bone	38
Kidney	0.0125
Muscle	0.064

The TID's to the thyroid and bone are plotted in Figs. 4.7 and 4.8 as a function of distance downwind of the source for the typical inversion and lapse conditions.

[10] T. J. Burnett, *Nuclear Sci. and Eng.* 2, 382 (1957).

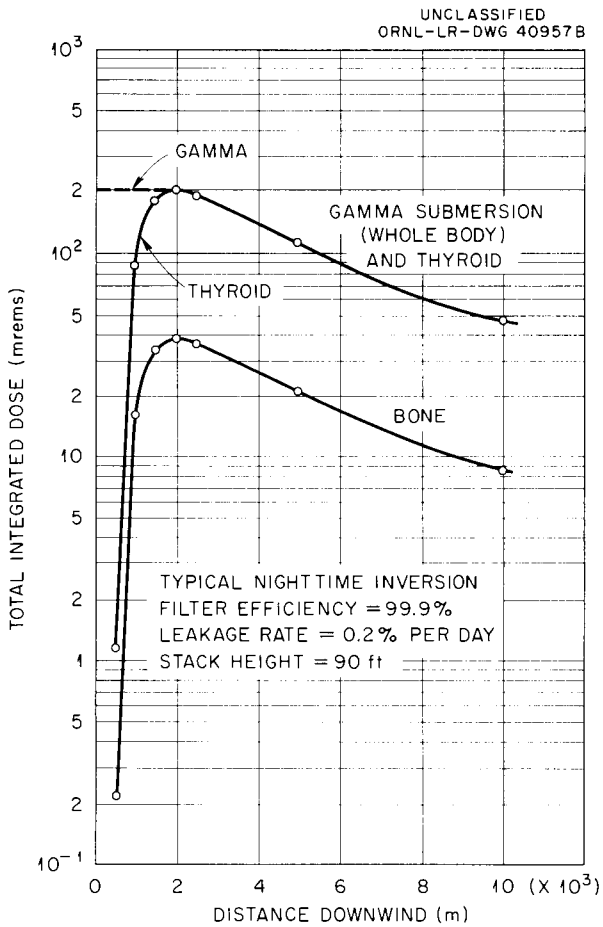

Fig. 4.7. Total Integrated Dose in 24 hr from Continuous Elevated Source During Nighttime Inversion.

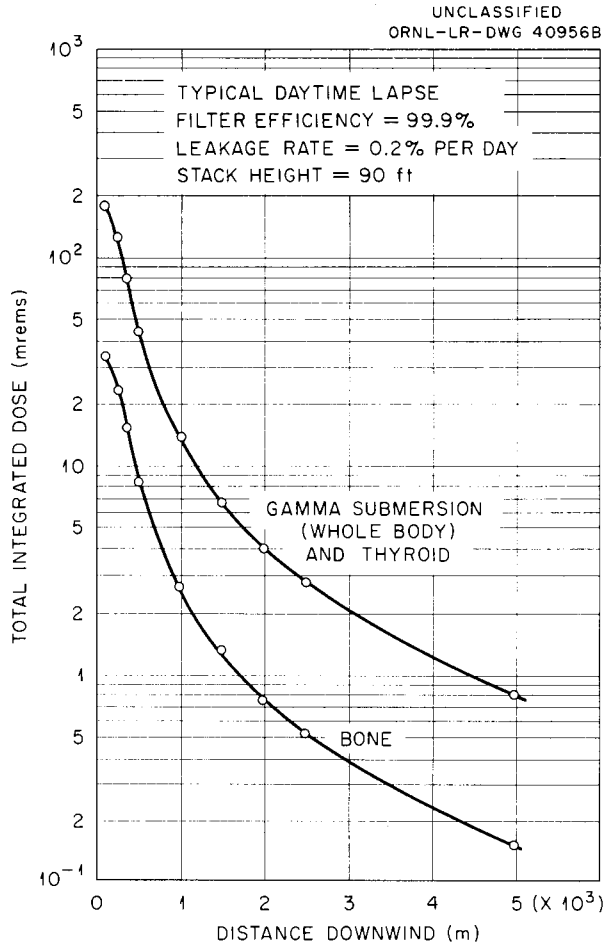

Fig. 4.8. Total Integrated Dose in 24 hr from Continuous Elevated Source During Daytime Lapse.

The external exposure from submersion in a radioactive cloud from a continuous source at the point of maximum ground concentration for inversion conditions was given above as 8.4 mrems/hr. If it is assumed that this exposure lasts for a period of 24 hr, the TID is 202 mrems. The 24-hr TID from submersion is also plotted in Figs. 4.7 and 4.8 as a function of distance downwind for inversion and lapse conditions. The dose at a distance less than 2000 m for inversion is the 2000-m dose given previously (see p 21).

It should be noted that in calculating these exposures it was assumed that the given meteorological conditions (wind direction, etc.) would prevail for a period of 24 hr. This is not usually the case, and lower exposure would be expected because of changes in wind direction and a change from lapse to inversion during the day-to-night period.

Ground-Level Source. – The same assumptions are made here as for the 90-ft source, and Eq. (3) yields the total integrated dose when $(\chi/Q)_x$ for a ground-level source is used. The resulting TID's are plotted in Figs. 4.9 and 4.10 for the inversion and lapse conditions. The maximum TID at the nearest residential area (approximately 350 m downwind) is 7.5 rems to the thyroid and 1.4 rems to the bone during inversion conditions.

The submersion exposure is obtained in the same manner as for a 90-ft-elevated source, except for the use of the ground-level $(\chi/Q)_x$. The external gamma-ray submersion TID is also plotted in Figs. 4.9 and 4.10 and may be seen to be identical with the thyroid TID. The maximum submersion TID in a residential area (~350 m) is 7.5 rems and occurs during inversion.

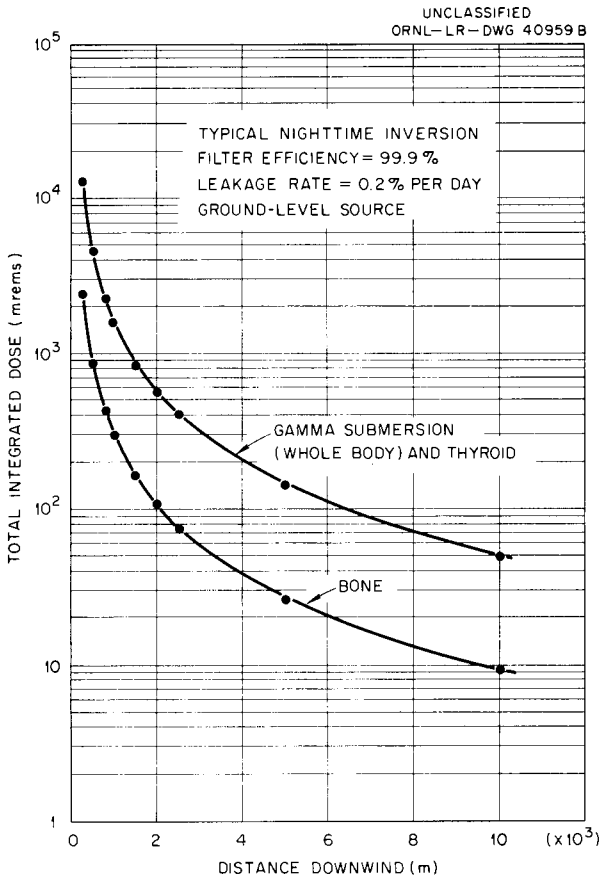

Fig. 4.9. Total Integrated Dose in 24 hr from Continuous Ground-Level Source During Inversion.

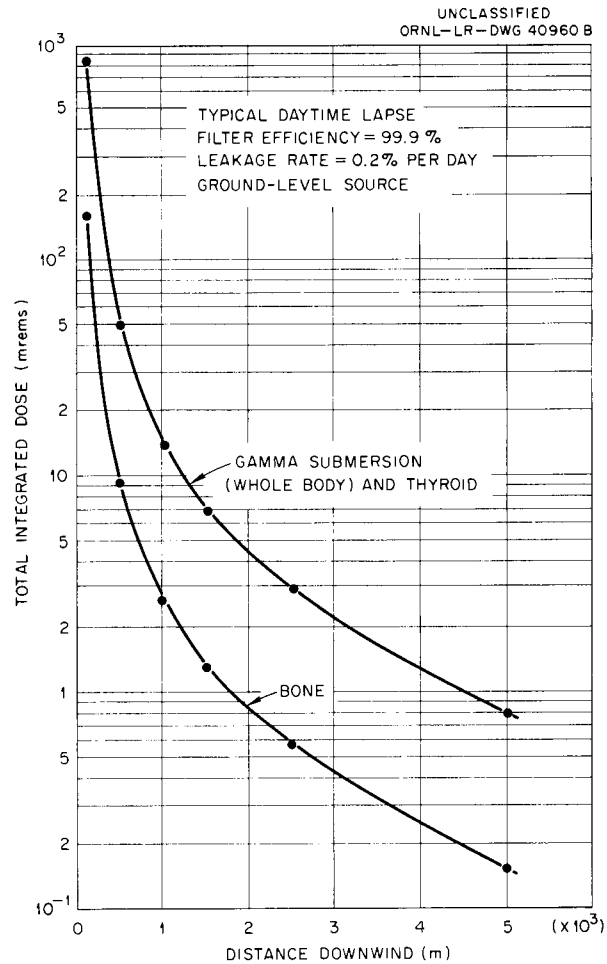

Fig. 4.10. Total Integrated Dose in 24 hr from Continuous Ground-Level Source During Lapse.

Exposure from MCA Occurring After Containment Vessel Is Opened

90-ft-elevated Source. – If the MCA were to occur after the containment vessel had been opened, much larger quantities of activity would be released to the environment. In order to estimate the consequences of such an accident it was assumed (1) that the activity would be released as an instantaneous point source at stack level, (2) that the filter would be 99.9% effective for particulate matter, and (3) that the release fractions would be those given in the preceding section. The activity release would be that due to failure of 100% of the fuel elements following operation at power for 52,000 Mwd, as reduced by the filter and release fractions.

The total integrated dose from the activity discharged from the stack may be calculated from the following information:

1. total integrated release (Q, in curies) of each isotope,
2. exposure from each element inhaled (D, in mrems/μc),[10]
3. breathing rate (taken as $BR = 5 \times 10^2$ cm^3/sec),
4. atmospheric dilution factor [$(\chi/Q)_x$, in sec/m^3].

For an instantaneous release $(\chi/Q)_x$ is the integrated fractional concentration at distances x meters downwind. Thus the total integrated dose in mrems is

$$\text{TID} = Q \times D \times BR \times \frac{\chi}{Q} \quad .$$

From the results for the continuous-exposure case, Table 4.1, it is obvious that only the

isotopes listed in Table 4.6 are important in determining the internal exposure. The curies of each isotope released are obtained from Table 4.1 by dividing the rate of release from the containment vessel by the fractional release rate, that is, 2.3×10^{-8} fraction/sec.

The integrated dose (in mrems) may be obtained from the last column of Table 4.6 by multiplying by the appropriate $(\chi/Q)_x$. The results are shown in Table 4.7 for the typical nighttime inversion and daytime lapse conditions as a function of distance downwind of the source. The exposure to the internal organs is shown in Fig. 4.11 for the nighttime inversion.

The submersion exposure for the instantaneous case can readily be calculated from the data for the continuous case by taking the following factors into consideration:

1. The source is now the total activity released, Q_T (in μc), instead of the release rate, Q (in μc/sec). ($Q_T = Q/F$, where $F = 2.3 \times 10^{-8}$ fraction/sec is the fractional release per second.)

2. The dilution is $(\chi/Q)_{TID}$, the total integrated "exposure" fraction, instead of χ/Q, the concentration fraction.

3. Instead of D (the dose rate), TID (the total integrated dose) is used.

Table 4.6. Integrated Dose from MCA Occurring After Containment Vessel Is Opened

Isotope	Q (curies)	D (mrems/μc)*		$Q \times D \times BR$
		Bone		
Sr^{89}	2.58×10^2	312		4.0×10^7
Sr^{90}-Y^{90}	1.30×10^1	34,800		2.26×10^8
Sr^{91}-Y^{91m}	3.2×10^2	217		3.4×10^7
Ba^{140}-La^{140}	3.6×10^2	109		1.95×10^7
Ce^{144}-Pr^{144}	2.60×10^0	1,160		1.51×10^6
			Total	3.2×10^8
		Thyroid		
I^{131}	1.95×10^3	963		9.4×10^8
I^{133}	3.7×10^3	227		4.2×10^8
I^{135}	3.4×10^3	63		1.06×10^7
			Total	1.46×10^9
		Kidney		
Te^{127m}-Te^{127}	3.3×10^{-1}	18.3		3.0×10^3
Te^{129m}-Te^{129}	2.06×10^0	46		4.7×10^4
Te^{132}	2.58×10^1	1.5		1.94×10^4
			Total	6.9×10^4
		Muscle		
Cs^{137}-Ba^{137m}	1.15×10^2	8.6		5.0×10^5
			Total	5.0×10^5

*The exposure rates listed here were calculated from values of D, total exposure per unit inhaled activity, taken from ref 10. It should be noted, however, that these values are subject to constant study and improvement. For example, the calculated dose in mr per mc of iodine breathed has been increased about 50% since ref 10 was written. The values for the other elements have changed less, and the total integrated dose values calculated from the data of this table are reasonably close to those calculated with the more recent data.

Table 4.7. Internal Dose to Critical Organs from MCA Occurring After Containment Vessel Is Opened

x (m)	χ/Q	TID (mrems)			
		Bone	Thyroid	Kidney	Muscle
		Nighttime Inversion			
250	2.6×10^{-13}	8.3×10^{-5}	3.8×10^{-4}	1.79×10^{-8}	1.3×10^{-7}
500	3.7×10^{-7}	1.18×10^{2}	5.4×10^{2}	2.55×10^{-2}	1.85×10^{-1}
1,000	2.8×10^{-5}	9.0×10^{3}	4.1×10^{4}	1.93×10^{0}	1.40×10^{1}
1,500	5.8×10^{-5}	1.86×10^{4}	8.5×10^{4}	4.0×10^{0}	2.90×10^{1}
2,000	6.6×10^{-5}	2.11×10^{4}	9.6×10^{4}	4.6×10^{0}	3.3×10^{1}
2,500	6.3×10^{-5}	2.02×10^{4}	9.2×10^{4}	4.3×10^{0}	3.2×10^{1}
5,000	3.6×10^{-5}	1.15×10^{4}	5.3×10^{4}	2.48×10^{0}	1.80×10^{1}
10,000	1.5×10^{-5}	4.8×10^{3}	2.19×10^{4}	1.04×10^{0}	7.5×10^{0}
20,000	5.7×10^{-6}	1.82×10^{3}	8.3×10^{3}	3.9×10^{-1}	2.85×10^{0}
		Daytime Lapse			
100	5.65×10^{-5}	1.81×10^{4}	8.2×10^{4}	3.9×10^{0}	2.83×10^{1}
250	4.00×10^{-5}	1.28×10^{4}	5.8×10^{4}	2.76×10^{0}	2.00×10^{1}
350	2.6×10^{-5}	8.3×10^{3}	3.8×10^{4}	1.79×10^{0}	1.30×10^{1}
500	1.45×10^{-5}	4.6×10^{3}	2.12×10^{4}	1.00×10^{0}	7.3×10^{0}
1,000	4.5×10^{-6}	1.44×10^{3}	6.6×10^{3}	3.1×10^{-1}	2.25×10^{0}
1,500	2.2×10^{-6}	7.0×10^{2}	3.2×10^{3}	1.52×10^{-1}	1.10×10^{0}
2,000	1.3×10^{-6}	4.2×10^{2}	1.90×10^{3}	9.0×10^{-2}	6.5×10^{-1}
2,500	9.0×10^{-7}	2.88×10^{2}	1.31×10^{3}	6.2×10^{-2}	4.5×10^{-1}
5,000	2.6×10^{-7}	8.3×10^{1}	3.8×10^{2}	1.79×10^{-2}	1.30×10^{-1}

The gamma submersion exposure from the krypton and xenon isotopes is the only case considered, since, as indicated above, it is the controlling case where the filter is 99.9% efficient for nongaseous activity. The following two formulas thus apply to the continuous and instantaneous release cases respectively:

$$D_\gamma \text{(rems/hr)} = 9.36 \times 10^{-4} \sum_i (E_i Q_i)_\gamma \left(\frac{\chi}{Q}\right) ,$$

$$\text{TID}_\gamma \text{(rems)} = \frac{9.36 \times 10^{-4}}{3600} \sum_i (E_i Q_{T,i}) \left(\frac{\chi}{Q}\right)_{\text{TID}} ,$$

where E is in Mev/dis and Q is microcuries released.

It turns out that χ/Q and $(\chi/Q)_{\text{TID}}$ are numerically the same for given meteorological conditions, and, since $Q_{T,i} = Q_i/F$, then

$$\text{TID}_\gamma \text{(rems)} = \left(\frac{D_\gamma}{F}\right) \frac{1}{3600} ,$$

where D_γ is in rems/hr. For the continuous case,

$$D_\gamma [\text{Kr} + \text{Xe}] = 8.4 \text{ mrems/hr}$$

at

$$\left(\frac{\chi}{Q}\right)_{\text{max}} = 6.6 \times 10^{-5} .$$

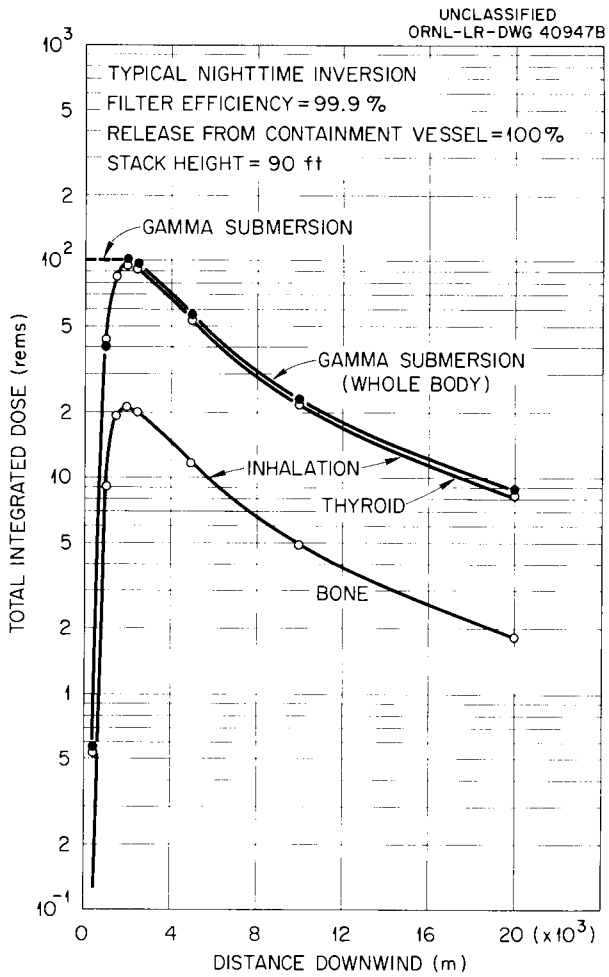

Fig. 4.11. Total Integrated Dose from Instantaneous Elevated Source During Inversion (Containment Vessel Voided).

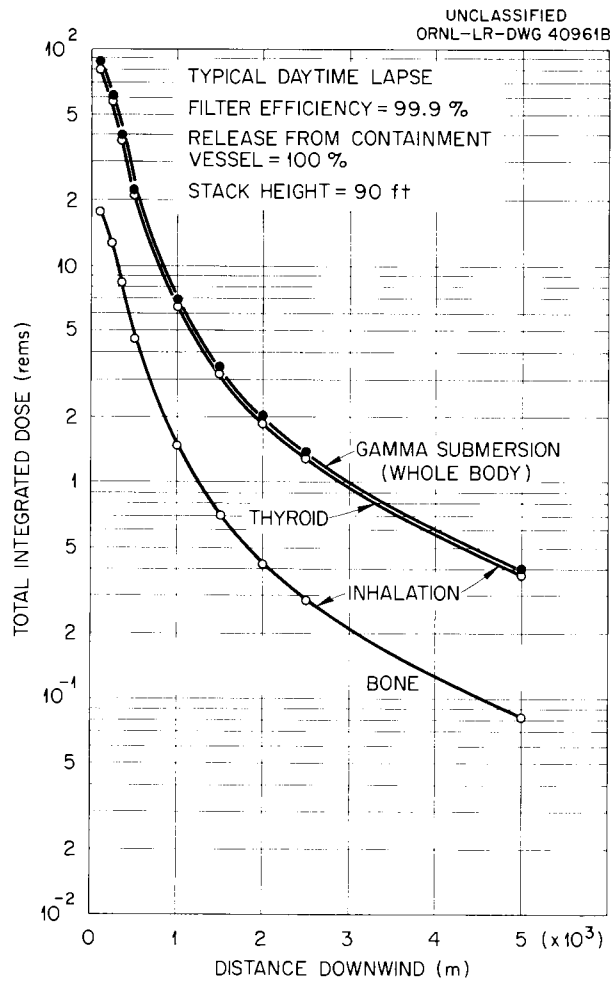

Fig. 4.12. Total Integrated Dose from Instantaneous Elevated Source During Lapse (Containment Vessel Voided).

Thus

$$TID_{\gamma}[Kr + Xe] = \frac{8.4 \times 10^{-3}\ \text{rem/hr}}{2.3 \times 10^{-8}\ \text{fraction/sec} \times 3600\ \text{sec/hr}} = 101\ \text{rems}\ ,$$

for nighttime inversion conditions, is the maximum dose which would occur at distances up to 2000 m downwind of the source. Table 4.8 and Figs. 4.11 and 4.12 show the gamma-submersion dose as a function of distance downwind for nighttime inversion and daytime lapse conditions. The dotted portion of the gamma-submersion curve for inversion is an extrapolation of the maximum dose rate (see p 21).

The exposures given in Figs. 4.11 and 4.12 were calculated on the basis of a number of assumptions that were, in general, conservative but which must be considered in order to evaluate adequately the calculated results. If, as in this instance, the resulting exposure levels were too great, appropriate steps would have to be taken to assure that the accident could not happen as described and that the consequences of any credible accident would be tolerable.

The accident described in the preceding analysis as the "maximum credible accident occurring when the containment vessel is opened" is representative of any accident in which the containment vessel, as well as the primary system, has been ruptured, as long as it is assumed that the resulting activity may be discharged through the

Table 4.8. Submersion Exposure with Container Open

x, Distance Downwind (m)	TID_γ [Kr + Xe] (rems)	
	Nighttime Inversion*	Daytime Lapse
100	1.01×10^2	8.8×10^1
250	1.01×10^2	6.2×10^1
350	1.01×10^2	4.0×10^1
500	1.01×10^2	2.22×10^1
1,000	1.01×10^2	7.0×10^0
1,500	1.01×10^2	3.4×10^0
2,000	1.01×10^2	2.03×10^0
2,500	9.7×10^1	1.38×10^0
5,000	5.6×10^1	4.0×10^{-1}
10,000	2.28×10^1	1.18×10^{-1}
20,000	8.8×10^0	

*The nighttime inversion TID's are identical out to 2000 m (see p 21).

filter and stack. If this assumption is not valid, the resulting internal exposures should be increased by the 10^3 filter factor, as well as by a factor to account for not having the effect of the stack elevation, which could further increase the dose by as much as a factor of 10^2. Inclusion of these factors would give intolerable doses.

Ground-Level Source. – The calculation of the exposure from the open-container MCA, considered as a ground-level source, follows that for an elevated source, as described above. The total integrated dose (in rems) can be scaled from the results given above for $(\chi/Q)_x/(\chi/Q)_{max}$, and the following equations result:

$$TID_{thyroid} = 96 \frac{(\chi/Q)_x}{(\chi/Q)_{max}},$$

$$TID_{bone} = 21.1 \frac{(\chi/Q)_x}{(\chi/Q)_{max}},$$

$$TID_{\gamma\ submersion} = 101 \frac{(\chi/Q)_x}{(\chi/Q)_{max}} .$$

Figures 4.13 and 4.14 give the total integrated dose for the typical inversion and lapse conditions as a function of the distance downwind. For the inversion condition the whole-body (submersion) dose is greater than 25 rems at all distances under 10,000 m, and this situation is considered to be unacceptable. During lapse conditions the 25-rem exposure occurs at a distance of about 500 m downwind. Since the nearest residential area is about 300 m downwind, this exposure is not felt to be acceptable, although it may be that no one off the site would be exposed to more than 25 rems during the lapse conditions.

Whole-Body Exposure from Ground Deposition

The deposition of radioactive materials on the ground, in addition to contaminating the ground, will produce a gamma-ray field that will contribute to the whole-body exposure of the people in the area. The beta exposure from ground deposition will not be considered here, since it has been shown, in the case of submersion, to be smaller by a factor of 3 than the gamma-ray dose, and it is essentially a skin dose which is not controlling. As discussed in Appendix A (p 76–78), there are three types of ground deposition, namely, dry deposition, rainout, and total instantaneous washout.

The term "dry deposition" is used to designate deposition during nonprecipitating weather and includes the effects of both gravitational settling and impaction. For the particle sizes assumed here, dry deposition is negligible. Rainout is defined as removal due to association of the particulate or gaseous matter with the precipitation element prior to its descent. As noted in Appendix A, the rate of rainout is fairly constant with the rate of rainfall and as used here would apply to rainfalls of the order of 0.1 in./hr. Washout is used to designate removal of material from the air due to capture by falling precipitation elements. Total instantaneous deposition is then the limiting case of the complete deposition of an entire cloud or plume of air-borne material, such as might occur in a sudden heavy rain shower.

The external whole-body exposure from the ground deposition is the only type of exposure considered. However, it should be noted that other types of exposure are possible, namely, contamination of water supplies and foodstuffs with an accompanying internal dose, actual deposition on the skin or clothing of an individual, and contamination of hands due to handling of

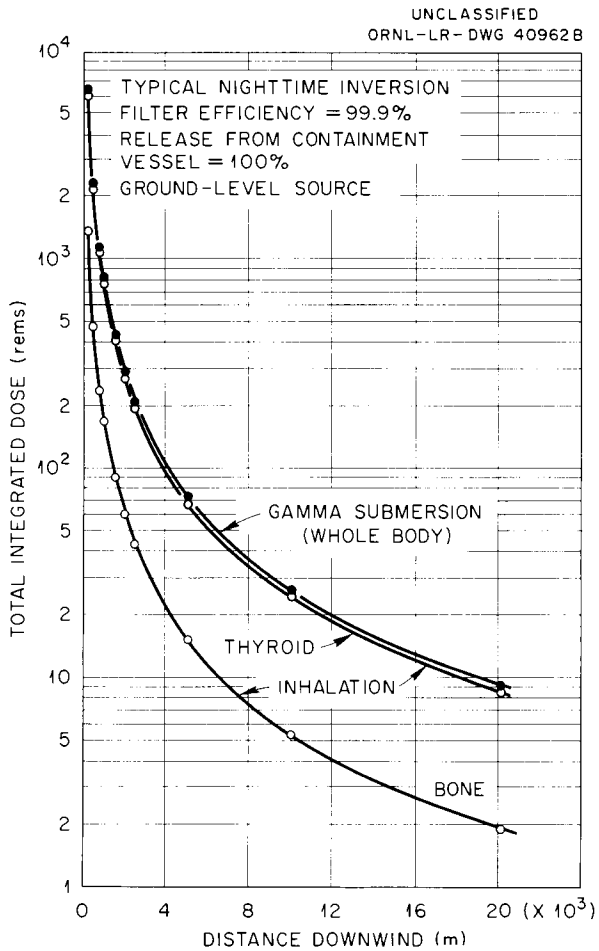

Fig. 4.13. Total Integrated Dose from Instantaneous Ground-Level Source During Inversion (Containment Vessel Voided).

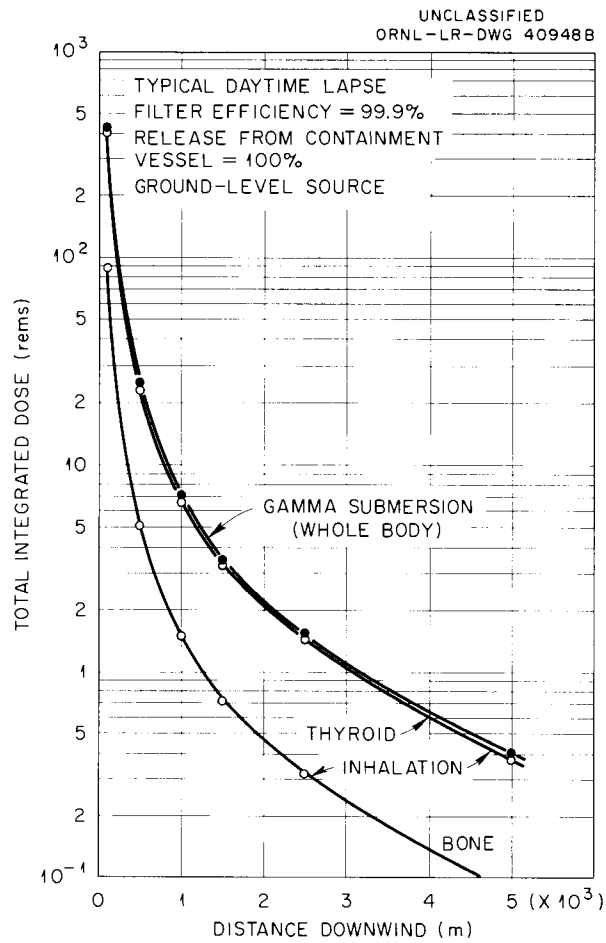

Fig. 4.14. Total Integrated Dose from Instantaneous Ground-Level Source During Lapse (Containment Vessel Voided).

contaminated material and subsequent transfer to the mouth (internal dose).

Formula for Whole-Body Exposure. – In deriving the formula for calculating the dose from ground deposition, the following assumptions are made:

1. The source is an infinite plane source, and the flux is one-half the total flux emanating from a unit area (the half directed upward).

2. An average gamma energy of 0.5 Mev/dis (see Table 4.3) is assumed for the activity released. The dose rate in rems/hr is

$$D = \frac{\text{Flux}}{\text{Flux equivalent to 1 rem/hr}} \ . \qquad (4)$$

The flux equivalent to 1 rem/hr is 9.5×10^5 photons·sec^{-1}·cm^{-2} for a photon energy of 0.5 Mev/dis (ref 11).

3. The dose point is taken as 100 cm above the contaminated plane, and the flux, as given in ref 11, p 348, is

$$\text{Flux} = B\frac{SA}{2}E_1(b_1) \ , \qquad (5)$$

where

B = symbolic buildup factor,

SA = plane source strength (photons·sec^{-1}·cm^{-2}),

[11]T. Rockwell III (ed.), *Reactor Shielding Design Manual*, Fig. 2.2, TID-7004 (March 1956).

$$E_1(b_1) = \int_{b_1}^{\infty} \frac{e^{-x}}{x} dx \ ,$$

$$b_1 = (\mu_{air})x,$$

μ_{air} = macroscopic cross section of air (cm^{-1}),

x = distance from plane to detection point (cm).

The macroscopic cross section of air at 1 atm and 20°C is about 1×10^{-4} cm^{-1}. Thus for x = 100 cm, b_1 is 1×10^{-2}, and from ref 11, p 372,

$$E_1(b_1) = 4 \ .$$

The plane source strength in photons·sec^{-1}·cm^{-2} thus becomes

$$SA = Q \times \left(\frac{\omega}{Q}\right) 10^{-4} \times 3.7 \times 10^{10} \ , \qquad (6)$$

where

Q = source strength (curies),

ω/Q = dispersion (m^{-2}) (see Tables A.2 and A.3).

The buildup factor, B, is taken to be 1.0, and it is not expected that the actual value will differ appreciably from this value for the dose at 100 cm in air from a plane source.

Substitution into Eq. (5) gives the flux in photons·sec^{-1}·cm^{-2} as

$$\text{Flux} = 7.4 \times 10^6 \, Q \left(\frac{\omega}{Q}\right) \ .$$

The dose rate in rems/hr is then

$$D = \frac{7.4 \times 10^6 \, Q(\omega/Q)}{9.5 \times 10^5}$$

$$= 7.8 \, Q\left(\frac{\omega}{Q}\right) \ . \qquad (7)$$

Continuous Source. – For deposition the source is taken to be all activity which has leaked from the containment vessel (excluding the noble gases, which will not be deposited). Assuming the failure of 100% of the fuel elements, the fractional releases tabulated on p 16, a containment vessel leak rate of 0.2% per day, and a filter efficiency of 99.9%, a summation of the individual isotopic leak rates (Table G.1) shows

$$\sum_i Q_i = 0.92 \times 10^{-3} \text{ curie/sec} \ ,$$

omitting isotopes with half lives shorter than 2 min or with significant fission yields.

As mentioned earlier, rainout conditions would occur under rainfall rates of the order of 0.1 in./hr. It is considered plausible that such a meteorological condition could exist for a period of 24 hr, during which the above leakage rate would be typical. The total quantity (Q) of activity released in 24 hr is

$$Q = 0.92 \times 10^{-3} \text{ curie/sec} \times 8.64 \times 10^4 \text{ sec} \ ,$$

or

$$Q = 7.9 \times 10^1 \text{ curies} \ .$$

Substituting in Eq. (7), the dose rate after 24 hr of leakage is

$$D = 7.8 \times 7.9 \times 10^1 \left(\frac{\omega}{Q}\right),$$

in rems/hr, or

$$D = 6.2 \times 10^5 \left(\frac{\omega}{Q}\right), \qquad (8)$$

in mrems/hr.

The resulting external 24-hr exposures from deposition due to rainout under typical lapse and inversion conditions are given in Table 4.9. The values of ω/Q for rainout are from Table A.2.

These exposures are seen to be small in comparison with inhalation exposures, and this case will not be examined further. A more accurate and less conservative determination could be made by integrating the exposure from each isotope over the 24-hr period.

Total instantaneous washout is assumed to occur during a heavy sudden shower. The source strength for a continuous source is

$$Q = 0.92 \times 10^{-3} \text{ curie/sec} \ .$$

The dose rate is [from Eq. (7)]

$$D = 7.8 \times 0.92 \times 10^{-3} \times \left(\frac{\omega}{Q}\right) \times 10^3$$

$$= 7.2 \times 10^0 \left(\frac{\omega}{Q}\right), \qquad (9)$$

in mrems/hr.

The dose rates as a function of distance downwind for the typical inversion and lapse conditions are given in Table 4.10 and Fig. 4.15. The exposure rates are seen to be less than those for inhalation exposures.

Table 4.9. Whole-Body Exposure Due to Rainout Deposition

Distance Downwind (m)	Inversion Conditions		Lapse Conditions	
	ω/Q (m^{-2})	D (mrems/24 hr)	ω/Q (m^{-2})	D (mrems/24 hr)
10	2.35×10^{-5}	1.75×10^{2}	4.15×10^{-6}	3.08×10^{1}
10^2	4.17×10^{-5}	3.10×10^{1}	5.35×10^{-7}	3.98
10^3	7.09×10^{-7}	5.28	6.73×10^{-8}	5.00×10^{-1}
10^4	8.45×10^{-8}	6.29×10^{-1}	7.12×10^{-9}	5.29×10^{-2}

Table 4.10. Whole-Body Exposure Due to Washout Deposition (Continuous Source)

Distance Downwind (m)	Inversion Conditions		Lapse Conditions	
	ω/Q (m^{-2})	D (mrems/hr)	ω/Q (m^{-2})	D (mrems/hr)
10	2.37×10^{-1}	1.71	4.15×10^{-2}	2.99×10^{-1}
10^2	4.21×10^{-2}	3.03×10^{-1}	5.35×10^{-3}	3.85×10^{-2}
10^3	7.47×10^{-3}	5.38×10^{-2}	6.88×10^{-4}	4.95×10^{-3}
10^4	1.33×10^{-3}	9.58×10^{-3}	8.87×10^{-5}	6.39×10^{-4}
10^5	2.48×10^{-4}	1.79×10^{-3}	1.14×10^{-5}	8.21×10^{-5}

Instantaneous Source. – While the instantaneous or open-container source has been ruled out as being implausible, it is discussed here to indicate the range of exposures that would result from an accident which could be caused intentionally by sabotage or war, or unintentionally by inadequate administrative control. It has been assumed for this analysis that the filtration system is operating and thus reducing the activity by a factor of 10^3. The source strength when all activity in the containment vessel is released is

$$Q = \frac{0.92 \times 10^{-3}}{2.3 \times 10^{-8}} \text{ curies} ,$$

or

$$Q = 4.0 \times 10^4 \text{ curies} .$$

For an MCA with the containment vessel open, it is assumed that rainout conditions could prevail during the entire period of release. The release of activity from an open-container MCA is assumed to follow the melting of fuel elements. Figure G.1 shows that 89% of the fuel elements have melted within 2 hr after onset of the MCA, and a maximum of 96% meltdown is reached within 10 hr. The actual release to the atmosphere will be stretched out over a longer period. To be on the conservative side, 100% melting was assumed.

The dose equation for a Q of 4.0×10^4 curies is [from Eq. (7)]

$$D = 7.8 \times 4.0 \times 10^4 \left(\frac{\omega}{Q}\right),$$

in rems/hr, or

$$D = 3.1 \times 10^8 \left(\frac{\omega}{Q}\right), \qquad (10)$$

in mrems/hr.

Table 4.11 and Fig. 4.16 show the resulting exposures as a function of distance downwind for the inversion and lapse conditions. Although no account has been taken of diminution of activity by decay or runoff, it is evident that the containment vessel should not be opened or left open.

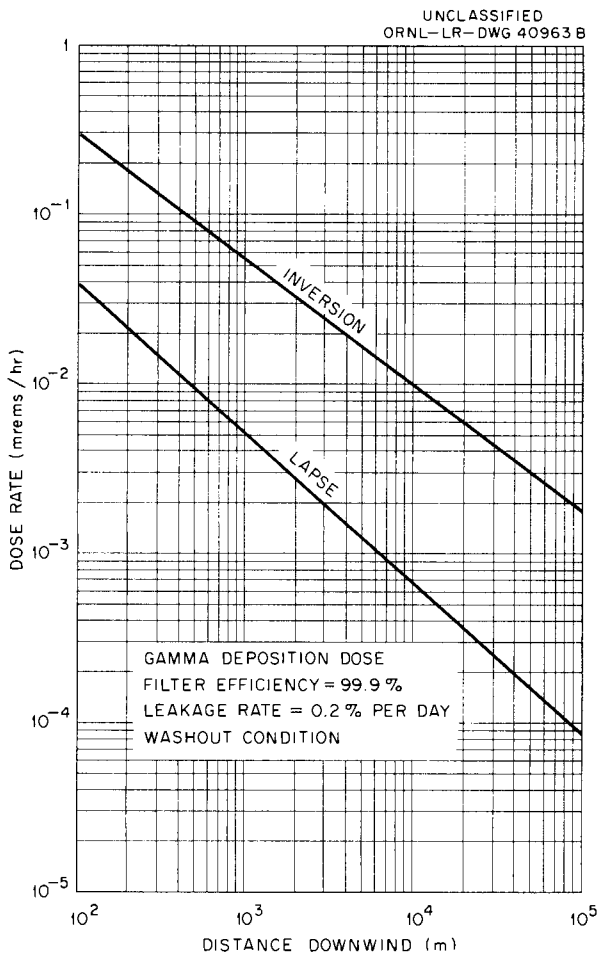

Fig. 4.15. Whole-Body Exposure Rate from Washout Deposition of a Continuous Elevated Source.

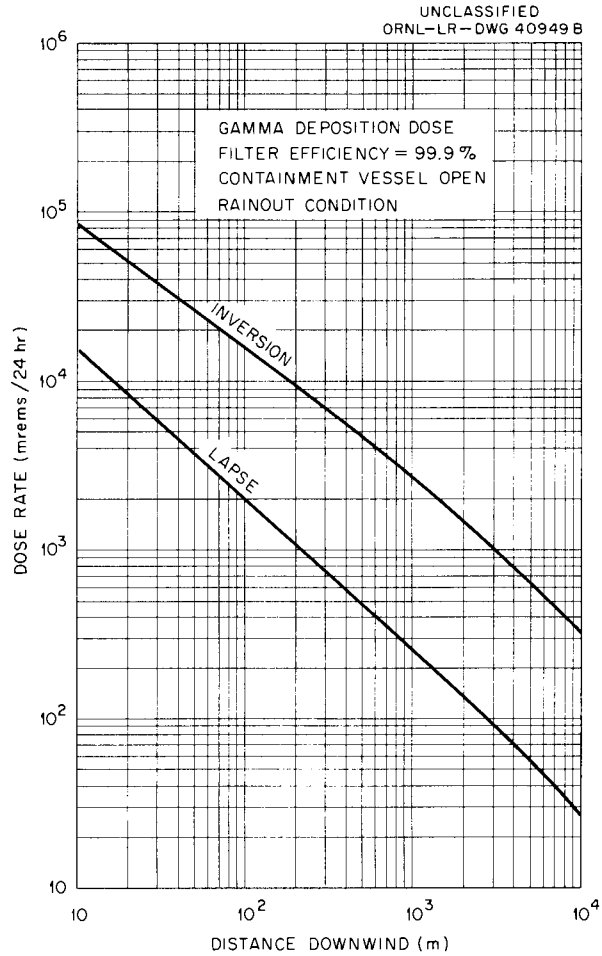

Fig. 4.16. Whole-Body Exposure Rate from Rainout Deposition of an Instantaneous Source. Containment vessel voided; 0.1 in./hr rainfall.

Table 4.11. Whole-Body Exposure Due to Rainout Deposition with Containment Vessel Open

Distance Downwind (m)	ω/Q (m^{-2})	D (mrems/24 hr)
	Inversion	
10	2.35×10^{-5}	8.75×10^{4}
10^2	4.17×10^{-6}	1.55×10^{4}
10^3	7.09×10^{-7}	2.64×10^{3}
10^4	8.45×10^{-8}	3.14×10^{2}
	Lapse	
10	4.15×10^{-6}	1.55×10^{4}
10^2	5.31×10^{-7}	1.98×10^{3}
10^3	6.67×10^{-8}	2.48×10^{2}
10^4	7.05×10^{-9}	2.63×10^{1}

Washout has not been calculated for the open-container case. If such a calculation were to be carried out, the main difficulty would be in arriving at the proper source strength. An instantaneous release of all the activity could be assumed; however, this would not be accurate, since the actual release would follow the melting of fuel elements, which is a function of time. The second approach would be to assume a continuous source represented by the maximum rate of fuel-element melting (see Appendix G). The dose rate would be

$$D = 7.8 \times Q_n \left(\frac{\omega}{Q}\right)_n ,$$

in rems/hr, where Q_n is either a continuous or instantaneous source and $(\omega/Q)_n$ is the corresponding dispersion value for a continuous or

instantaneous source for washout conditions (see Appendix A).

RELEASE TO THE HYDROSPHERE

In the preceding sections, only the dispersion of radioactive contaminants by the atmosphere has been considered. Since the reactor is located on a ship, the problems associated with discharge of radioactivity to bodies of water and, in particular, to rivers, estuaries, and harbors are of vital importance.

Of immediate concern if a large quantity of radioactivity were released to a harbor would be the exposure the general populace would receive as a direct consequence of the accident. The exposure might be received by (1) contacting the harbor water during swimming or boating, (2) drinking contaminated water supplied from the harbor, and (3) eating fish and other biota from the contaminated area. The first two types of exposure are considered in detail here. They would present the most pressing problems following an accidental discharge, since they would result in the largest population exposure.

A further problem considered here is that of exposure in the immediate vicinity of the source. In this case, where the mixing due to the action of the tide, river turbulence, and diffusion has not taken place, the concentration will be many times greater than that present after one tidal cycle. The exposure conditions will be limited, however, both in time and area affected.

The problems that would be associated with release of radioactivity to the Delaware River Estuary are of particular concern. The release point chosen is the dock site at the New York Shipbuilding Corporation (NYS) yards at Camden, New Jersey, where the NS "Savannah" is under construction and where the initial testing and reactor startup will take place. Of particular interest is the possible contamination of the Torresdale filter plant that supplies drinking water to Philadelphia.

The behavior of the radioactivity after release to the river has been extrapolated from model experiments carried out by the Corps of Engineers.[12–14] In addition to the physical dispersion of the activity by the action of the tide, river flow, etc., as represented in the model data, the physical decay of the individual isotopes and the uptake of these isotopes by the mud, fish, and river biota have been considered.

The two types of release mechanisms considered are (1) leakage from the containment vessel following the MCA after sinking of the "Savannah" and (2) the deposition of an atmospheric MCA release on the surface of the river by rainout or washout. The main emphasis has been placed on the leakage from the containment vessel of a sunken ship, since such leakage would give the greatest doses. It is assumed that no reduction in the total quantity of activity released would be accomplished by filtration.

Types of Accidental Release of Activity

Leakage from a Sunken Vessel. – If activity from an MCA were released to the water from a sunken vessel, two cases would have to be considered: (1) instantaneous release from a ruptured containment vessel and (2) leakage without rupture of the containment vessel. An analysis of ship collision data[15] has shown that the accidental rupture of the "Savannah" containment vessel subsequent to sinking of the ship in a port, harbor, or river area is not credible. Unless sabotage or other similar circumstances are considered, there are no credible postulated accidents that would lead to rupture of the containment vessel and instantaneous release of activity to the hydrosphere. Thus the only case to be considered is that of leakage from the unruptured containment vessel.

The experimental model data used in this analysis were obtained by the U.S. Army Engineers[13] in three tests in which the source was continuous. (A continuous source is here considered to have a duration of several days or tidal cycles.) The same dye release point, located at the left channel prism line opposite channel station 31, was used for all tests. Channel stations are located 1000 ft apart, and station 0 is located opposite Allegheny Avenue, Philadelphia. Stations downstream are

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[12] D. W. Pritchard, *A Study of Flushing in the Delaware Model*, Technical Report VII, The Chesapeake Bay Institute (April 1954).

[13] *Contamination Dispersion in Estuaries – Delaware River*, Miscellaneous Paper No. 2–332, Report I, U.S. Army Engineer Waterways Experiment Station (April 1959).

[14] *Delaware River Model Study Report No. 1 – Hydraulic and Salinity Verification*, Technical Memorandum No. 2-337, U.S. Army Engineers Waterways Experiment Station (May 1956).

[15] J. H. MacMillan (ed.), *Nuclear Merchant Ship Reactor Project Preliminary Safeguards Report*, BAW-1117, vol I (rev) (Dec. 22, 1958).

numbered positively and those upstream negatively. Station 31 is located approximately opposite the covered ways at NYS, as determined by measuring 31,000 ft downstream from station 0 on Coast and Geodetic Survey chart No. 295 (or 101 miles above the mouth of Delaware Bay). Six liters of methylene blue chloride dye of an initial concentration of 1000 ppm was released in each model test. The concentration detected at a given sampling station is reported as a percentage of the initial concentration.

All sampling was done at the time of local high-water slack at each sampling station. Sampling stations were located on the center line of the navigation channel at 5-ft intervals in the model (every five stations in the prototype). Samples were obtained throughout the contaminated reach during tidal cycles 1, 3, and 5, and every fifth cycle thereafter.

In order to obtain additional information on the possible contamination of the Torresdale filter plant, samples were taken every second tidal cycle at the postulated intake point. These observations were made at a location about halfway between the edge of the navigation channel and the shore, where the average depth of water is about 10 ft; channel center-line observations at station −35, opposite this location, were generally higher than observations made at the assumed intake location.

In model test 2, one-half the volume of dye was introduced at a uniform rate during the 3-hr interval (0.24 tidal cycle) following local low-water slack at the release point; the remaining volume was introduced at a uniform rate during the next 19.76 tidal cycles. Thus the dye release covered a period of 20 tidal cycles. Release at low-water slack results in the greatest potential upstream spread of the contaminant. The fresh-water discharge at and including the Schuylkill River conformed to the hydrograph for September–November 1931. This was a period of low water flow with an average discharge of about 4000 cfs. All the tests were made for conditions of mean tide.

Test 2 simulated an accident in which a large portion of the contamination was released in a very short time and the rest over a period of several days. The problem in selecting the prototype dosing source strength was that of determining a leakage rate for the containment vessel under water. It was arbitrarily decided to use the same leakage rate as for the vessel in the air, recognizing that the actual situation might be quite different. In particular, it should be noted that water pressure on the external side of the submerged vessel might average 15 psi, thereby reducing the effective average internal pressure during the first day from 60 psi to 45 psi. Of equal, if not greater, importance is the cooling effect of the water on the submerged vessel, which would reduce the internal pressure following the MCA more rapidly than in the case with the vessel exposed to the atmosphere. Because of these factors the use of the leakage rate to air should give conservative dose rates.

Test 2 was evaluated by assuming the initial 3-hr release to be that quantity of activity that would leak to the air during one tidal cycle, the total discharge during the remaining 20 tidal cycles being an equal amount. The total source strength, Q, was thus the amount of activity that would leak to the atmosphere during two tidal cycles ($12\frac{5}{12}$ hr per tidal cycle). The leakage rate assumed was the fraction 2×10^{-3} of the containment vessel volume per day (1.03×10^{-3} per tidal cycle). Since the leakage would extend over 20 tidal cycles, the fuel-element failures were taken to be 100% for long-term operation.

In an attempt to simulate an accident that would entail the slow release of contamination over an appreciable period of time, all the dye was released in tests 3 and 5 at a uniform rate over a period of 20 tidal cycles. Test 3 was carried out under the same low fresh-water discharge conditions as test 2; that is, it conformed to the hydrograph of September–November 1931. Test 5 was made for a sustained mean fresh-water discharge of 16,475 cfs at and including the Schuylkill River.

The dosing mechanism used to evaluate tests 3 and 5 was taken to be the uniform leakage rate of 0.2% per day throughout the 20 tidal cycles. This is certainly a conservative value, since the internal pressure would be greatly reduced and would most likely approach the external pressure before the end of this period. Since long release times were considered, it was assumed that all the fuel pins melted.

Model tests 1 and 4 involved release of all the dye at a uniform rate during a 3-hr interval following low-water slack at the release station. Test 1 was for the fresh-water discharge hydrograph of September–November 1931 and was continued until the increasing river flow in late November halted the upstream spread of the contamination.

Test 4 was for the sustained mean fresh-water discharge of 16,475 cfs at and including the Schuylkill River.

An MCA leading to an instantaneous source (such as a 3-hr release) was not considered credible; the instantaneous source considered here is deposition of an air-borne release from a leaking containment vessel due to rainout or washout.

Deposition of Air-Borne Activity. – It is possible to determine only roughly the activity that may be deposited in the river due to the deposition of air-borne activity. In the case of rainout or washout, activity may reach the river by direct deposition from the atmosphere and by water erosion of material initially deposited on land areas. The direct deposition may be calculated if the parameters of the source and meteorological conditions are known, that is, location of source, source strength during occurrence, wind direction, wind velocity, and the type of rainfall (rainout or washout). It would be considerably harder to determine the activity that might be washed into the river, since knowledge of the runoff, the surface terrain, any purification or settling out that might occur, and the immediate meteorological history (such as rain prior to the MCA) would be required.

Because of the difficulty in evaluating the deposition of air-borne activity to the river, the source strengths used were the total amounts deposited on the ground, as discussed previously.

Source Data and Exposure Equations

In determining the exposure that the general populace might receive as the result of possible contamination of the Delaware River, calculations were made of the fraction of the drinking water MPC that a given critical organ would receive from the river concentration at a given location and time and of the submersion exposure a person would receive from the river during swimming or boating.

Calculation of the MPC Fraction. – The fraction of the MPC for a given critical organ (co) was determined from the expression

$$\sum_i \left(\frac{\chi_i}{\mathrm{MPC}_i}\right)_{\mathrm{co}} ,$$

where χ_i is the concentration of isotope i in the water, and MPC_i is the maximum permissible concentration of isotope i for the given critical organ. Since χ/Q can be obtained from the model data (see Appendix F), the fraction of the MPC can be calculated from the expression

$$\sum_i \left(\frac{\chi_i}{\mathrm{MPC}_i}\right)_{\mathrm{co}} = \sum_i \left[\frac{Q_i(t)}{\mathrm{MPC}_i}\right]_{\mathrm{co}} \frac{\chi}{Q} , \qquad (11)$$

where

$Q_i(t)$ = source strength of isotope i in μc,

χ/Q = dispersion in cm^{-3},

MPC_i = MPC of isotope i in $\mu\mathrm{c/cm}^3$ for water.

All the fission products, their production rates, and their corresponding MPC values were examined to determine the isotopes of interest. Table 4.12 lists the isotopes of interest for both the internal and submersion cases and gives the half lives, gamma-ray energies, MPC values, and the total curies, $Q_T(t_0)$, that would be released to the inside of the containment vessel due to failure of all the fuel elements. The total curie value is given because it permits easy determination of the amount released for various fractions of fuel elements failed and for various leakage rates. It should be noted that $Q_T(t_0)$ is the total at time t_0, the time of onset of the MCA, for which previous long-term operation has been assumed.

Table 4.12 presents sufficient information to calculate

$$\sum \left[\frac{Q_T(t_0)}{\mathrm{MPC}}\right]_{\mathrm{co}}$$

for the activities present at time t_0. Since the transportation of contamination by the river is a relatively slow process, considerable radioactive decay will take place before the activity reaches the more distant locations up- and downstream from the release point. Decay was therefore calculated for the following times after onset of the MCA: 5, 10, 15, 20, 25, 30, 50, 100, and 150 tidal cycles. The factor

$$\sum \left[\frac{Q_T(t)}{\mathrm{MPC}}\right]_{\mathrm{co}}$$

was calculated for the thyroid, bone, total body, and gastrointestinal tract [lower large intestine, GI(LLI)] as the critical organs. The resulting values are plotted in Fig. 4.17 as a function of

Table 4.12. Source Data for Isotopes of Interest in Hydrospheric Release

Isotope	Half Life	E_γ, Gamma Energy (Mev/dis)	Q_T (μc)	MPC Exposure ($\mu c/cm^3$) to Critical Organ from Drinking Water*			
				Thyroid	Bone	Total Body	GI(LLI)
Sr^{89}	54d		2.57×10^{11}		10^{-4}	7×10^{-4}	4×10^{-4}
Sr^{90}	28y		1.31×10^{10}		10^{-6}	4×10^{-6}	5×10^{-4}
Sr^{91}	9.7h	0.85	3.2×10^{11}		7×10^{-3}		7×10^{-4}
Y^{91}	58d		3.2×10^{9}				3×10^{-4}
Y^{93}	10.0h	0.7	3.6×10^{9}				3×10^{-4}
Zr^{95}	63d	0.73	3.8×10^{9}				6×10^{-4}
Zr^{97}	17.0h	0.75	3.5×10^{9}				2×10^{-4}
Te^{129m}	33d	0.106	2.07×10^{9}	8×10^{-3}	3×10^{-3}	2×10^{-3}	3×10^{-4}
Te^{132}	77h	0.231	2.57×10^{10}			5×10^{-3}	3×10^{-4}
I^{131}	8.05d	0.39	1.97×10^{12}	3×10^{-5} [b]		2×10^{-3}	(Insoluble)[c]
							6×10^{-4}
I^{132}	2.4h	1.99	2.57×10^{12}	8×10^{-4} [b]		4×10^{-2}	
I^{133}	20.8h	0.56	3.7×10^{12}	10^{-4} [b]		9×10^{-3}	(Insoluble)[c]
							4×10^{-4}
I^{134}	52.5m	1.27	4.3×10^{12}	2×10^{-3} [b]			(Insoluble)[c]
							6×10^{-3}
I^{135}	6.68h	1.54	3.4×10^{12}	4×10^{-4} [b]		2×10^{-2}	(Insoluble)[c]
							7×10^{-4}
Cs^{136}	13d	1.02	3.7×10^{10}		10^{-2}	9×10^{-4}	(Insoluble)[c]
							6×10^{-4}
Cs^{137}	26.6y		1.15×10^{11}		5×10^{-4}	2×10^{-4}	(Insoluble)[c]
							4×10^{-4}
Ba^{140}	12.8d	0.237	3.6×10^{11}		2×10^{-3}	5×10^{-3}	3×10^{-4}
La^{140}	40.2h	2.11	3.5×10^{9}				2×10^{-4}
Ce^{144}	290d	0.043	2.57×10^{9}				10^{-4}
Pr^{143}	13.7d		3.5×10^{9}				5×10^{-4}
Mo^{99}	67h	0.24	3.5×10^{10}			8×10^{-3}	2×10^{-3}
							(Insoluble)[c]
							4×10^{-4}
Kr^{83m}	114m	0.0415	2.57×10^{11}				
Kr^{85m}	4.36h	0.181	7.8×10^{11}				
Kr^{87}	78m	0.56	1.43×10^{12}				
Kr^{88}	2.77h	2.07	1.97×10^{12}				
Xe^{133m}	2.3d	0.233	7.3×10^{10}				
Xe^{133}	5.27d	0.081	3.7×10^{12}				
Xe^{135m}	15.6m	0.52	1.02×10^{12}				
Xe^{135}	9.13h	0.268	3.5×10^{12}				
		Total	2.99×10^{13}				

[a]Based on permissible occupational exposure for 168-hr week.

[b]These values were taken from NBS Handbook 52. This has now been superceded by NBS Handbook 69, in which the thyroid MPC's for $I^{131-135}$ are listed as 2×10^{-5}, 6×10^{-4}, 7×10^{-5}, 1×10^{-3}, and 2×10^{-4}, respectively. The differences that corrections to the later list would make in the pertinent tables and graphs are small.

[c]Not included in the calculations.

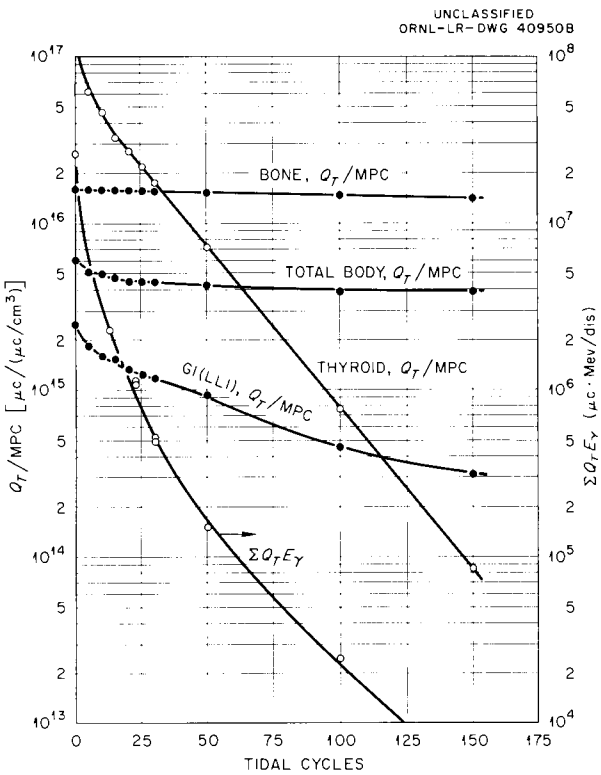

Fig. 4.17. Radioactive Decay as a Function of Time in Tidal Cycles.

time in tidal cycles. The source strength Q_0 in terms of Q_T and the values of χ/Q needed to calculate the Σ (χ/MPC) value from Eq. (11) were then determined. The source strength Q_0 is determined by the expression

$$Q_0 = Q_T \times L \times t \times F \quad , \tag{12}$$

where, in the case of test 2, t is two tidal cycles, or 8.9×10^4 sec, F is the fraction of fuel elements failed (all in this case), and L is the containment leakage fraction (0.2%/day, or 2.3×10^{-8} fraction/sec). Thus, for test 2,

$$Q_0 = Q_T \times 2.3 \times 10^{-8} \times 8.9 \times 10^4 \times 1.0 \quad , \tag{13}$$

or

$$\frac{Q_0}{Q_T} = 2.05 \times 10^{-3} \quad . \tag{13a}$$

For tests 3 and 5, the time of leakage was for 20 tidal cycles instead of 2, and therefore

$$\frac{Q_0}{Q_T} = 2.05 \times 10^{-2} \quad . \tag{13b}$$

The total activity inside the containment vessel (Q_T) is 2.99×10^7 curies (from Table 4.12), and thus the doses to the river would be the following:

$$Q_0 = 6.2 \times 10^4 \text{ curies} \tag{13c}$$

for test 2, and, for tests 3 and 5,

$$Q_0 = 6.2 \times 10^5 \text{ curies} \quad . \tag{13d}$$

Multiplication by

$$\sum \left(\frac{Q_T}{\text{MPC}}\right)_{\text{co}} \frac{Q_0}{Q_T}$$

converts the values in Table 4.12 into the proper source strength. In Appendix F the dispersion (χ/Q) is shown to be

$$\frac{\chi}{Q} = (1.67 \times 10^{-14})\, P \quad , \tag{14}$$

where P is the percentage of the initial concentration that is detected at any given sampling station (the value given in ref 16). Substituting the values of Eqs. (13a) and (14) into Eq. (11) yields, for test 2,

$$\sum_i \left(\frac{\chi_i}{\text{MPC}_i}\right)_{\text{co}} = 3.4 \times 10^{-17} \sum \left(\frac{Q_T}{\text{MPC}}\right)_{\text{co}} P \quad . \tag{15}$$

For tests 3 and 5, $Q_0/Q_T = 2.05 \times 10^{-2}$, and Eq. (11) becomes

$$\sum_i \left(\frac{Q_i}{\text{MPC}}\right)_{\text{co}} = 3.4 \times 10^{-16} \sum \left(\frac{Q_T}{\text{MPC}}\right)_{\text{co}} P \quad . \tag{15a}$$

The data of Fig. 4.17 were used to calculate the values of

$$3.4 \times 10^{-17} \sum \left(\frac{Q_T}{\text{MPC}}\right)_{\text{co}}$$

for various times. These values are tabulated in Table 4.13 as a function of time in tidal cycles.

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[16] *Contamination Dispersion in Estuaries — Delaware River*, Miscellaneous Paper No. 2-232, Report 1, U.S. Army Engineer Waterways Experiment Station (April 1959).

Table 4.13. Exposure to Critical Organs and Submersion Exposures as a Function of Time

Number of Tidal Cycles*	Number of MPC Units for Critical Organ in River Divided by Percentage Concentration in Model [Eq. (15) for $Q_0/Q_T = 2.05 \times 10^{-3}$]				Submersion Exposure [mrems/hr from Eq. (23)] Divided by Percentage Concentration in Model
	Thyroid	Bone	Total Body	GI(LLI)	
0	3.9	0.55	0.201	0.086	2.26
1	3.4	0.55	0.200	0.079	1.42
3	2.58	0.55	0.189	0.072	0.82
5	2.10	0.55	0.179	0.064	0.55
10	1.57	0.54	0.174	0.056	0.226
15	1.13	0.54	0.163	0.052	0.168
20	0.93	0.53	0.158	0.046	0.097
25	0.75	0.53	0.153	0.043	0.063
30	0.60	0.53	0.153	0.040	0.043
35	0.49	0.53	0.153	0.038	0.032
40	0.39	0.53	0.153	0.035	0.0231
45	0.32	0.52	0.147	0.033	1.79×10^{-2}
50	0.247	0.52	0.147	0.0289	1.34×10^{-2}
60	0.163	0.52	0.147	0.0268	8.6×10^{-3}
70	0.103	0.52	0.142	0.0221	5.8×10^{-3}
80	0.073	0.52	0.142	0.0200	3.8×10^{-3}
90	0.042	0.51	0.142	0.0174	2.74×10^{-3}
100	0.0268	0.50	0.142	0.0158	2.21×10^{-3}
110	0.0173	0.49	0.137	0.0144	1.37×10^{-3}
120	0.0111	0.49	0.137	0.0134	9.9×10^{-4}
130	0.0072	0.49	0.137	0.0125	7.2×10^{-4}
140	0.0045	0.49	0.137	0.0117	5.3×10^{-4}
150	0.00295	0.49	0.137	0.0109	3.7×10^{-4}

*One tidal cycle is 4.47×10^4 sec.

The fraction of the MPC present in the river water at a given location and time for test 2 was obtained by multiplying the appropriate value in Table 4.13 by the percentage (P) values in ref 16. To determine the MPC_{co} fraction for tests 3 and 5, the values of Table 4.13 were multiplied by ten times the percentage values of ref 16. In a similar fashion, the MPC_{co} fraction for other tests or different source strengths may be obtained by multiplying the values of Table 4.13 by the ratio of source strengths

$$\frac{Q(\text{test } x)}{Q(\text{test } 2)},$$

where $Q(\text{test } 2) = 2.05 \times 10^{-3} Q_T$, and by the percentage values of ref 16.

Water Submersion Equation. – In determining the dose rate from submersion in an infinite or semi-infinite volume of water, the dose buildup factor (B_r) must be taken into account. This factor is a

function of energy, and it is thus necessary to integrate over the energy to determine the exposure if the volume contains gamma rays of more than one energy. Since it is not convenient to integrate over the buildup factors, seven discrete gamma energies ranging from 0.255 to 3.25 Mev have been examined.

The dose rate from submersion in an infinite homogeneous volume of water is

$$D = \int_0^{4\pi} C(E) \frac{S e^{-\mu(E)R} B_\gamma(\mu R)\, d\Omega}{4\pi R^2} , \quad (16)$$

where

$d\Omega$ = differential solid angle in steradians,

$C(E)$ = flux-to-dose-rate conversion factor[17] [(rems·hr^{-1}) per (Mev·cm^{-3}·sec^{-1})],

S = source strength in Mev·cm^{-3}·sec^{-1},

$B_\gamma(\mu R)$ = dose buildup factor for point isotropic source, dimensionless,

$e^{-\mu(E)R}$ = total attenuation factor, dimensionless,

μ = attenuation factor per unit length in cm^{-1},

R = straight-line path length in cm.

For discrete energies and an infinite volume, Eq. (16) becomes

$$D = C(E)\, S \int_0^\infty e^{-\mu R} B_\gamma(\mu R)\, dR . \quad (17)$$

The dose buildup factor may take the form[17]

$$B_\gamma(\mu R) = A e^{-\alpha_1(\mu R)} + (1 - A)\, e^{-\alpha_2(\mu R)} , \quad (18)$$

where the parameters A, α_1, and α_2 are functions of energy and have been tabulated.[17] Substitution of Eq. (18) in Eq. (17) and integration yields

$$D(E) = S \frac{C(E)}{\mu(E)} \left(\frac{A}{1 + \alpha_1} + \frac{1 - A}{1 + \alpha_2} \right) , \quad (19)$$

where $C(E)$ is the dose rate (rems/hr) as a function of the source strength in Mev·cm^{-3}·sec^{-1}. Assuming a source strength of 1 Mev·cm^{-3}·sec^{-1}, the dose rate has been calculated for seven gamma-ray energies and is given in Table 4.14. The dose rate from a gamma energy of 0.255 Mev was calculated by numerical integration of Eq. (17), using the point isotropic source buildup factors.[18]

The dose rate may be seen to be relatively constant as a function of energy, and the value 7×10^{-5} was chosen as representative of all energies. The equation for the submersion dose rate, in rems/hr, thus becomes

$$D = (7 \times 10^{-5})\, S . \quad (20)$$

It should be noted that Eq. (20) applies to submersion in an infinite medium, and for a semi-infinite medium the dose rate is

$$D = (3.5 \times 10^{-5})\, S .$$

Calculation of the Submersion Exposure. – The source strength S has been determined by a summation of the gamma energies of the isotopes present in the activity released from the containment vessel. Thus the source strength in Mev·cm^{-3}·sec^{-1} is

$$S = 3.7 \times 10^{10} \sum_i Q_{T,i} E_{\gamma,i} \frac{\chi}{Q} \frac{Q_0}{Q_T} , \quad (21)$$

[17] T. Rockwell III (ed.), *Reactor Shielding Design Manual*, Fig. 2.2, TID-7004 (March 1956).

[18] H. Goldstein and J. E. Wilkins, Jr., *Calculations of the Penetration of Gamma Rays*, Table 7.112, NYO-3075 (June 30, 1954).

Table 4.14. Submersion Dose Rate as a Function of Energy

Energy (Mev/photon)	Dose Rate (rems/hr) for a Source Strength of 1 Mev·cm^{-3}·sec^{-1}
	$\times 10^{-5}$
0.255	5.4
0.65	8.6
1.125	7.1
1.675	7.1
2.00	6.6
2.40	6.2
3.25	6.3

where

$Q_{T,i}$ = total amount of isotope i (curies) released to containment vessel for failure of 100% of the fuel elements,

$E_{\gamma,i}$ = gamma energy of isotope i (Mev/dis),

χ/Q = dispersion (cm^{-3}).

The $\sum Q_T E_\gamma$ has been carried out for the isotopes of interest shown in Table 4.12 and is plotted in Fig. 4.17 as a function of the time (tidal cycles) after onset of the MCA. For test 2, $\sum Q_T E_\gamma$ is converted to the proper scale factor by multiplying by $Q_0/Q_T = 2.05 \times 10^{-3}$. As noted in Appendix F, $\chi/Q = 1.67 \times 10^{-14} P$. Substituting into Eq. (21), the source strength in Mev·cm^{-3}·sec^{-1} for test 2 becomes

$$S = 2.05 \times 10^{-3} \sum (Q_T E_\gamma) \times 3.7 \times 10^{10} \times \times 1.67 \times 10^{-14} P$$

$$= 1.27 \times 10^{-6} \sum Q_T E_\gamma P \quad . \qquad (22)$$

Similarly, for tests 3 and 5, where

$$\frac{Q_0}{Q_T} = 2.05 \times 10^{-2} \quad ,$$

$$S = 1.27 \times 10^{-5} \sum Q_T E_\gamma P \quad . \qquad (22a)$$

Substitution of Eq. (22) in Eq. (20) yields the dose rate, in mrems/hr, as

$$D = 8.9 \times 10^{-8} \sum Q_T E_\gamma P \quad . \qquad (23)$$

Values of $8.9 \times 10^{-8} \sum Q_T E_\gamma$ are given in Table 4.13 for various times in tidal cycles. The corresponding submersion dose rates may then be obtained by multiplication by the percentage (P) values given in ref 16. As in the case of the MPC fraction, the submersion exposures may be scaled to any initial source strength.

Uptake by Muds and River Biota. – The uptake of radioactivity by the muds and river biota may be an important factor in reducing the river contamination.[19,20] This uptake may be by the suspended sediments, bottom muds, fish, shellfish, plankton, microorganisms, and plant life. The activity may then be deposited on the bottom or in plants and animals and effectively removed from estuary circulation. If the uptake is by edible biota, the activity may constitute a more serious hazard than if the material were dispersed in the estuary waters. This hazard would result from the concentration that takes place from the marine environment to the edible biota. The marine biota may concentrate activities by as much as a factor of 10^4. (A more complete discussion of the uptake phenomena, with additional references, is contained in Appendix F, p 94.)

Considerable research needs to be done before it can be stated with confidence what fraction of the activity in a body of water will be absorbed by the marine environment. The uptake calculations described here have been based on the best data available, with the understanding that such computations may be in error by as much as a factor of 10 or more.

The uptake by the biota is assumed to be exponential, and the term "half life," as used in the calculations, is analogous to the physical half life of radioactive isotopes. The uptake half lives assumed for the isotopes of interest (see Appendix E) are listed below:

Isotope	Uptake Half Life (hr)
Sr, Cs, Ce	1.0
I	No uptake
Others (see Table 4.12)	7.5

The activity $Q(t)$ present at any given time (t) is then

$$Q(t) = Q(t_0)\, e^{-0.7t} \qquad \text{(Sr, Cs, Ce)},$$

$$Q(t) = Q(t_0)\, e^{-0.1t} \qquad \text{(others, except I)}.$$

Figure 4.18 is a plot of the fraction of initial activity $Q(t)/Q(t_0)$ remaining as a function of time. The activity decay may be seen to be extremely rapid, and, since the iodine is not removed, it becomes the controlling isotope.

The calculations of the MPC fraction and the submersion exposure were repeated to include the uptake in the same manner as the activity decay. The decay of Q_T/MPC for the thyroid and total body and the decay of $Q_T E_\gamma$ for the submersion exposure are shown in Fig. 4.19. The uptake has not been included in the submersion case, since

[19] *Radioactive Waste Disposal into Atlantic and Gulf Coastal Waters*, NAS-NRC-655 (1959).

[20] *Radioactive Waste Disposal from Nuclear-Power Ships*, NAS-NRC-658 (1959).

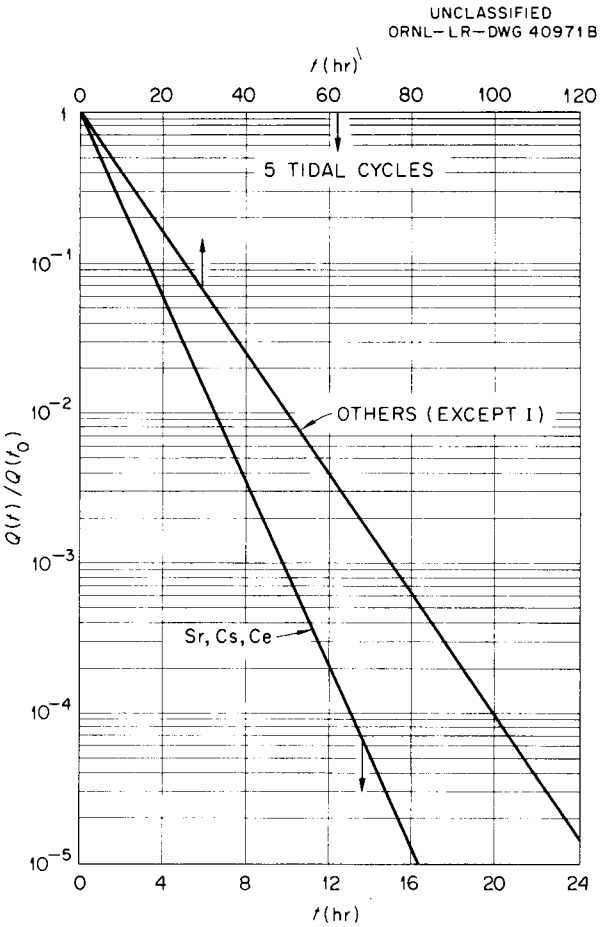

Fig. 4.18. Uptake Decay as a Function of Time.

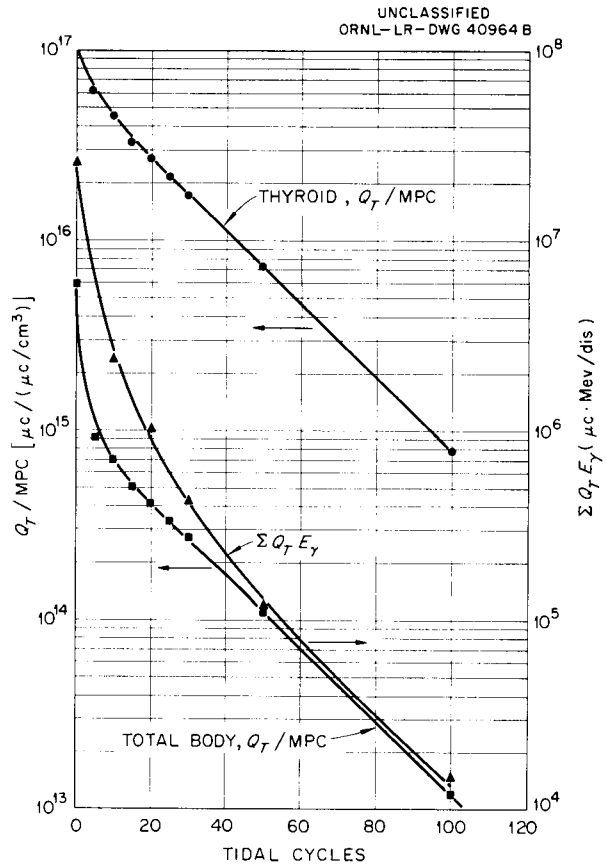

Fig. 4.19. Radioactive Decay as a Function of Time in Tidal Cycles, Including Uptake.

there is no means for evaluating the fraction of the uptake material removed from suspension in the river water. Activity absorbed on suspended sediments would contribute to the submersion exposure in the same manner as if uptake had not occurred. Such suspended activity would, however, be removed by municipal filtration plants (such as the Torresdale plant) and would not enter water mains.

The exposure factors with uptake included are listed in Table 4.15. The bone and GI(LLI) exposures may be seen to be insignificant after one tidal cycle. The controlling exposure is the thyroid dose from the iodine isotopes which are not removed; the iodine isotopes are also the controlling isotopes for the total-body and submersion exposures.

Continuous-Source Exposure

The exposures resulting from an MCA release of activity to the Delaware River from the submerged containment vessel are treated in two cases: (1) where only activity decay and river dispersion occur and (2) where uptake by the river environment is added to the activity decay and river dispersion.

The model data of ref 21 were used to determine the river dispersion. The calculational procedures described above were used in determining the corrections for physical decay and uptake.

The following general comments apply to the specific tests or calculations:

1. The dosing point is at channel station 31 in the vicinity of the NYS yards.

[21] *Contamination Dispersion in Estuaries – Delaware River*, Miscellaneous Paper No. 2-232, Report I, U.S. Army Engineer Waterways Experiment Station (April 1959).

Table 4.15. Exposure to Critical Organs and Submersion Exposures with Uptake Included as a Function of Time

Number of Tidal Cycles	Number of MPC Units for Critical Organ in River Divided by Percentage Concentration in Model [Eq. (15) for $\mathcal{Q}_0/\mathcal{Q}_T = 2.05 \times 10^{-3}$]				Submersion Exposure [mrems/hr from Eq. (23)] Divided by Percentage Concentration in Model
	Thyroid	Bone	Total Body	GI(LLI)	
0	3.9	5.5×10^{-1}	2.01×10^{-1}	8.6×10^{-2}	2.26
1	3.4	1.89×10^{-3}	8.2×10^{-2}	1.20×10^{-2}	1.42
3	2.58	1.37×10^{-4}	4.9×10^{-2}	8.9×10^{-4}	0.82
5	2.10	1.13×10^{-5}	3.1×10^{-2}	8.4×10^{-5}	0.55
10	1.57		2.42×10^{-2}		0.226
15	1.13		1.74×10^{-2}		0.168
20	0.93		1.41×10^{-2}		9.7×10^{-2}
25	0.75		1.13×10^{-2}		6.3×10^{-2}
30	0.60		9.2×10^{-3}		4.3×10^{-2}
35	0.49		7.4×10^{-3}		3.2×10^{-2}
40	0.39		5.8×10^{-3}		2.31×10^{-2}
45	0.32		4.6×10^{-3}		1.79×10^{-2}
50	0.247		3.7×10^{-3}		1.34×10^{-2}
60	0.163		2.42×10^{-3}		8.6×10^{-3}
70	0.103		1.54×10^{-3}		5.8×10^{-3}
80	0.073		9.8×10^{-4}		3.8×10^{-3}
90	0.042		6.2×10^{-4}		2.74×10^{-3}
100	0.0268		4.0×10^{-4}		2.21×10^{-3}

2. The initial dosing started at local low-water slack.

3. River concentrations are measured at local high-water slack and represent the condition of maximum upstream contamination.

4. Submersion exposures are for an infinite volume and should be divided by 2 for a semi-infinite volume (as for a person boating on the river).

5. The uptake calculations are to be considered as an indication of what might occur, with the notation that they may be grossly in error.

6. The containment vessel is assumed to leak at the rate of 0.2% per day, which gives a total of 0.2% for test 2 and 2.0% for tests 3 and 5; 100% of the fuel elements are assumed to have failed.

Exposure with Activity Decay and River Dispersion. – As noted previously, test 2 involved a combination of rapid and slow release of contamination. It was assumed that one-half the activity was released during the first 3 hr after local low-water slack and that an equal amount was released during the following 20 tidal cycles. The source strength for prototype dosing was taken as the amount that would leak from the containment vessel during two tidal cycles with a leakage rate of 0.2% per day. Two tidal cycles are $24\frac{5}{6}$ hr, so approximately 0.2% of the activity released to the containment vessel was assumed to reach the river. This test is considered to most nearly represent the conditions of leakage from a submerged containment vessel following the MCA.

All samples were taken at local high-water slack, which represents the greatest upstream contamination. The data of Table 4.13 and the percentage values for test 2 found in ref 21 (Table 3) were used to calculate the maximum exposures as a function of 1000-ft channel stations, and the results are plotted in Fig. 4.20. The exposures plotted are the maximum fractions of the MPC (for the thyroid, bone, and total body as the critical organs) that the river water will contain at a given channel station. The submersion exposure is the maximum dose rate (in mrems/hr) that will exist at a given location. It should be noted that the submersion exposure is based on an infinite medium, and, if the person exposed is swimming at the surface or boating, the dose rate should be reduced by one-half. The maximum exposures, as plotted in Fig. 4.20, do not necessarily occur at the time of maximum dye concentration, as given in ref 21, because of activity decay. Also, the maximum submersion exposures and the maximum exposures to the various critical organs at a given station do not necessarily occur at the same time because of the different decay rates of the controlling activities. This is true for all tests and maximum exposures.

The variation of the exposure as a function of time is of interest, and the exposures at Torresdale, Philadelphia, and Wilmington have been plotted in Figs. 4.21, 4.22, and 4.23. Figure 4.21 is a plot of data calculated by using the data of plate 11 of ref 21, which gives results of analyses of samples taken halfway between the bank and midchannel at a postulated intake point for the Torresdale filter plant, a principal supplier of Philadelphia municipal water. These samples gave slightly lower concentrations than samples taken at midchannel station 35 opposite Torresdale. Figure 4.22 was obtained from the data of ref 21 (Table 3) for channel station 32.5, which is located approximately at the release point (station 31), near the Walt Whitman Bridge. The exposure at Wilmington, Fig. 4.23, is for channel station 162.5.

For tests 3 (low river flow) and 5 (mean river flow), a uniform release of activity over 20 tidal

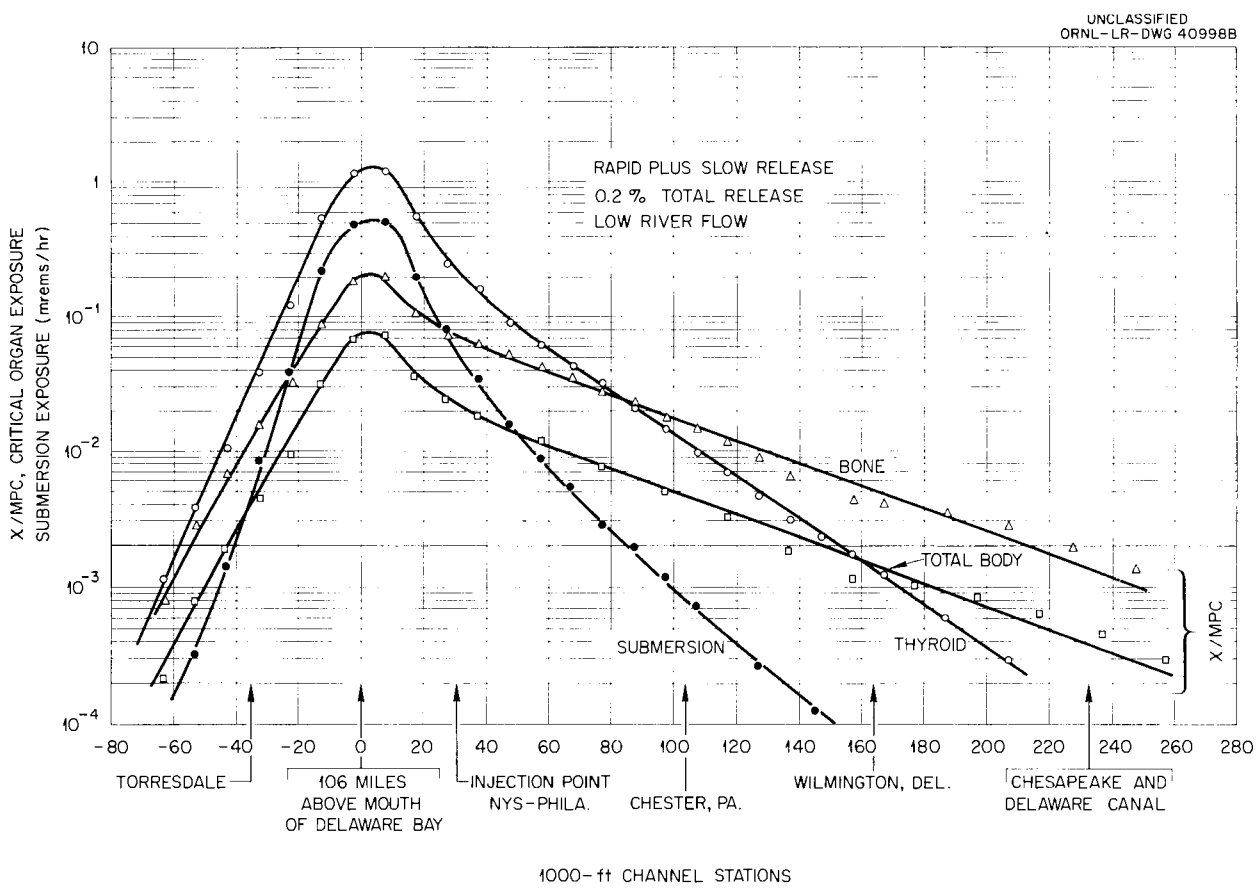

Fig. 4.20. Maximum Exposure as a Function of River Location (Model Test 2).

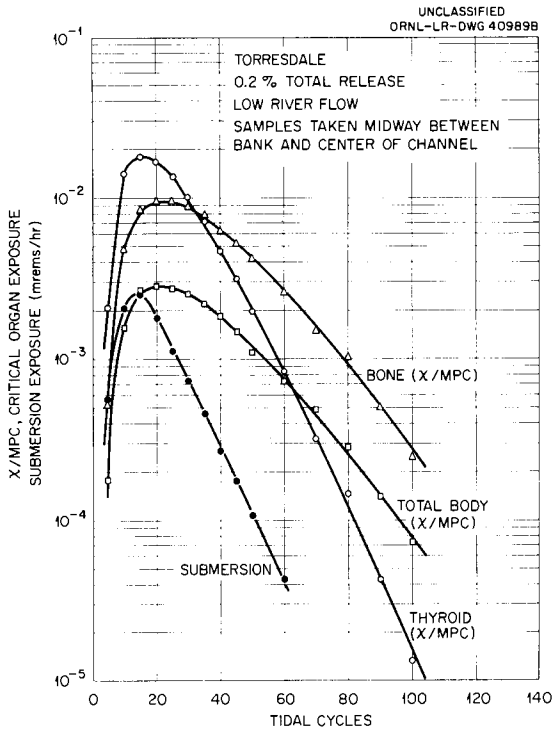

Fig. 4.21. Exposure at Torresdale Municipal Water Intake Plant as a Function of Time in Tidal Cycles (Model Test 2).

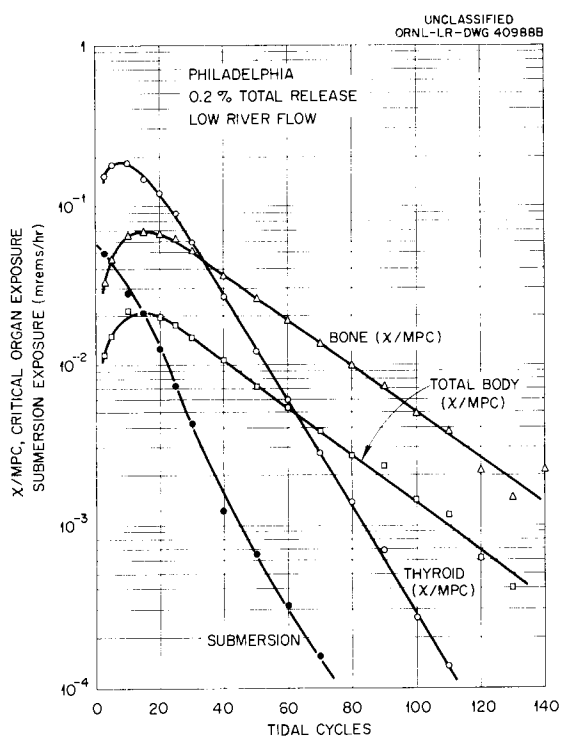

Fig. 4.22. Exposure at Philadelphia as a Function of Time in Tidal Cycles (Model Test 2).

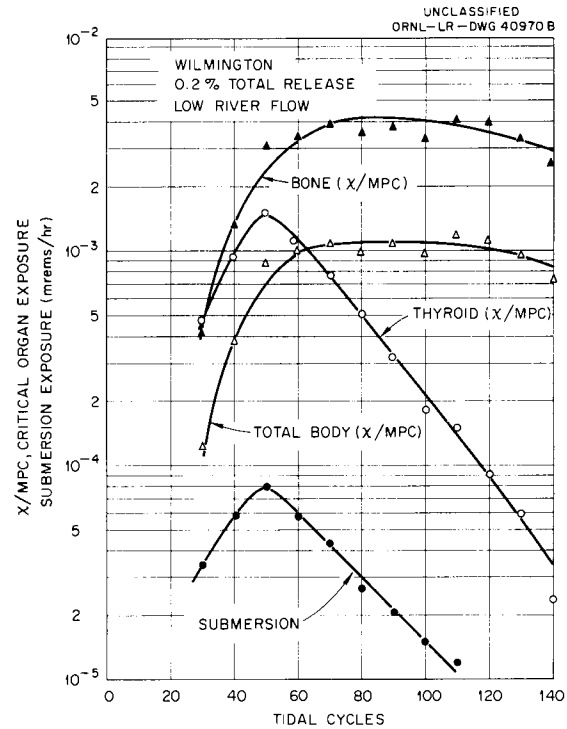

Fig. 4.23. Exposure at Wilmington as a Function of Time in Tidal Cycles (Model Test 2).

cycles was assumed. The leakage rate was taken as 0.2% per day and all the fuel elements were assumed to have failed. Since 20 tidal cycles cover a period of approximately ten days, roughly 2% of the activity was released to the river. All samples were taken at local high-water slack, which represents the condition of greatest upstream river contamination.

The maximum MPC fractions and maximum submersion dose rates at each 1000-ft river channel station, as obtained in tests 3 and 5, are presented in Figs. 4.24 and 4.25. The submersion exposures are for submersion in an infinite medium and should be reduced by a factor of 2 to obtain river-surface exposure rates. As noted for test 2, the maximum exposures at a given station do not necessarily occur at the time of maximum dye concentration. The exposures obtained from tests 3 and 5 as a function of time (in tidal cycles) for locations at Torresdale, Philadelphia, and Wilmington are presented in Figs. 4.26 through 4.30, except that model test 5 did not give sufficient data to plot the exposure at Torresdale as a function of time.

Exposure with Activity Decay, River Dispersion, and Uptake Considered. – A considerably lower

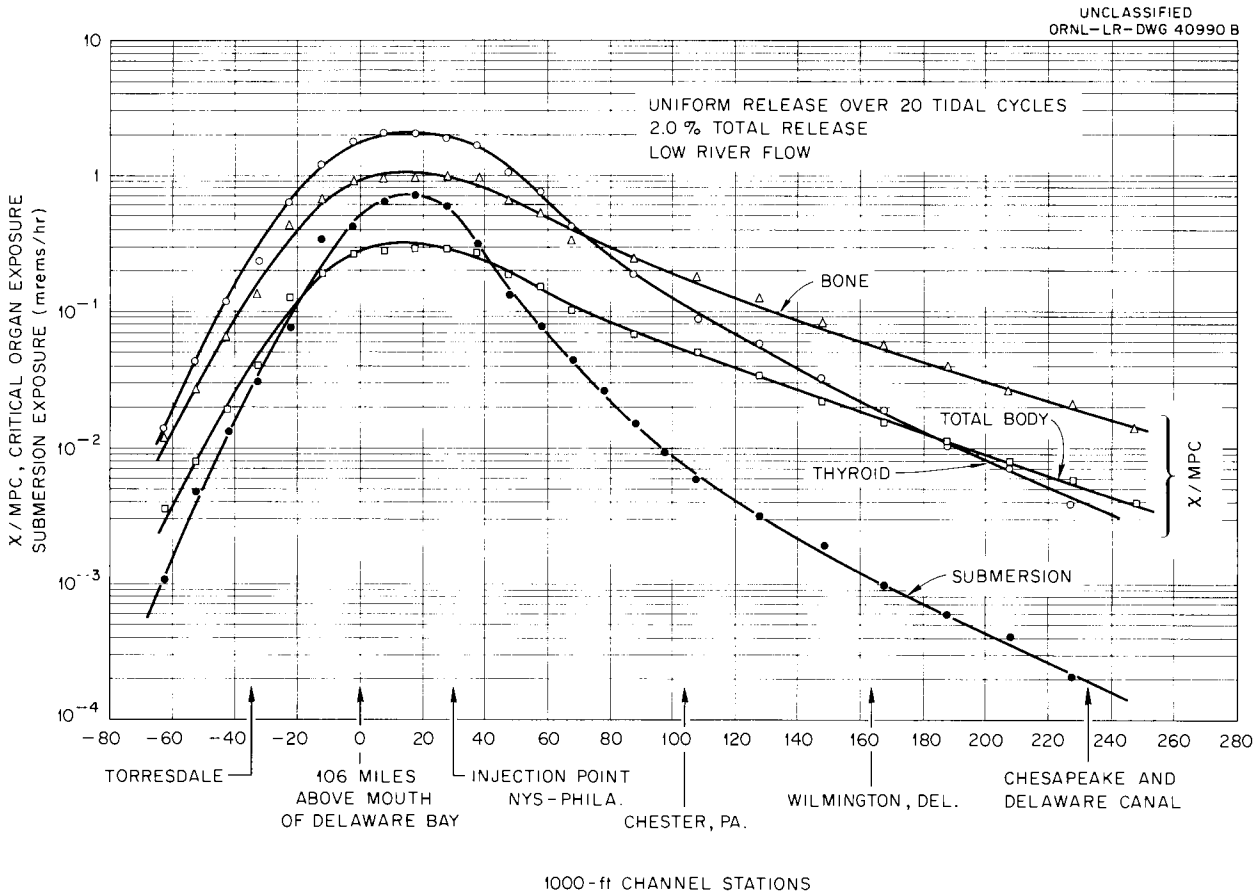

Fig. 4.24. Maximum Exposure as a Function of River Location (Model Test 3).

level of river contamination and resulting exposure can be predicted, but without quantitative assurance, by including the uptake of activity by the marine environment. The data given above and in ref 21 were used to calculate the exposures with uptake for tests 2, 3, and 5. It should be noted that the data upon which the uptake calculations are based are neither complete nor considered to be reliable. Consequently, these computations should not be taken to represent the actual situation, but rather to be an indication of what might take place based on the best evidence available, which is admittedly very sketchy. The conservative approach would be to assume no uptake.

No uptake of the iodine isotopes has been assumed, since preliminary evidence indicates that these isotopes would not readily be removed from suspension. Some material removed by uptake would be removed by a municipal water filter plant; however, a significant fraction might remain in sediment which would contribute to a submersion exposure or to an internal exposure if the raw river water were ingested.

Test 2, as mentioned previously (p 37), involved a combination of rapid and slow release of contamination in which a total of approximately 0.2% of the activity released to the containment vessel because of failure of all the fuel elements was discharged to the river. Test 2 results are plotted in Figs. 4.31 through 4.34, with uptake included. The maximum MPC fraction and submersion dose rate as a function of channel station are given in Fig. 4.31. The dosing point is at channel station 31, and all concentrations are at the time of local high-water slack in order to represent the condition of maximum upstream activity.

The exposures at Torresdale, Philadelphia, and Wilmington as a function of time in tidal cycles ($12\frac{5}{12}$ hr per tidal cycle) are plotted in Figs. 4.32,

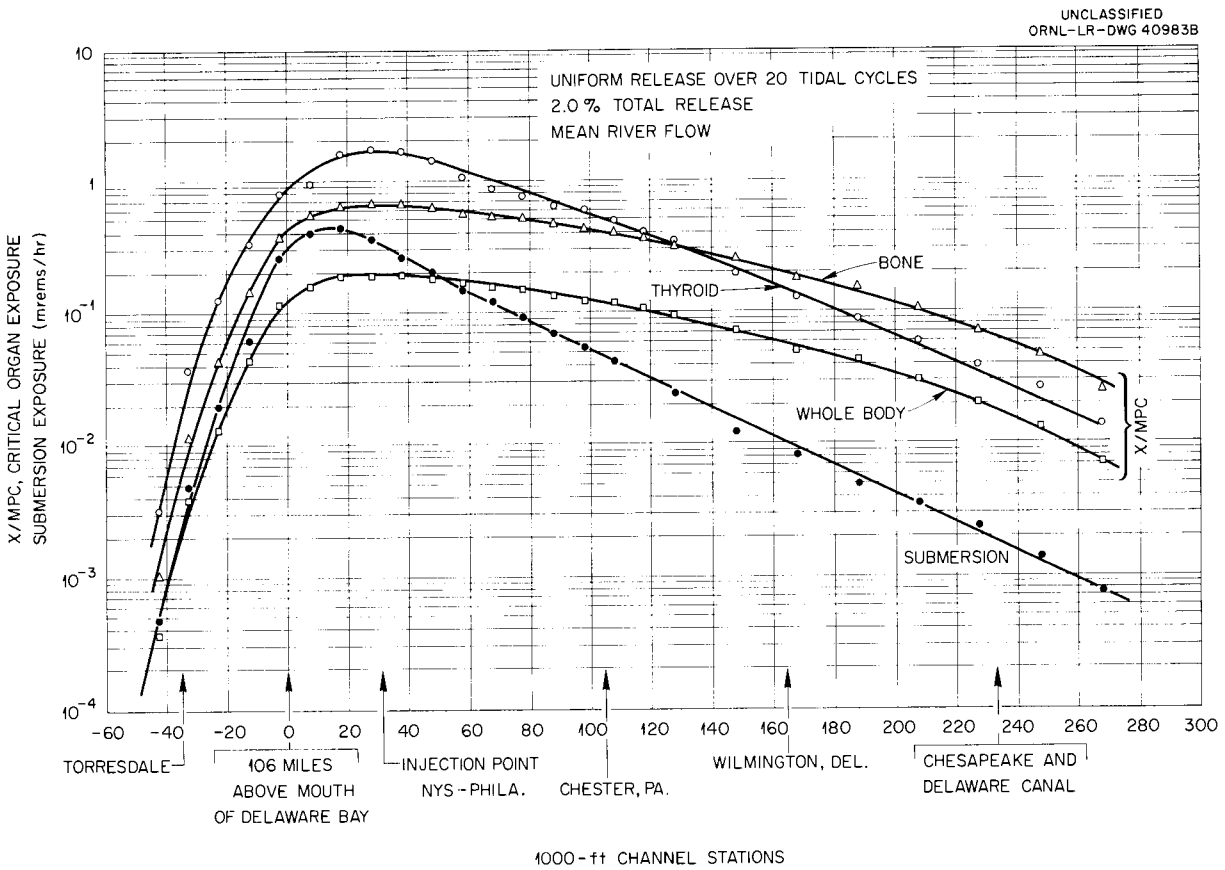

Fig. 4.25. Maximum Exposure as a Function of River Location (Model Test 5).

4.33, and 4.34. The Torresdale exposure is at the assumed filter plant intake, which gives a lower concentration than the midchannel sampling point at station 35. The Philadelphia sampling point is station 32.5, which is approximately at the Walt Whitman Bridge. The Wilmington concentration is for channel station 162.5. The submersion exposure is for submersion in an infinite medium and should be reduced by one-half for a person boating or swimming at the water surface.

For tests 3 and 5, as mentioned previously, uniform release of activity at the rate of 0.2% per day for a period of 20 tidal cycles was assumed, and thus approximately 2.0% of the activity was released. River concentrations were calculated for the time of local high-water slack, but plots of the results of these two tests are not presented here because the shapes of the curves and the reductions in exposure as a function of tidal cycles are similar to those for test 2.

Exposures in the Immediate Vicinity of the Source. – The concentrations in the vicinity of the sunken vessel immediately after leakage of activity from the containment vessel were also calculated. Since about 90% of the fuel elements will fail within 2 hr after onset of the MCA and most of the isotopes listed in Table 4.12 have half lives greater than 10 hr, decay was not included. The diluting rate was taken as the volume of water flowing past or around the containment vessel per unit time. The activity involved was taken as the quantity that would leak from the vessel if a leakage rate of 0.2% per day (2.3×10^{-8} fraction/sec) was assumed.

The mean maximum current velocities in the navigation channel between Philadelphia and the sea are of the order of 3.0 to 5.0 fps. The maximum velocities and duration of ebb currents are generally greater than those of flood currents, with the predominance of ebb currents increasing

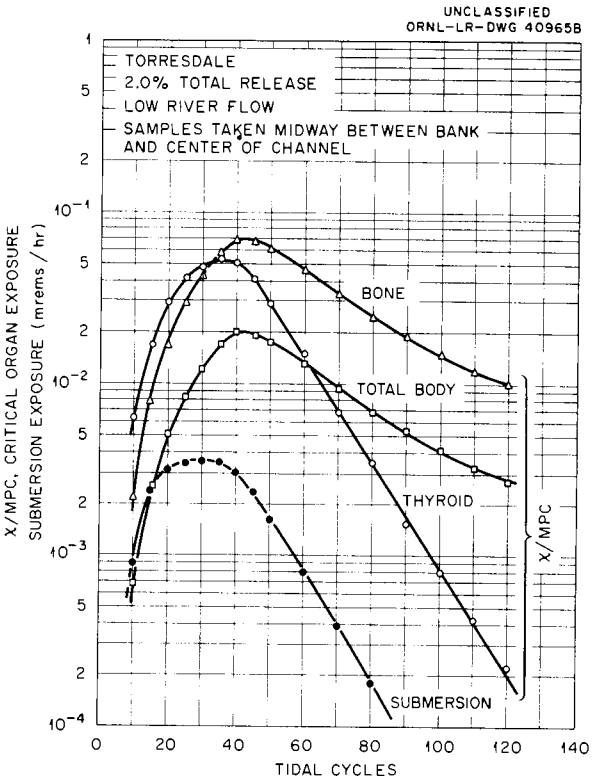

Fig. 4.26. Exposure at Torresdale Municipal Water Intake Plant as a Function of Time in Tidal Cycles (Model Test 3).

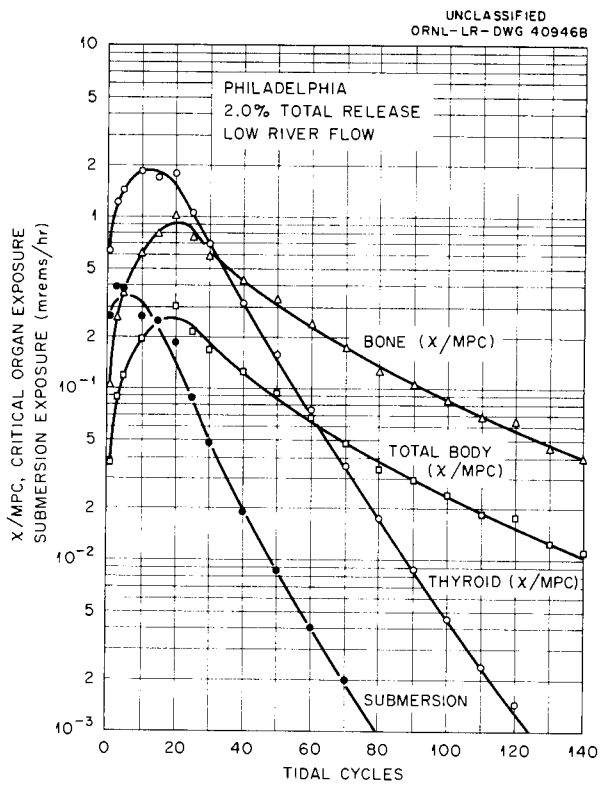

Fig. 4.27. Exposure at Philadelphia as a Function of Time in Tidal Cycles (Model Test 3).

with distance upstream. The velocity of 3.0 fps was used to determine the volume per second flowing through a cross-sectional area equal to that of the containment vessel (here assumed to be a circle 35 ft in diameter). It should be noted that the velocity of 3.0 fps is a mean maximum current in the navigation channel and would be representative only during flood and ebb of the tide and only if the vessel had sunk in the navigation channel.

In an attempt to evaluate the most hazardous local condition, that is, the situation in which the source is not located in the navigation channel and the tide is not advancing or receding, the river flow based on the fresh-water discharge was also calculated. The mean fresh-water discharge at Philadelphia is 16,475 cfs (including the Schuylkill River), and the low fresh-water discharge is about 4000 cfs. The Delaware River at Philadelphia is about 2200 ft wide, and, assuming an average depth of 40 ft (authorized depth of the navigation channel, which has a minimum bottom width of 800 ft), the cross-sectional area at Philadelphia is 88,000 ft^2. The average river velocity (v) is then the fresh-water discharge rate divided by the cross-sectional area. For mean fresh-water discharge,

$$v_m = \frac{16{,}475 \text{ cfs}}{88{,}000 \text{ ft}^2} = 0.187 \text{ fps} ,$$

and for low fresh-water discharge,

$$v_L = \frac{4000 \text{ cfs}}{88{,}000 \text{ ft}^2} = 0.045 \text{ fps} .$$

These velocities may be fairly representative of the conditions during low-water slack and in the shallower locations at other times. In any case it is felt that they are conservative.

The diluting volume V is then the product of the cross-sectional area of the containment vessel and the average river velocity v. Expressed in

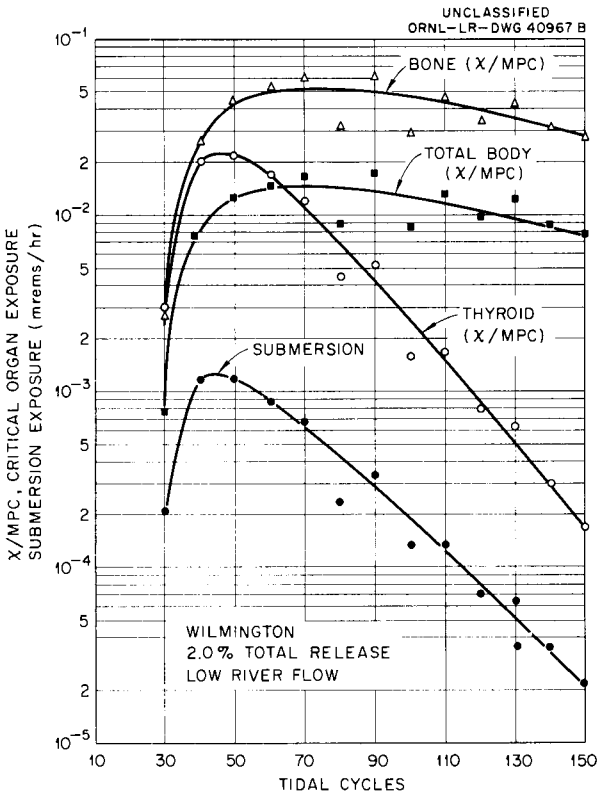

Fig. 4.28. Exposure at Wilmington as a Function of Time in Tidal Cycles (Model Test 3).

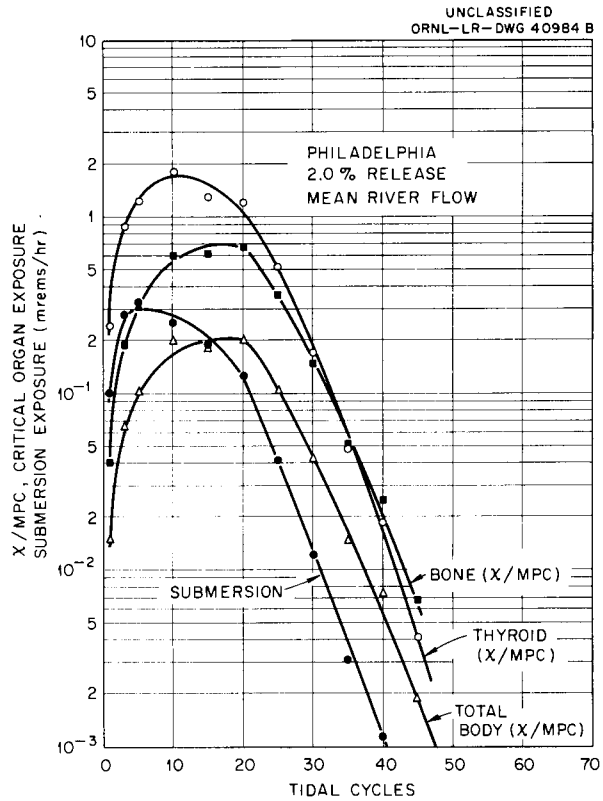

Fig. 4.29. Exposure at Philadelphia as a Function of Time in Tidal Cycles (Model Test 5).

cubic feet the volume is

$$V = \frac{\pi}{4}(35)^2\, v = 960v \ , \qquad (24)$$

and in cubic centimeters it is

$$V = 960 \times 2.83 \times 10^4\, v \ , \qquad (25)$$

where v is in feet per second. The quantity $1/V$ will be designated χ/Q, since it has the same properties, and thus

$$\frac{\chi}{Q}\,(\text{sec/cm}^3) = \frac{1}{V} = \frac{3.7 \times 10^{-8}}{v} \ .$$

The fraction of the MPC for internal exposure is

$$\frac{\chi}{\text{MPC}} = \frac{Q_T}{\text{MPC}}\,\frac{Q}{Q_T}\,\frac{\chi}{Q} \ , \qquad (26)$$

where the values of Q_T/MPC are those given in Fig. 4.17, and Q/Q_T is the fraction of the total release per second (2.3×10^{-8} fraction/sec). Values of χ/Q and the MPC fractions are tabulated in Table 4.16 for the three different flow conditions and velocities.

The source strength (S) for the submersion exposure is

$$S = 3.7 \times 10^{10} \sum Q_T E_\gamma \frac{Q}{Q_T}\,\frac{\chi}{Q} \ , \qquad (27)$$

where $\sum Q_T E_\gamma$, which is plotted in Fig. 4.17, has the value 2.58×10^7 for time zero. Substituting into Eq. (20) for a semi-infinite medium yields

$$D = \frac{7 \times 10^{-5}}{2} \times 2.58 \times 10^7 \times 2.3 \times 10^{-8} \times$$
$$\times\, 3.7 \times 10^{10}\,\frac{\chi}{Q} \ ,$$

$$D = 7.7 \times 10^5\,\frac{\chi}{Q} \ ,$$

in rems/hr. Values of D are given in Table 4.16

for the three cases where the medium is assumed to be semi-infinite (i.e., a person boating on the river in the contaminated area). It should be noted that Eq. (20) assumes a semi-infinite medium which may not be representative of the limited volume of water affected immediately after leakage from the containment vessel. Thus there would certainly be fringe effects, with the exposures indicated in Table 4.16 being approached only at the center of the contaminated area.

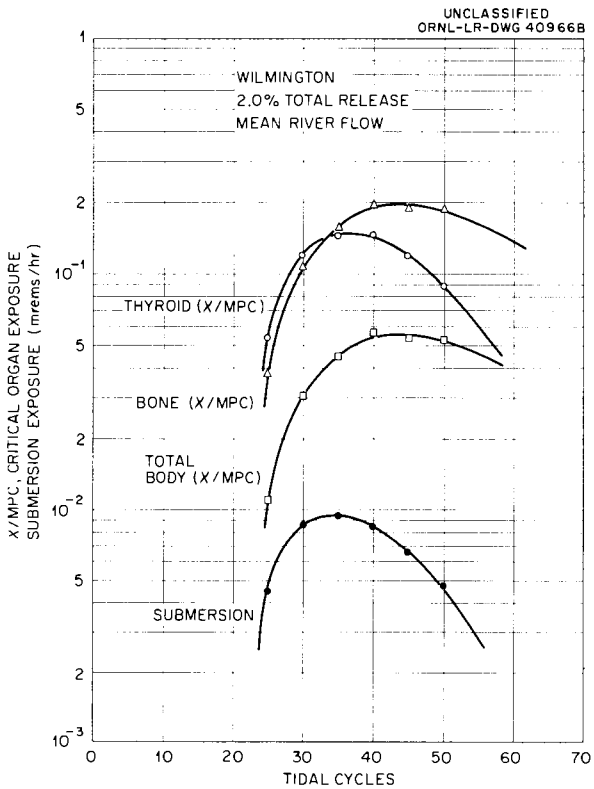

Fig. 4.30. Exposure at Wilmington as a Function of Time in Tidal Cycles (Model Test 5).

Deposition of Air-Borne Activity

The deposition of air-borne activity onto the surface of the river is the second method by which the river may become contaminated following the MCA. Such deposition may be caused by rainout or washout conditions (see Appendix A). Rainout assumes that a portion of the air-borne cloud is deposited as a function of time (here, 1×10^{-4} fraction/sec for rainfalls of 0.05 to 0.2 in./hr), whereas washout assumes that the total air-borne activity (except noble gases) is deposited by a sudden heavy rain.

As discussed above, it was assumed that the total deposition from the given meteorological condition either directly or indirectly reaches the river. The dispersal of the activity in the river was assumed to follow that of the model data.[22] It should be noted, however, that the methods of dosing for the model data and the deposition case are very different. The model was dosed as a point source and thus would be expected to give different results than would be obtained for deposition of activity on the surface of the river. The point-source dosing gave a fairly homogeneous dispersal in the contaminated reach during the first tidal cycle and tended to support the use of the model data for the deposition case. If the vertical mixing was not fairly rapid in the stretch of river considered, however, the model data extrapolation might be inaccurate. In this case the surface-water concentration would be greater than that indicated, whereas the depth concentration would be less. In lieu of any better approach, the model data extrapolation was used.

[22] *Contamination Dispersion in Estuaries – Delaware River*, Miscellaneous Paper No. 2-232, Report I, U.S. Army Engineer Waterways Experiment Station (April 1959).

Table 4.16. Exposures in the Immediate Vicinity of the Source

Flow Condition	River Velocity (fps)	χ/Q	χ/MPC			Submersion Exposure (rems/hr)
			Thyroid	Bone	Total Body	
Maximum in navigation channel	3.0	1.23×10^{-8}	33	4.6	1.7	0.0095
Mean fresh-water discharge	0.187	1.98×10^{-7}	5.3×10^{2}	7.3×10^{1}	2.75×10^{1}	0.15
Low fresh-water discharge	0.045	8.2×10^{-7}	2.15×10^{2}	3.0×10^{2}	1.13×10^{2}	0.63

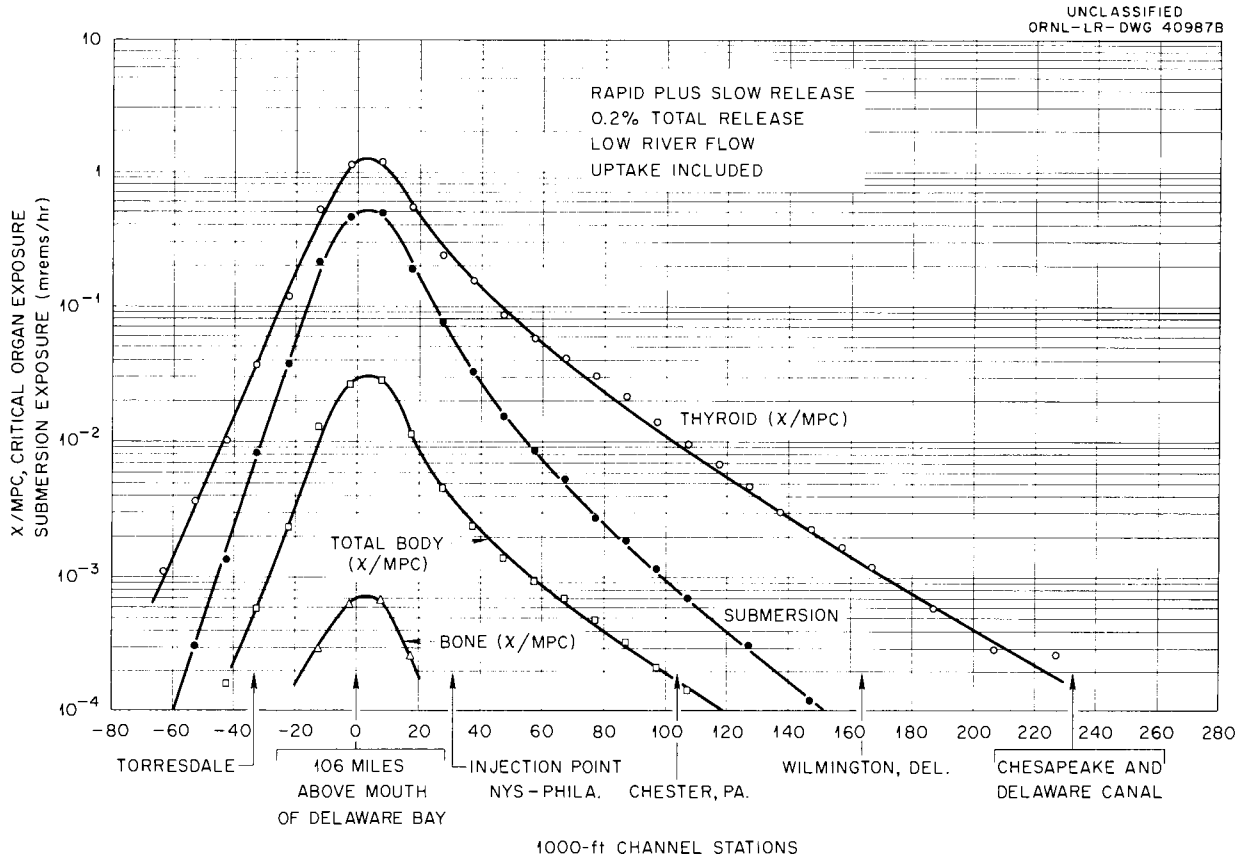

Fig. 4.31. Maximum Exposure as a Function of River Location with Uptake (Model Test 2).

Activity Available for Deposition. – Following an MCA, it is here assumed that the air flow through the compartment and out the stack through the intact filter continues unabated for at least 24 hr, that the leakage rate from the containment vessel remains constant at 0.2% per day (2.3×10^{-8} fraction/sec), and that all the fuel elements melt. Since the solubilities of noble gases in water are negligible by comparison, their activities are not included in deposition calculations. The availability of activity in the air for deposition is stated as

$$Q = Q_T L E_F t P_D \quad , \tag{28}$$

where

Q = total activity leaving the stack in time t (curies);

Q_T = total nonnoble-gas activity (curies) in the gas inside the containment vessel following the MCA, shown in the derivation of Eq. (10) to be 4×10^7 curies;

L = fraction of Q_T leaking from the containment vessel per second ($= 2.3 \times 10^{-8}$ sec^{-1});

E_F = fraction of $Q_T L$ not removed by the filter;

t = duration of time (= 24 hr for rainout) in which $Q_T L E_F$ continues to be emitted and meteorological conditions remain constant ($Q_T L E_F t$ = total amount in curies of subject activity emitted from the stack in time t);

P_D = fraction of $Q_T L E_F t$ deposited; for rainout conditions during the passage of the radioactive cloud over a downwind distance X in time τ with the fraction Λ being deposited per second, $P_D = 1 - e^{-\Lambda\tau}$; for washout conditions, $P_D = 1.00$ (this means that 100% of the subject activity is deposited vertically downward).

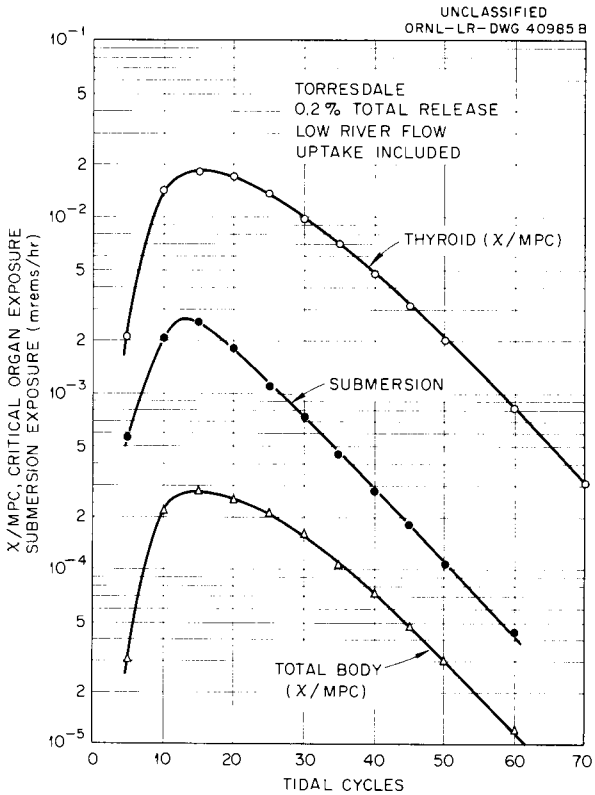

Fig. 4.32. Exposure at Torresdale Municipal Water Intake Plant as a Function of Time in Tidal Cycles with Uptake (Model Test 2).

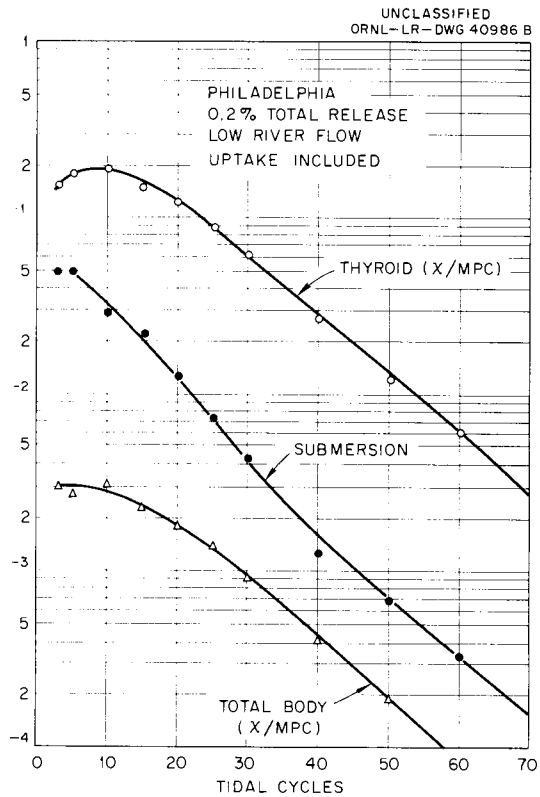

Fig. 4.33. Exposure at Philadelphia as a Function of Time in Tidal Cycles with Uptake (Model Test 2).

For rainout conditions over a 24-hr period following the MCA,

$$\frac{Q}{Q_T} = 2.3 \times 10^{-8} \times 1 \times 10^{-3} \times$$

$$\times\, 8.64 \times 10^4 (1 - e^{-\Lambda\tau})$$

$$= 2.0 \times 10^{-6} (1 - e^{-\Lambda\tau}) \ , \qquad (29)$$

or

$$Q = 8.0 \times 10^1 (1 - e^{-\Lambda\tau}) \ . \qquad (30)$$

From ref 23, Fig. 7.5, $\Lambda = 10^{-4}$ for rainfall of 0.1 in./hr. For deposition in the river, τ is the time each unit volume spends over the river; τ = distance divided by velocity. If the wind is blowing directly across the 3000-ft-wide river at 2.24 m/sec (7.3 fps), τ = 3000/7.3 = 410 sec, $\Lambda\tau = 4.10 \times 10^{-2}$, and, from Eq. (29),

$$\frac{Q}{Q_T} = 2.0 \times 10^{-6} (1 - e^{0.04}) = 8 \times 10^{-8} \ , \qquad (31)$$

$$Q = 3.2 \times 10^0 \ . \qquad (31a)$$

For washout deposition in the river with the same wind direction and velocity, t will be 410 sec and $P_D = 1$, and, from Eq. (28),

$$\frac{Q}{Q_T} = 2.3 \times 10^{-8} \times 1 \times 10^{-3} \times$$

$$\times\, 4.10 \times 10^2 = 9.4 \times 10^{-9} \ , \qquad (32)$$

$$Q = 3.8 \times 10^{-1} \ . \qquad (32a)$$

Exposure from Deposition. – Equations (31) and (32) show that Q/Q_T for deposition is much less than for continuous underwater release to the river [Eqs. (13*a*) and (13*b*)]. Therefore exposures from deposition in the river were not calculated.

Rough calculations were made, however, for one case. The wind was assumed to be blowing from

[23] *Meteorology and Atomic Energy*, AECU-3066 (July 1955).

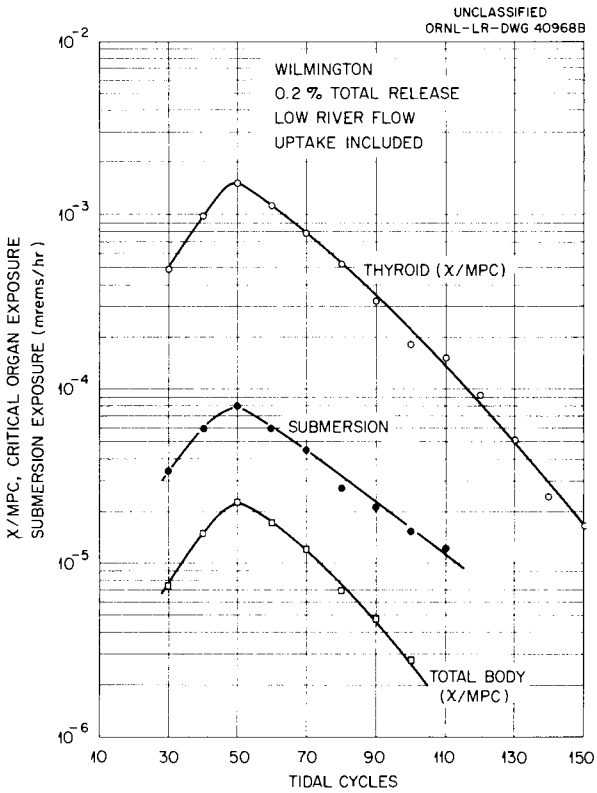

Fig. 4.34. Exposure at Wilmington as a Function of Time in Tidal Cycles with Uptake (Model Test 2).

the NYS site directly toward the Torresdale filter plant during inversion conditions, an MCA had occurred following which there was continuous leakage from the containment vessel at the rate of 0.2% per day, all the fuel elements had failed, and, when the radioactive cloud reached Torresdale, total instantaneous washout occurred.

The deposition resulted in surface activity of ω curies/m^2. Torresdale is approximately 20,000 m from NYS. From Table A.4 and Fig. A.4, ω/Q for 2×10^4 m is 7.9×10^{-4} sec/m^2. From Eq. (28) $Q/t = 9.2 \times 10^{-7}$ curie/sec. At a wind speed of 2.24 m/sec, this results in a "concentration" of $9.2 \times 10^{-7}/2.24 = 3.57 \times 10^{-7}$ curie/m. Because of mixing at the stack exit and finite stack-exit size, it is conservative to call the exit concentration at the stack 3.57×10^{-7} curie/m^3. The deposit on Torresdale for washout conditions is then

$$\omega = 3.57 \times 10^{-7} \times 7.9 \times 10^{-4}$$
$$= 2.82 \times 10^{-10} \text{ curie/m}^2 \quad . \qquad (33)$$

If it is assumed that this activity is deposited in the settling ponds at Torresdale or the river at the intake point and, further, that it is mixed uniformly to a depth of 1 m prior to discharge to the water mains, the water concentration becomes

$$\omega_w = 2.82 \times 10^{-10} \text{ curie/m}^3 \quad ,$$

or

$$\omega_w = 2.82 \times 10^{-10} \ \mu\text{c/cm}^3 \quad .$$

The MPC for a mixture of unidentified radionuclides in water if Ra^{226} and Ra^{228} are not present is 10^{-6} μc/cm^3 for occupational exposure for a 168-hr week. One-tenth of this value should be used for interim application in the neighborhood of an atomic plant.[24] The MPC values are for continuous exposure, which is not the case here. In any event the water concentration is extremely low.

POPULATION DENSITY AND TOTAL POPULATION DOSE

So-called "Greater Philadelphia," including 11 counties in Pennsylvania, New Jersey, and Delaware, encloses all the area of interest. The total area of these counties is 4565 square miles and is equivalent to that of a circle with a 43-mile radius. Table 4.17 presents data[25] on each of the 11 counties and totals for the combined area.

The mean population density of the city of Philadelphia is about 17,300 per square mile (1957). In some wards the density is greater than 50,000 per square mile and is highest approximately northwest of NYS. The population density in the city varies sharply within short distances, and accurate calculations of details of population density within radioactive isopleth areas would be extremely laborious. The population density was assumed to be 35,000 per square mile in order to give conservative values of the product dose times population in Philadelphia.

No population densities were obtainable for the city of Camden. It appears probable that they are somewhat smaller than for Philadelphia. Conservative values of the population-times-dose product

[24] *Maximum Permissible Body Burdens and Maximum Permissible Concentrations of Radionuclides in Air and in Water for Occupational Exposure*, NBS Handbook 69 (June 5, 1959).

[25] *Greater Philadelphia Facts*, Chamber of Commerce, Philadelphia, Pa. (1957).

Table 4.17. Data on Counties in Philadelphia-Camden Area

State	County	Land Area (square miles)	Population (1960 est)	Population Density (persons per square mile)	Dwelling Units as of January 1, 1957 (thousands)	Farms as of 1954
Pennsylvania	Bucks	617	290,200	435	79	2,730
	Chester	760	202,400	262	51	3,383
	Delaware	185	564,600	3,120	151	493
	Montgomery	492	509,500	1,020	132	2,505
	Philadelphia	127	2,256,000	17,700	665	76
New Jersey	Burlington	819	203,100	250	52	1,835
	Camden	221	391,300	1,770	114	658
	Gloucester	329	130,300	395	38	1,608
	Mercer	228	298,000	1,285	75	828
	Salem	350	58,700	165	18	1,478
Delaware	New Castle	437	304,700	627	84	1,130
	Total	4565	5,208,800	1,125 avg	1459	16,724

were calculated by assuming 25,000 per square mile as the population density in Camden.

Table 4.18 lists the product of dose times population for the calculated dispersions from the assumed MCA. The total exposure for the worst wind direction considered was calculated to be 4060 man-rems. Doses of less than 20 mrems/person were not included. This is a small total when compared with criteria proposed for site selection (see Appendix D for further discussion).

DIRECT EXPOSURE FROM THE REACTOR COMPARTMENT, VENTILATION PIPING, AND FILTERS

The direct exposures on shipboard from activity released during the MCA can be important because of the high activity concentrations and the large total quantities of activity involved. It is predicted that the MCA would release about 3×10^7 curies of activity to the containment vessel (with melting of all the fuel elements). For a containment vessel leakage rate of 0.2% per day, 6×10^4 curies would be released to the reactor compartment ventilation system in 24 hr.

The direct exposure from the reactor compartment, ventilation piping, and filters, following the MCA, has been calculated. These calculations do not include the effects of deposition of activity or of shielding by ship structures. The upper void of the reactor compartment has been approximated by a cylinder of equal volume. The filters are considered as a point source. The ventilation piping has been taken as an infinitely long cylinder. It is felt that these assumptions have yielded conservative exposure values.

Ventilation Piping

In order to arrive at an upper limit on the exposure from the reactor compartment ventilation piping, a 10-in.-dia, infinitely long, unshielded pipe has been considered. The formula for the flux is[26]

$$\phi = \frac{BR^2 S}{2(a+z)} F(\theta, b) \quad , \qquad (34)$$

where

ϕ = flux in Mev·cm^{-2}·sec^{-1},

B = symbolic buildup factor, taken to be 1.0,

R = radius of the cylinder, 12.7 cm,

a = distance from cylinder to the dose point in cm,

z = effective self-attenuation distance in cm,

[26] T. Rockwell III (ed.), *Reactor Shielding Design Manual*, TID-7004 (March 1956).

Table 4.18. Individual and Total Population Maximum Doses for Radioactive Isopleth Areas[a]

	Area A	Area B	Area C	Area D	All 4 Areas
Maximum downwind distance (miles to F_{min})[b]	3.41	5.03	6.89	11.25	11.25
F_{max}	1.0	0.5	0.3	0.2	1.0
F_{min}	0.5	0.3	0.2	0.1	0.1
Area between F_{max} and F_{min} (square miles)	0.125	0.263	0.338	1.108	1.834
Whole-body dose (rems/person)[c]	0.20	0.10	0.06	0.04	
Philadelphia (~35,000 persons per square mile), wind toward northwest					
Population in the area	4375	9205	11,830	38,780	64,200
Dose in the area (man-rems)[c]	875	920	710	1550	4060
Camden (~25,000 persons per square mile), wind toward north-northeast					
Population in the area	3125	6775	8450	27,000	45,850
Dose in the area (man-rems)[c]	625	658	507	1108	2900

[a]See Fig. A.5.

[b]$F = \dfrac{\text{Dose at } x \text{ meters}}{\text{Maximum dose at 2000 meters}}$.

[c]Total integrated dose from submersion in continuous source cloud for 24 hr based on maximum concentration calculated for area.

S = volume source strength in Mev·cm^{-3}·sec^{-1},

$$F(\theta, b) = \int_0^{\theta} e^{-b} \sec\theta \, d\theta,$$

θ = angle between the perpendicular through the dose point to the cylinder axis and the line from the dose point to the end of the cylinder

= $\pi/2$ for infinite cylinder,

$b = \Sigma \mu_i t_i + \mu_s z$,

μ_i = macroscopic cross section of ith shield in cm^{-1},

μ_s = macroscopic cross section of source material in cm^{-1},

t_i = thickness of ith shield in cm.

Values of z and $F(\theta, b)$ may be obtained from information in ref 26.

The source strength (S) is considered to be the rate of activity leakage from the containment vessel divided by the rate of dilution by the reactor compartment ventilation system. The activity is approximately that due to krypton and xenon, since the filter removes the other isotopes with an assumed efficiency of 99.9%. From the preceding calculations (p 21),

$$QE_\gamma = 0.136 \text{ (Mev/dis)(curies/sec)}$$

for krypton and xenon. The air flow rate is 4000 cfm or 1.89×10^6 cm^3/sec. The source strength is then

$$S = \frac{0.136 \times 3.7 \times 10^{10}}{1.89 \times 10^6}$$

$$= 2.66 \times 10^3 \text{ Mev·cm}^{-3}\text{·sec}^{-1} .$$

For a dose at 1 m from an infinitely long 10-in.-dia pipe, Eq. (34) yields, if z is neglected, a flux of

$$\phi = \frac{2.66 \times 10^3 \times (12.7)^2}{2 \times 100} \times 1.5$$

$$= 3.2 \times 10^3 \text{ Mev}\cdot\text{cm}^{-2}\cdot\text{sec}^{-1} \ .$$

From ref 26, Fig. 2.2, the flux-to-dose-rate conversion yields the following dose-rate formula for a gamma energy of about 0.5 Mev:

$$D = 2 \times 10^{-6} \times \phi \ , \qquad (35)$$

where D is in rems/hr. The dose rate at 1 m from an infinitely long pipe is then

$$D = 2 \times 10^{-6} \times 3.2 \times 10^3 \text{ rems/hr}$$

$$= 6.4 \text{ mrems/hr} \ .$$

This is a very low exposure rate when compared with other consequences of an MCA. Also, since most of the piping is in remote areas, this exposure is certainly tolerable.

Reactor Compartment

The direct exposure from the reactor compartment has been roughly approximated by calculating the dose from a cylinder with a volume equal to that of the compartment upper void. An examination of the specification for the upper void yields a volume of roughly 30,000 ft^3. (Note that the lower void lies within the secondary shielding and therefore has not been considered.) The cylinder considered is 40 ft in length and 15 ft in radius, and the dose point chosen is 10 m from the surface on the perpendicular bisector of the length.

The source strength considered is the unfiltered contaminant leaking from the containment vessel for which

$$\sum QE_\gamma = 0.59 \text{ (Mev/dis)(curie/sec)} \ .$$

This yields

$$S = 1.15 \times 10^4 \text{ Mev}\cdot\text{cm}^{-3}\cdot\text{sec}^{-1} \ .$$

The flux equation (34) yields

$$\phi = \frac{1.15 \times 10^4 \times (4.71 \times 10^2)^2 \times 0.53}{2 \times (1000 + 471)}$$

$$= 4.59 \times 10^5 \text{ Mev}\cdot\text{cm}^{-2}\cdot\text{sec}^{-1} \ ,$$

and thus the dose rate is

$$D = 2 \times 10^{-6} \times 4.59 \times 10^5$$

$$= 0.92 \text{ rem/hr} \ .$$

This dose rate is quite high in the immediate vicinity of the reactor compartment following an MCA. (The shielding effect of the compartment walls is not included in these calculations.) Health-physics instrumentation is available to determine the actual dose rates that would exist, and the shipboard management must exercise control over personnel to minimize exposures. This would entail the evacuation of personnel from the immediate area to areas that are more distant, that are better shielded, and that have lower dose rates.

Ventilation Filters

The reactor-compartment ventilation filters are assumed to remove 99.9% of all activity other than that of the noble gases. The value of $\sum QE_\gamma$ is 0.45 (Mev/dis)(curies/sec) (see p 22), and the resulting calculated source strength where leakage has continued for one day is

$$S = 0.45 \times 3.7 \times 10^{10} \times 8.64 \times 10^4$$

$$= 1.44 \times 10^{15} \text{ Mev/sec} \ .$$

Assuming all this activity to be deposited in the filters, which are considered as a point source, the flux at 10 m is

$$\phi = \frac{1.44 \times 10^{15}}{4\pi(1000)^2}$$

$$= 1.14 \times 10^8 \text{ Mev}\cdot\text{cm}^{-2}\cdot\text{sec}^{-1} \ .$$

The dose rate at 10 m is

$$D = 2 \times 10^{-6} \times 1.14 \times 10^8$$

$$= 228 \text{ rems/hr} \ .$$

This dose rate is so high that some shielding will have to be provided. It should be noted that decay has not been considered in the above calculations, and if 24-hr decay is included, the value of $\Sigma\ QE_\gamma$ becomes 0.051 (Mev/dis)(curies/sec). The dose at 10 m is then

$$D = 25.8 \text{ rems/hr} \ .$$

This exposure is still excessive, although it should be realized that the remote location of the filters (forward of the containment vessel) affords considerable isolation. Also, the shielding effects of the secondary shield and of structural materials are not included here. In any case a more detailed analysis of the effective shielding already present and the additional shielding needed should be carried out.

5. CONSEQUENCES OF ACCIDENTS OTHER THAN THE MAXIMUM CREDIBLE ACCIDENT

INADVERTENT RELEASES OF GASEOUS ACTIVITY

If gaseous activity should escape from fuel elements and subsequently escape from the ship with no associated nongaseous isotopes, essentially the only doses received by people in the area would be external. Three credible mechanisms for such an inadvertent release are: (1) a puff up through the stack caused by excessive pressure buildup in the pressurizer and the effluent condensing tank while venting the containment vessel or in the buffer seal surge tank while venting the reactor compartment; (2) loss of cooling to an isolated charcoal adsorption unit, which would cause rupture from the pressure buildup of the gas desorbed from the charcoal (there are differences of opinion as to the extent of credible pressure increase); (3) release from a charcoal adsorption unit dropped by a crane and ruptured while being removed and transported to storage.

In any of these events the dosages received may be predicted in the manner described for external doses in Chap. 4, with only xenon and krypton considered.[1] The dosage can be calculated from the data of Chap. 4, since it is in direct proportion to the amount of xenon and krypton escaping from the ship. Estimates of the amounts escaping are functions of the following assumptions: (1) reactor operating history to time of incident, (2) number of fuel elements failed, (3) efficiencies of charcoal adsorption traps, and (4) the operating characteristics of the pressure-relief valves.

Potential Dosage from Ruptured Charcoal Adsorption Unit

The data from which estimates of the dosage from a ruptured charcoal adsorption unit were made are available in Babcock & Wilcox Company reports.[2,3] Reference 3 lists the estimated maximum activity in curies of gaseous fission product activity in the adsorption units per 100 days of operation with exposure of 726 kg of fuel for four selected isotopes of krypton and seven of xenon. The total listed is 3740 curies (3300 of which are from Xe^{133}) for two adsorbers. One adsorber might therefore contain 1870 curies of xenon plus krypton.

The estimates of the dosage resulting from one saturated adsorber that was ruptured as by dropping it from a crane are compared in Tables 5.1 and 5.2 with the dosages from an MCA with the container closed. The external dose vs distance downwind from the incident is also given. It was conservatively assumed for these calculations that all the noble gases would escape from a ruptured adsorber.

Gas Puffs Caused by Pressure Relief

A number of mechanisms for emission of gas puffs through the ship stack from auxiliary units

[1] In this case, Q is the integrated total amount of activity from a release, and the calculated dosage is an integrated total. See *Theoretical Possibilities and Consequences of Major Accidents in Large Nuclear Power Plants*, WASH-740 (March 1957), for a more detailed discussion.

[2] *The Effects of Fission Product Leakage on the NMSR Plant*, BAW-1110 (May 1958).

[3] F. R. Thomasson (approved by P. E. Carroll), Spec. No. AEC-352-2/483900, Babcock & Wilcox Atomic Energy Division (Feb. 2, 1959).

Table 5.1. Maximum Activity in One Gas Adsorber Compared with Integrated 24-hr Activity from Maximum Credible Accident

Isotope	Half Life	Maximum Activity in One Adsorber					Maximum Integrated 24-hr Activity from MCA (curies·Mev)*		Ratio of Adsorber Activity to MCA Activity	
		Q, Maximum Activity (curies)	E (Mev/dis)		QE (curies·Mev/dis)					
			Beta	Gamma	Beta	Gamma	Beta	Gamma	Beta	Gamma
Kr^{85m}	4.4h	4.98	0.233	0.181	1.16	0.90				
Kr^{85}	9.4y	52	0.232		12.1					
Kr^{87}	78m	0.93	1.01	0.56	0.94	0.52				
Kr^{88}	2.8h	5.7	0.331	2.07	1.89	11.8				
Xe^{131m}	12d	28.1		0.163		4.58				
Xe^{133m}	2.3d	19.2		0.233		4.47				
Xe^{133}	5.27d	1660	0.115	0.081	191	135				
Xe^{135m}	15.6m	15.9		0.52		8.27				
Xe^{135}	9.13h	83	0.302	0.268	25.1	22.2				
Xe^{137}	3.9m	0.02	1.33		0.03					
Xe^{138}	17m	0.24	1.0		0.24					
Total		1870			233	187	6050	11,800	0.039	0.0158

*The MCA doses listed here are for an elevated source (90 ft); see Chap. 4 of this report.

Table 5.2. Dose from Ruptured Gas Adsorber

Distance Downwind (m)	Ratio of χ/Q for Ground Source to $(\chi/Q)_{max}$ for 90-ft-elevated Source[a]	Ratio of External Dose from Ruptured Adsorber to Maximum External Dose from MCA with 90-ft-elevated Source[b]		Integrated Dose from Ruptured Adsorber (mrems)[c]	
		Beta	Gamma	Beta	Gamma
250	6.4×10^{1}	2.46	1.01	174	204
500	2.26×10^{1}	0.87	0.36	61	73
800	1.12×10^{1}	0.43	0.177	30	36
1,000	8.0×10^{0}	0.31	0.126	21.9	25.5
1,500	4.3×10^{0}	0.166	0.068	11.7	13.7
2,000	2.83×10^{0}	0.109	0.045	7.7	9.1
2,500	2.02×10^{0}	0.078	0.032	5.5	6.5
5,000	7.1×10^{-1}	0.0273	0.0112	1.93	2.26
10,000	2.53×10^{-1}	0.0097	0.0040	0.68	0.81
20,000	8.9×10^{-2}	0.0034	0.00141	0.240	0.285

[a]For typical inversion conditions at Camden.

[b]Product of previous column times last column of Table 5.1, for beta and gamma, respectively.

[c]Product of previous column times 24-hr MCA elevated source maximum dose 2050 m from source. These 24-hr MCA values are $24 \times 2.94 = 70.6$ mrems (beta) and $24 \times 8.4 = 202$ mrems (gamma) (from Fig. 4.3).

become apparent upon analysis of flow diagrams and the Babcock & Wilcox reports cited in this and previous chapters. The mechanisms have various degrees of credibility. The probable frequency of occurrence of any of the mechanisms is estimated to be low, but several of the mechanisms are credible.

Sufficient overpressure in the pressurizer and effluent condenser tank system would cause the pressure-relief valve of the latter to release gas and steam to the containment vessel, which would be vented through the stack if the containment vessel valve to the stack were open. One of several mechanisms for overpressurizing the buffer seal surge tank is misoperation or malfunction of a hydrogen pressure-reducing system. If the tank is sufficiently overpressurized, its relief valve will vent the gases through the manifold and through the stack if the valve to the stack is open.

Babcock & Wilcox has recommended[4] incorporating gas-removal units and venting to them to obtain the lower activity levels predicted in the liquids and voids of the primary coolant and purification systems. The tabulations in this chapter and in Chap. 4 indicate that the Babcock & Wilcox analysis leads to the prediction that an inadvertent puff to the atmosphere of the xenon and krypton contained in the buffer seal surge tank void would release more activity than would a puff from any of the other voids analyzed. The limit of such a release is about 3% of the limiting release from a ruptured gas-adsorption unit and a still smaller fraction (about 0.1%) of the 24-hr integrated release from the MCA with the containment vessel closed.

DAMAGE TO FUEL ELEMENTS DURING REFUELING

In the event of rupture of spent fuel pins in the open air or inadvertent removal of a fuel element (164 fuel pins) from its shield, a hazard to the environment would exist. Either or both of these conditions might occur if a spent fuel element were dropped on the ship or dock by a crane, for example. An analysis of the effects of such an event if it occurred two weeks after shutdown from 52,200 Mwd of operation at 63.5 Mw is presented below.

Element Not Submerged in Water

If, as seems probable, the surfaces of the fuel pins are everywhere at a temperature below the melting point of iodine (mp, 236°F; bp, 364°F), only xenon and krypton release to the air needs to be considered in analyzing the air contamination from ruptured pins. While it is believed that most of the xenon and krypton will be retained in the fuel, it is conservatively assumed that 100% of these gases will escape.

The concentrations and activities of the significant isotopes of xenon and krypton in each fuel pin after 52,200 Mwd of operation are listed in Table 5.3. The atmospheric concentrations of activity from failed fuel pins, at increasing distances downwind (product of amount released times the corresponding χ/Q from Appendix A, Fig. A.2), are shown in Table 5.4. The data of Table 5.4 for the external exposure dose were obtained with the use of the equation[5]

$$D = 2.6 \times 10^{-7} E_s QT \ ,$$

in which $E_s QT$ (μc·Mev/dis) represents the total QE from Table 5.3 multiplied by the χ/Q from Fig. A.1, Appendix A, for the distances noted. That is,

$$D = 2.6 \times 10^{-7} \times 29.0 \times 10^6 \times \frac{\chi}{Q} = 7.54 \frac{\chi}{Q}$$

in rems, or

$$D = 7.54 \times 10^3 \times \frac{\chi}{Q}$$

in mrems received per pin failed.

Table 5.4 shows, in brief, that, for the meteorological conditions assumed (inversion and ground-level source) at distances 500 m or greater from the incident, the air-submersion dose received from fuel pin failures would not exceed about 11 mrems per failed pin or about 2 rems in the unlikely event that all 164 pins in an element failed.

Table 5.5 lists the results of calculations made to obtain the activity (in curies·Mev) of a spent

[4] F. R. Thomasson and F. W. Davis, *NS Savannah, Analysis of Operation with Regard to Waste Collection and Disposal*, BAW-1109, p 30 (September 1958).

[5] T. J. Burnett, *Nuclear Sci. and Eng.* 2, 383 (1957).

Table 5.3. Activities of Xenon and Krypton in Spent Fuel Pins

Isotope	Atoms of Isotope per Pin[a]		Isotopic Activity per Pin	
	At Shutdown	14 Days Later	Q (curies)	QE^b (curies·Mev)
Kr^{85m}	1.3×10^{17}	~0	~0	~0
Kr^{85}	1.2×10^{20}	1.2×10^{20}	7.0	0.54
Kr^{88}	3.6×10^{17}	~0	~0	~0
Xe^{131m}	3.0×10^{17}	2.2×10^{17}	4.0	0.87
Xe^{133m}	3.0×10^{17}	7.5×10^{15}	0.68	0.21
Xe^{133}	3.0×10^{19}	5.7×10^{18}	230	27.37
Xe^{135}	1.0×10^{18}	~0	~0	~0
		Total	242	29.0[c]

[a] J. O. Blomeke and M. F. Todd, *Uranium-235 Fission-Product Production as a Function of Thermal Neutron Flux, Irradiation Time, and Decay Time*, TID-4500, 13th ed. (Aug. 19, 1957).

[b] T. J. Burnett, *Nuclear Sci. and Eng.* 2, 383 (1957). (E, effective energy, is the gamma energy plus one-third of the beta energy.)

[c] This result indicates that the effective mean $E = 0.120$ Mev.

Table 5.4. Air-Submersion Dose from Spent Fuel Pins Ruptured in Air

Distance Downwind (m)	χ/Q	Dose from Failure of One Pin (mrems)	Dose from Failure of One Fuel Element (rems)
100	1.67×10^{-2}	126	20.7
500	1.49×10^{-3}	11.2	1.84
1000	5.27×10^{-4}	3.97	0.65
2000	1.87×10^{-4}	1.41	0.23

fuel element (164 pins) for use in calculating the direct gamma-ray dose which would be received from an unshielded spent element. The calculations are based on the following assumptions:

1. There is 7980 kg of fuel per reactor contained in 32 fuel elements of 164 fuel pins each, or 2.475×10^{25} atoms of U^{235} per element.
2. The time operated at 63.5 Mw was 7.1×10^7 sec, corresponding to 52,200 Mwd at 63.5 Mw.
3. The time elapsed after shutdown and before the incident occurred that exposed the fuel element to the air (removal of the shield) was 6.21×10^6 sec (14 days).
4. The mean flux, Φ, during operation was 8×10^{12} neutrons·cm^{-2}·sec^{-1}.

Table 5.6 shows the dose rates vs distance calculated from the data of Table 5.5 with the use of the approximate equation[6]

$$D = \frac{6CE}{F^2},$$

where

D = dose rate, rems/hr,

C = activity, curies,

E = energy rate, Mev/dis,

F = distance from source, ft.

It is clear that the direct gamma radiation from an exposed 164-pin fuel element would result in a severe dose to any person in the immediate vicinity of such an accident. Longer elapsed times after shutdown before removing fuel elements for replacement would mean keeping the ship out of service. The alternative is designing for prevention of inadvertent removal of the shielding as a credible accident, including dropping from a crane.

[6] S. Glasstone, *Principles of Nuclear Reactor Engineering*, p 545, Eq. 9.47.1, Van Nostrand, New York, 1955.

Table 5.5. Data for Calculating Direct Gamma-Ray Dosage from an Unshielded Spent Fuel Element (164 Fuel Pins)

	Energy Group			
	I	II	III	IV
Energy range, Mev	0–0.25	0.25–1.00	1.00–1.70	1.70–∞
Disintegrations per second per atom of U^{235}	6.4×10^{-10}	9.0×10^{-10}	1.7×10^{-10}	1.5×10^{-11}
Disintegrations per second per pin	9.8×10^{13}	1.34×10^{14}	2.56×10^{13}	2.26×10^{12}
Disintegrations per second per fuel element	1.6×10^{16}	2.2×10^{16}	4.2×10^{15}	3.7×10^{14}
Estimated energy E_γ per disintegration	0.2	0.6	1.35	2.0
Concentration, C, of activity, curies per element	4.3×10^5	5.9×10^5	1.14×10^5	1.00×10^4
$6CE$, curies·Mev per element	5.2×10^5	2.1×10^6	9.2×10^5	1.2×10^5

Table 5.6. Direct Gamma Dosage from an Unshielded Spent Fuel Element (164 Fuel Pins) vs Unobstructed Distance from the Element

Energy Group	$6CE$*	Gamma Dose (rems/hr) per Spent Fuel Element				
		At 100 ft	At 300 ft	At 1000 ft	At 5000 ft	At 10,000 ft
I	5.2×10^5	52	5.8	0.52	0.021	0.0052
II	2.1×10^6	210	23	2.1	0.085	0.021
III	9.2×10^5	92	10	0.92	0.037	0.0092
IV	1.2×10^5	12	1.3	0.12	0.048	0.0012
	Total	364	40	3.7	0.15	0.037

*From Table 5.5.

Element Submerged in Water

If a shielded element were dropped into the water and some of the pins were ruptured, some of the fission products would be released into the river. Since the activity concentration in the water in the immediate vicinity of the ruptured pins might far exceed a tolerable level for a short time, the area should be monitored until mixing lowers the activity to a tolerable level. Monitors for sampling the river in the environs of the ruptured pins should be available in the case of a spill, in addition to the more conventional appropriately placed monitors on the ship and dock.

Table 5.7 shows that 100% release from two fuel pins into the river would not result in the Sr^{90} concentration in the river water exceeding the MPC for continuous occupational exposure at any point in the river not immediately adjacent to the ruptured pins at any times greater than three tidal cycles after the incident. Table 5.8 shows that if the rate of escape of fission

Table 5.7. Maximum MPC for Ingestion (Drinking) of Delaware River Water After Rupture of Submerged Spent Fuel Pins[a]

Isotope[b]	Initial[c] Content per Pin		Concentration ($\mu c/cm^3$) at Sampling Point		Value of One MPC Unit[d] ($\mu c/cm^3$)	Number of Failures per MPC Unit	
	Number of Atoms	Activity (curies)	Per Pin	Per Element		Pins	Elements
Sr^{89}	9.45×10^{19}	3.9×10^{2}	2.8×10^{-6}	4.6×10^{-4}	1×10^{-4}	36	0.22
Sr^{90}	2.89×10^{21}	6.2×10^{1}	4.5×10^{-7}	7.4×10^{-5}	1×10^{-6}	2.2	0.014
I^{131}	4.36×10^{16}	1.2×10^{-3}	2.6×10^{-12}	1.4×10^{-9}	2×10^{-5}	7.7×10^{6}	1.4×10^{4}
I^{132}	3.9×10^{11}	8.4×10^{-4}	6.0×10^{-12}	9.8×10^{-10}	8×10^{-4}	1.3×10^{8}	8.3×10^{5}

[a]Assuming instantaneous escape and solution of all fission products from all ruptured pins, and using the minimum dispersion (maximum χ/Q) from model data for elapsed time of three tidal cycles after the accident which ruptured and submerged the pins: $\chi/Q = 7.2 \times 10^{-15}$, as shown in Appendix F. The MPC values shown are for continuous occupational exposure. The recommended MPC for nonoccupational exposure is one-tenth of the value given for occupational exposure.

[b]These isotopes yield the controlling exposures.

[c]At time of failure (6.2×10^{6} sec after shutdown).

[d]See Chap. 4.

Table 5.8. Maximum Number of MPC Units in Delaware River from Rupture of Submerged Spent Fuel Pins

	Controlling Isotopes	
	Sr^{89}	Sr^{90}
Initial concentration, μc/pin	3.9×10^{8}	6.2×10^{7}
Escape rate, μc/pin		
In first second	3.9×10^{-3}	6.2×10^{-4}
In one tidal cycle (4.47×10^{4} sec)	1.74×10^{2}	2.77×10^{1}
Dispersion factor, χ/Q	7.2×10^{-15}	7.2×10^{-15}
Concentration after dispersion, $\mu c/cm^3$		
Per pin failure	1.25×10^{-12}	1.99×10^{-13}
Per element failure	2.05×10^{-10}	3.26×10^{-11}
Value of one MPC unit, $\mu c/cm^3$	1×10^{-4}	1×10^{-6}
Allowable failures (elements per MPC unit)	2×10^{6}	3×10^{5}

products from a ruptured pin is not more than several orders of magnitude greater than the rates experimentally determined from the third PWR test run at Chalk River,[7] then 100% of the pins could rupture without causing significant activity in the main body of the river.

Table 5.9 shows that an immediate 100% release of fission products from an element into the water (assuming complete solubility) would result in a whole-body submersion exposure that would be less than the permissible occupational level after three or more tidal cycles.

[7]P. W. Frank, K. H. Vogel, and P. Cohen, *Radiochemistry of Third PWR Fuel Material Test X-1 Loop NRX Reactor*, WAPD-TM-29 (February 1957).

Table 5.9. Maximum MPC for Submersion in Delaware River from Rupture of Submerged Spent Fuel Pins*

Isotopes	Initial Cantent per Pin		Energy Concentration ($Mev \cdot cm^{-3} \cdot sec^{-1}$)		Number of Failures per MPC Unit	
	Number of Atoms	Beta and Gamma Energy (Mev/sec)	Per Pin Failure	Per Element Failure	Pins	Elements
Xe^{133}	5.7×10^{18}	1.7×10^{12}	1.22×10^{-2}	2.0×10^{0}	8.2×10^{2}	5.0×10^{0}
Other gases		8.5×10^{10}	6.1×10^{-4}	1.0×10^{-2}	1.6×10^{4}	1.0×10^{3}
I^{131}	4.3×10^{7}	2.5×10^{7}	1.8×10^{-7}	3.0×10^{-5}	5.6×10^{7}	3.3×10^{5}
I^{132}	3.1×10^{7}	7.5×10^{7}	5.4×10^{-7}	8.9×10^{-5}	1.9×10^{7}	1.2×10^{5}
Cs^{136}	1.52×10^{16}	9.6×10^{9}	6.9×10^{-5}	1.1×10^{-2}	1.4×10^{5}	9.1×10^{2}
Cs^{137}	2.65×10^{21}	4.2×10^{11}	3.0×10^{-3}	4.9×10^{-1}	3.3×10^{3}	2.0×10^{1}
Ba^{140}	1.45×10^{18}	4.6×10^{11}	3.3×10^{-3}	5.4×10^{-1}	3.0×10^{3}	1.8×10^{1}
La^{140}	2.07×10^{17}	2.6×10^{12}	1.87×10^{-2}	3.1×10^{0}	5.3×10^{2}	3.2×10^{0}
		Total	3.8×10^{-2}	6.2×10^{0}		
		Average			260	1.6

*See Table 5.7 for definitions of terms and conditions.

Removal of a dropped element from either ship, dock, or river (submerged) would require separate consideration of the specific conditions resulting from the accident. If such removal were carried out with reasonable forethought and care, it is not apparent that it should be a hazardous operation.

LEAK TO RIVER FROM DOUBLE-BOTTOM TANKS

If some mishap should cause a puncture of the ship's hull into the double-bottom (or inner-bottom) tanks, some of the contaminated liquid in the tanks would escape into the river.

The concentrations of activities in liquid and gas effluents from some of the major systems and components were calculated by Babcock & Wilcox.[8] The highest liquid concentration shown which might be drained into the double-bottom tanks is that of the effluent from a condensing tank without venting or gas removal units: 0.202 $\mu c/cm^3$ or 0.202 curies/m^3. Part V of the Appendix of the same report (Dwg. SC-48-13E-3)[8] shows the combined volume of the inner-bottom tanks to be 700 ft^3 or 19.82 m^3. The maximum total activity, Q, of the tanks is then 4.00 curies. The highest χ/Q found from mixing in the river after three tidal cycles is 7.5×10^{-15} (see Chap. 4 of this report). Therefore the greatest concen- of activity from an instantaneous release of liquid from these tanks to the river would be

$$7.5 \times 10^{-15} \times 4.00 = 3.0 \times 10^{-14} \text{ curie/cm}^3 .$$

Comparison with Table 5.7 shows that this concentration is less than the MPC for Sr^{90} of 1×10^{-6} $\mu c/cm^3$, or 1×10^{-12} curie/cm^3, by a factor of about 30. With gas removal and venting of primary voids, the factor increases[9] to $0.202/0.00626 \times 30$, or about 10^3. Another increase in the factor would result from assuming the tanks to be less than full and assuming mixing with lower activity water from other units than the effluent condensing tank. As in the case of ruptured fuel pins dropped in the river, the local activity soon after the accident might be too high to tolerate, and a monitored exclusion area might be required.

[8] F. R. Thomasson and F. W. Davis, *NS Savannah, Analysis of Operation with Regard to Waste Collection and Disposal*, BAW-1109, Table IV (September 1958).

[9] *Ibid.*, Table VI.

SPILLAGE OF ION EXCHANGE RESIN

It was assumed by Babcock & Wilcox as a basis for hazards evaluations that 9% of the fuel pins (475 pins) failed simultaneously after 300 days of operation at 63.5 Mw and that the reactor operated 100 additional days at 63.5 Mw before shutdown.

Two cases of accumulation of fission product activities in the primary water were tabulated.[10] In one case the pins continued to leak, and the bypass through the demineralizer continued to operate after shutdown. In the other case the pin leakage and demineralizer bypass flow stopped at shutdown. The difference in these two cases represents the accumulation of fission product activities in the demineralizer (omitting xenon and krypton isotopes). The resulting total fission product activity accumulation is given below:

	Activity (curies)
Per failed pin	8.90
Per 475 failed pins (9.05% of fuel)	4.23×10^3
Per 362 failed pins (5% of fuel)	2.35×10^3

Since the referenced calculations were made for 100 days of full-power operation and it is proposed that one ion exchanger will be operated not more than 50 days, the calculated activities are conservatively high. Also, it is considered unlikely that the number of pin failures will approach the design figure of 475 pins, so another conservative factor is introduced. The amount of fission product activity which may exist in a demineralizer then is 4230 curies times a fraction combining the two conservative factors just defined. In the discussion below, the fraction is assumed to be 1.0.

The accumulated corrosion product activity in a demineralizer during 50 days of operation at 63.5 Mw was estimated to be 407 curies,[11] as indicated below:

Isotope	Accumulated Activity (curies)
Mn^{56}	1.15
Fe^{59}	3.81
Fe^{55}	75.0
Co^{60}	75.3
Ta^{182}	103
K^{38}	0.57
Na^{24}	1.05
Cr^{51}	147.5

The "worst" predictable accumulation of combined fission product activity and corrosion product activity then is 407 + 4230 = 4640 curies, including the conservative factors described above.

Direct Radiation from Unshielded Demineralizer

If a demineralizer with 4640 curies of activity were accidentally separated from its shield, as by being dropped from a crane, it would constitute a radiation hazard to persons in the vicinity. Using the approximate equation[12]

$$D = \frac{6CE}{F^2},$$

it is found that if the average gamma photon energy is 0.5 Mev, the dose is

$$D \cong \frac{1.4 \times 10^4}{F^2}$$

in rems/hr, and the dosage vs unobstructed distance would be as shown in Fig. 5.1. Steps should be taken to preclude this accident.

River Water Contamination from Ruptured Submerged Demineralizer

If a demineralizer containing the predicted amount of activity (4640 curies) were ruptured and sunk in the Delaware River, and the activity were dispersed as described in Chap. 4, the maximum concentration in the river water after three tidal

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[10] *The Effects of Fission Product Leakage on the NMSR Plant*, BAW-1110, Table III, p 37 (May 1958).

[11] F. R. Thomasson and F. W. Davis, *NS Savannah, Analysis of Operation with Regard to Waste Collection and Disposal*, BAW-1109, App. Part II, p 4a (September (1958).

[12] S. Glasstone, *Principles of Nuclear Reactor Engineering*, p 545, Eq. 9.47.1, Van Nostrand, New York, 1955.

cycles[13] would be the product of Q and χ/Q, where

$$\frac{\chi}{Q} = 1.67 \times 10^{-14} \times 0.0043$$

for minimum dilution, from model data for test 1. Therefore

$$\text{Concentration} = 4.64 \times 10^{9} \times 1.67 \times 10^{-14} \times 0.0043$$

$$= 3.33 \times 10^{-7}\ \mu c/cm^3 \ .$$

This total concentration is less than the MPC for the most sensitive fission product, Sr^{90}. The MPC for Sr^{90} ($1 \times 10^{-6}\ \mu c/cm^3$) is the smallest listed for occupational exposures.[14] The next smallest, for I^{131}, is higher by a factor of 20. Strontium-90 is ~0.2% of the total activity, that is, $\sim 7 \times 10^{-10}\ \mu c/cm^3$, which is about 0.1% of the MPC. Iodine-131 is ~25% of the total activity, that is, $\sim 1.1 \times 10^{-7}\ \mu c/cm^3$, which is ~0.5% of the MPC. Therefore, except for the time immediately following such an incident, no significant dosage would result from ingestion of the water. Comparison of the total concentration ($3.33 \times 10^{-7}\ \mu c/cm^3$) with the data of column 6 of Table 5.7 shows that no significant submersion dose could occur from such an incident after some time less than three tidal cycles after the incident.

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[13] Note that the local concentration soon after such an incident might be excessive and the immediate area would require monitoring and temporary control.

[14] *Maximum Permissible Body Burdens and Maximum Permissible Concentrations of Radionuclides in Air and in Water for Occupational Exposures*, NBS Handbook 69 (June 5, 1959).

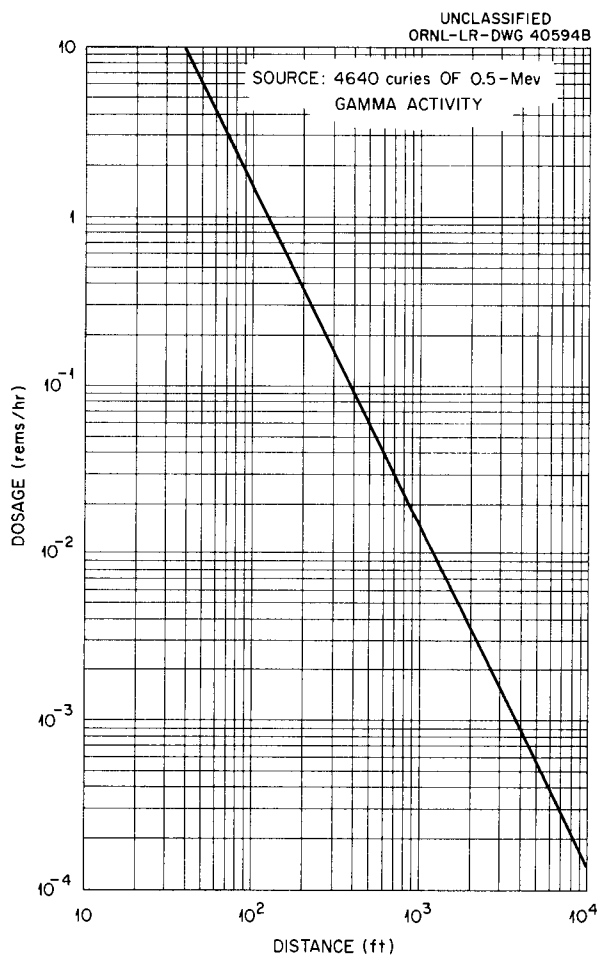

Fig. 5.1. Direct Gamma-Ray Dosage from Unshielded Saturated Demineralizer as a Function of Distance.

6. STARTUP AND OPERATION AT CAMDEN SITE

A maximum credible accident and other potentially less dangerous accidents at the Camden site were analyzed in Chaps. 4 and 5 and shown to present reasonably low exposure rates based on the established design and inspection schedule and the planned administrative controls. Because of these low exposure rates it is felt that no limit need be placed on the power level and operating time of the NS "Savannah" reactor at Camden. However, the consequences of an MCA after limited operating times at various power levels are evaluated here. It should be noted that the whole-body submersion dose due to the MCA after operation at full power for 100 hr approaches the exposure from long-term operation. This is due to the saturation of krypton and xenon in short operating periods.

The administrative control that must be maintained to ensure the integrity of the containment vessel at all times is also discussed here. It is pointed out that the reactor-compartment ventilation system and the stack filtration system must always be operative, and therefore standby equipment must be ready for emergency use. The release of gaseous activity as a routine operational procedure is also discussed, as are the limits on the amount of activity that can be stored in the double-bottom tanks.

OPERATIONAL CONTROL

In considering the consequences of the MCA, the containment vessel leakage rate is assumed to be $\leq 0.2\%$ per day; the reactor compartment is to be ventilated continuously and the discharge filtered with an efficiency of $\geq 99.9\%$ (except for the noble gases); and the containment vessel is assumed to be intact.

Leakage Rate

The assumed leakage rate of 0.2% per day or less is the design criterion, and the experimental data are expected to show that the actual leakage rate will be at least this low. The exposure rates are so low, however, that a leakage rate greater than this could be tolerated. Following completion of construction and initial testing, further tests will be required if penetrations are removed, disconnected, or added, or if repairs are made. Also, the ship's administrators should see that routine checks of penetrations are made for the detection of damage and that the containment vessel leak test is repeated routinely (say, once a year or when the core is refueled).

Reactor-Compartment Ventilation

The ship's administrators must require that the reactor-compartment ventilation system be adequately designed, constructed, and operated to ensure the proper control of gaseous activity. This means that both the upper and lower voids should be ventilated through the radioactive filtration system and released via the radioactive discharge stack. The ventilation system must maintain a negative pressure in these voids to prevent the outward seepage of activity. The ventilation system should have adequate flow (4000 cfm) to keep the air-borne radioactivity below MPC levels during normal operation. Standby equipment should be available for use in the event of a blower failure.

Routine administrative control must assure (1) that doors, hatches, and openings into the reactor compartment are not left open, (2) that the fan and motor are kept in good repair and that a spare unit is installed and ready for use, (3) that the filters are properly inspected and installed and are routinely checked, and (4) that the radioactivity monitors are routinely inspected and calibrated and that a record is kept of the activities of all discharges.

Integrity of Containment Vessel

The administrators must ensure that the integrity of the containment vessel is not voided by hatches or air locks being left open or improperly secured. The containment vessel should not be opened unless sufficient time exists to reseal it before occurrence of fuel melting following an MCA. Thus, upon shutdown, the containment vessel should not be opened unless the requirements described in Appendix H are met and the data indicate that sufficient decay of afterheat has taken place to allow replacement of hatches during the period between a primary rupture and fuel-element failure. This does not, however, prevent an earlier entrance through the air lock if the radiation and air concentration levels are sufficiently low.

Appendix H, Table H.1, summarizes the effect of shutdown time on the elapsed time between primary system rupture and fuel-element melting. For example, Table H.1 indicates that 3 hr will elapse between the primary system rupture and initial fuel-element melting if the reactor has been shut down for 10 hr after 100 hr of operation at 50% power.

POWER LEVEL AND OPERATING TIME

Conditions and Assumptions

For the initial startup at Camden, the conditions presented earlier (fission product inventory for 600 days at full power) are obviously not realistic. In this section the exposures resulting from an MCA are calculated for short-term operation and power levels of 20, 50, and 100% of full power. The operating times considered are 10 and 100 hr. The type of accident considered is the continuous-source MCA. It was arbitrarily decided (p 17) to take 24 hr after the onset of the MCA as the time at which the total integrated dose was to be determined. The percentage of total fuel elements failed, taken from Appendix G, is summarized in Table 6.1 as a function of power level and time of operation.

For these conditions the internal doses for the thyroid, bone, kidney, and muscle and the external (whole-body) dose from submersion due to the krypton and xenon isotopes have been calculated in the manner outlined in Chap. 4. Separate calculations were necessary for the 100- and 10-hr operating times. For each operating time, Q_T (fission product inventory) was calculated for 30 isotopes of interest[1] for the internal dose and for the krypton and xenon isotopes for the external exposure. (The data of Appendix G were used to determine the fission product inventory for operation at full power for 10 and 100 days.) The amount released to the environment, Q, was then determined for full-power conditions in the manner outlined in Chap. 4.

The activity buildup for 10 hr of operation was determined from the data of Appendix G for 100 hr of operation. The buildup of a given isotope in the core is given by

$$N_i(t) = K(P,Y_i)\,(1 - e^{-\lambda_i t}) \quad , \qquad (1)$$

where

$N_i(t)$ = amount of isotope i accumulated for a reactor operation time of t hr,

$K(P,Y_i)$ = function of the power level and the yield of isotope i,

λ_i = decay constant for isotope i, sec^{-1},

t = operating time of the reactor, sec.

Thus, for a given power level, the ratio of the buildup for different operating times is

$$\frac{N_i(t_1)}{N_i(t_2)} = \frac{(1 - e^{-\lambda_i t_1})}{(1 - e^{-\lambda_i t_2})} . \qquad (2)$$

The buildup for 100 hr of operation was calculated from the data of Appendix G, and the buildup for 10 hr of operation was determined from those values by the use of Eq. (2).

[1] T. J. Burnett, *Nuclear Sci. and Eng.* 2, 382–93 (1957).

Table 6.1. Fuel Element Failure Rate

Operating Time (hr) Prior to MCA	Fuel Elements Failed (%) 24 hr After MCA Following Operation at Indicated Power Level		
	At 69 Mw*	At 35 Mw**	At 14 Mw
100	94	93	82
10	89	84	50

*The values given here are the maximum numbers of fuel elements that will have failed, and these values will be reached about 10 hr after the accident.

**The values given here are approximately the maximum numbers of fuel elements that will have failed, and these values will be reached about 20 hr after the accident.

Exposure from the Continuous Source

The total integrated doses from an MCA following 10- and 100-hr operating periods at full power are summarized in Table 6.2. The exposure at any other power level can be obtained from a ratio of power levels and the fraction of the fuel elements that have failed (see Table 6.1). The TID exposures as a function of power level for operating times of 10 and 100 hr are given in Figs. 6.1 and 6.2. The exposures were calculated on the basis that the activity had been leaking at the maximum rate for the entire 24 hr. It should be noted that this is not the case, since the leakage of activity from the containment vessel is zero at $t = 0$ and increases as the fuel elements fail. The resulting doses are conservative, especially for short operating periods, since it would take a few hours after onset of the MCA for the first fuel element to fail. The doses in Table 6.2 are for $(\chi/Q)_{max} = 6.6 \times 10^{-5}$ sec/m^3 during the typical inversion condition.

The doses listed in Table 6.2 include a filtration factor of 10^{-3} for all isotopes except the noble gases. If filtration is not included, the internal organ doses should be increased by a factor of 10^3 and the whole-body dose by a factor of 5. The controlling exposure is then the thyroid

Table 6.2. TID from Continuous Source During First 24 hr After Onset of MCA

Type of Exposure	TID (mrems)	
	After 10-hr Operating Period	After 100-hr Operating Period
Whole-body (Kr and Xe)	50	209
Thyroid	13.7	106
Bone	0.109	1.09
Kidney	2.88×10^{-3}	1.81×10^{-2}
Muscle	3.6×10^{-5}	3.8×10^{-4}

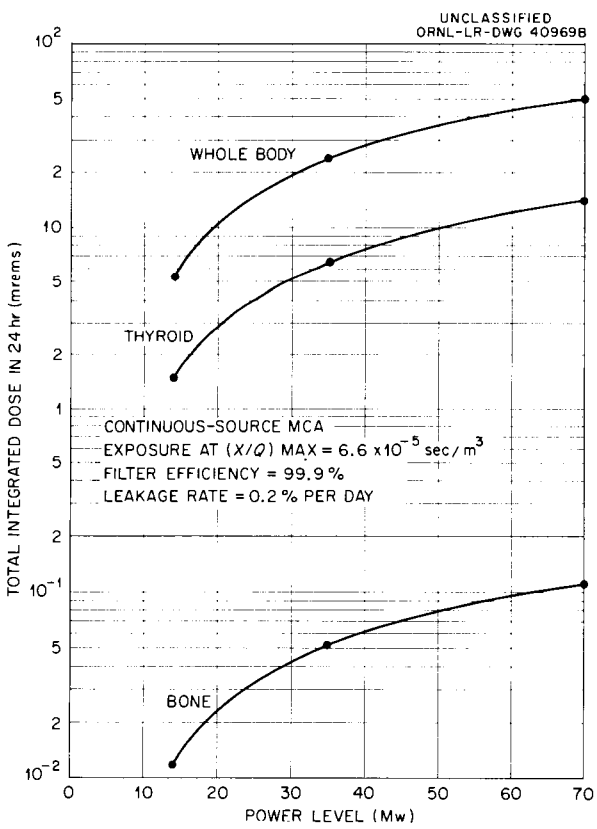

Fig. 6.1. Total Integrated Exposure in 24 hr as a Function of Power Level for 100 hr of Operation.

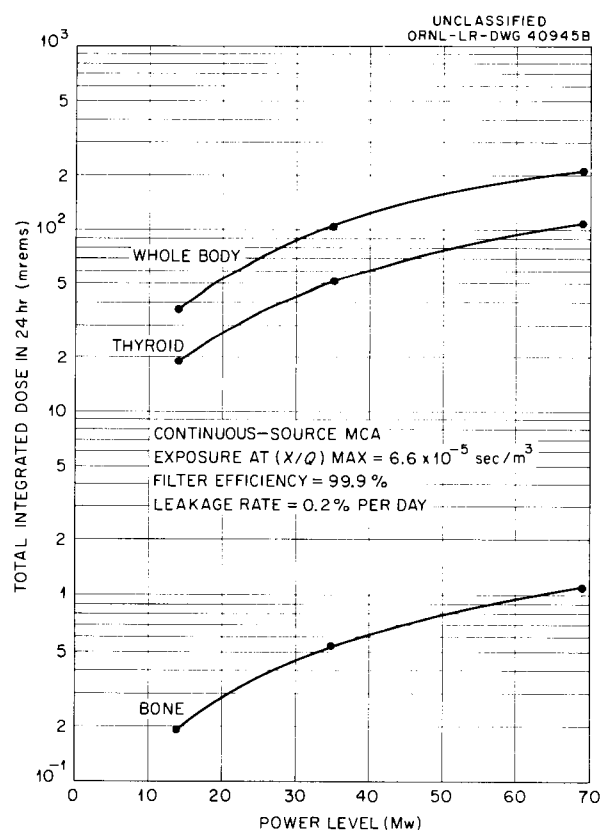

Fig. 6.2. Total Integrated Exposure in 24 hr as a Function of Power Level for 10 hr of Operation.

dose of 106 rems, which is in excess of the once-in-a-lifetime dose of 67 rems, corresponding to a whole-body dose of 25 rems (see Appendix C).

OPERATIONAL ACTIVITY LIMITS

Activity Stored in the Double-Bottom Tanks

No radioactive liquid wastes will be dumped from the NS "Savannah," and the liquid waste storage tanks aboard the vessel may therefore contain significant activity. In the not impossible event that the ship were to run aground and cause the double-bottom tanks to be ruptured, this activity would be released. It is important that the activity stored in these tanks not be so great that excessive concentrations would exist if this activity were accidentally released to the Delaware River. For this situation it is assumed that the MPC for occupational workers[2] after one tidal cycle is an acceptable criterion.

The minimum dispersion for an instantaneous release (here released over a period of 3 hr) is approximately $\chi/Q = 1 \times 10^{-14}$ cm^{-3}. Thus the maximum amount of activity, Q, that may be stored in the double-bottom tanks is defined by

$$Q_i = \chi_{MPC} \times 10^{14} \ ,$$

where χ_{MPC} is the MPC for occupational exposure (168-hr week).

Thus for an unidentified mixture of radionuclides that does not contain Ra^{226} or Ra^{228},

$$\chi_{MPC} = 10^{-6} \ \mu c/cm^3 \qquad \text{(ref 2).}$$

The amount of this mixture that may be stored in the double-bottom tanks is then

$$Q = 10^{-6} \ \mu c/cm^3 \times 10^{14} \ cm^3 \ ,$$

or

$$Q = 100 \text{ curies} \ .$$

The amount of any other mixture or specific isotope may be determined in a similar fashion.

[2] *Maximum Permissible Body Burdens and Maximum Permissible Concentrations of Radionuclides in Air and Water for Occupational Exposure,* NBS Handbook 69 (June 5, 1959).

Discharge of Gaseous Activity

The concentration of gaseous activity should not be allowed to exceed the MPC for continuous public exposure, which is defined in ref 2 as one-tenth of the MPC for occupational exposure. The listed MPC values for several isotopes of interest are:

Isotope	MPC ($\mu c/cm^3$)
Ar^{41}	4×10^{-7}
Kr^{87}	2×10^{-7}
I^{129}	6×10^{-10}
Xe^{135}	10^{-6}

Since the iodine will be reduced by a factor of 10^3 by the filter, the controlling gaseous activity will be Kr^{87}. For continuous venting, the activity at the stack discharge may be ten times the concentration listed above as the MPC for occupational exposure without exceeding the MPC for continuous public exposure at the point of maximum ground concentration. The amount of activity that may be released is then

$$Q = \text{dilution} \times 10\chi_{MPC} \ .$$

The dilution from the 4000-cfm stack discharge is

$$1.6 \times 10^{11} \times \frac{1}{F_F} \ cm^3/day \ ,$$

where F_F is the filtration factor and is assumed to be 10^{-3} for all isotopes except the noble gases. Thus

$$Q = \frac{1.6 \times 10^{11} \times 10}{F_F} \times \chi_{MPC} \ .$$

For the release of Kr^{87}, for which $F_F = 1$ and $\chi_{MPC} = 2 \times 10^{-7} \ \mu c/cm^3$,

$$Q = 1.6 \times 10^{12} \times 2 \times 10^{-7} \ ,$$

or

$$Q = 3.2 \times 10^{-1} \text{ curie/day} \ .$$

Higher release rates could be allowed under favorable meteorological conditions, but for continuous release in port the stack monitors should be set for this limit.

Appendix A

ATMOSPHERIC DISPERSION OF RADIOACTIVITY

A review of the literature[1-4] on factors influencing population exposures has revealed similarities of theory and discussion, but the extreme complexity of meteorological phenomena and the wide ranges of meteorological parameters make predictions of concentrations and dose rates uncertain. However, it appears that, except for unusual weather conditions, the calculated dispersions from a point source, for example, the stack of the NS "Savannah," are probably correct to within a factor of 3. The uncertainties involved in the calculations of activity release by an assumed accident must, of course, be added to the meteorological uncertainties.

The nomenclature commonly used in calculations of exposure is shown in Table A.1. Symbols not defined here are defined where they are used.

[1] *Meteorology and Atomic Energy*, AECU-3066 (July 1955).

[2] *A Meteorological Survey of the Oak Ridge Area*, ORO-99 (November 1953).

[3] *Theoretical Possibilities and Consequences of Major Accidents in Large Nuclear Power Plants*, WASH-740 (March 1957).

[4] T. J. Burnett, *Nuclear Sci. and Eng.* 2, 382–93 (1957).

Table A.1. Nomenclature

Symbol	Definition	Units
C_x, C_y, C_z	Diffusion coefficients in the x, y, and z planes, respectively	$m^{n/2}$
h	Height of source (or plume) above ground level	m
n	Parameter associated with meteorolagical stability; $n = \dfrac{2}{1 + [\ln (z_2/z_1)/\ln (\bar{U}_2/\bar{U}_1)]}$	dimensionless
Q	Source strength, as total or rate:	
	1. Instantaneous source strength, total	curies
	2. Continuous point source emission rate	curies/sec
t	Time	sec
$\bar{U}$	Mean wind velocity	m/sec
x	Distance directly downwind from source	m
y	Horizontal distance normal to x	m
z	Vertical distance from ground level (as to center of radioactive cloud or to source, etc.)	m
χ	Concentration	curies/m^3 or curies$\cdot m^{-3} \cdot sec^{-1}$
F	Fraction of the maximum χ/Q at (x,y); $F = \dfrac{(\chi/Q)_{x,y}}{(\chi/Q)_{max}}$	dimensionless
ω	Deposition	curies$\cdot m^{-2} \cdot sec^{-1}$ or curies/m^2

DISPERSIONS OF RADIOACTIVITY RELEASES AS AFFECTED BY METEOROLOGICAL CONDITIONS

Meteorological Conditions Considered

Two meteorological conditions are considered in detail here that give a somewhat conservative evaluation of the dispersion during typical lapse (daytime) conditions and typical inversion (nighttime) conditions. The evaluations are conservative in the sense that they give high values of χ. The parameter values used[5] are:

	Day	Night
$\bar{U}$, m/sec	4.5	2.24
n, dimensionless	0.22	0.50
C_y, $m^{n/2}$	0.39	0.19
C_z, $m^{n/2}$	0.36	0.09
h, m	27.4	27.4

No compass direction of the wind is so infrequent at Camden as to be excludable from consideration.[6] As a result, it is necessary to consider all directions in which the integral of concentration χ times the population density is a maximum in order to determine maximum effects of activity releases. All the dispersion equations indicate that increasing wind velocities give monotonically decreasing doses χ at *all* points as a direct consequence of increasing dilution by air. Therefore unusually high wind velocities need not be studied.

The calculation of the probable limits[7] of maximum downwind concentrations for continuous release of activity, based on Sutton's equation,[8] is described below:

$$\chi_{max} = \frac{2Q}{\pi e \bar{U} h^2} \frac{C_z}{C_y} = 0.2342 \frac{Q}{\bar{U} h^2} \frac{C_z}{C_y} ,$$

$$x(\chi_{max}) = \left(\frac{h^2}{c^2} \right)^{1/(2-n)} .$$

Probable limits of C_y, C_z, and $\bar{U}$ for typical lapses and inversions, as adapted from ref 3, p 48, for a 90-ft stack height are given below, together with the range of calculated values of χ/Q:

	Typical Lapse	Typical Inversion
h, m	27.4	27.4
n, dimensionless	0.2–0.35	0.4–0.8
C_y, $m^{n/2}$	0.25–0.50	0.08–0.50
C_z, $m^{n/2}$	0.3–0.45	0.02–0.07
$\bar{U}$, m/sec	3–15	1–15
C_z/C_y		
Maximum	1.6	0.9
Minimum	0.6	0.04
$(\chi/Q)_{max}$		
Minimum	1.25×10^{-5}	8.31×10^{-7}
Maximum	1.49×10^{-3}	2.80×10^{-4}

As may be seen in the following section, the extreme meteorological conditions could result in concentrations about four times greater than during the worst typical inversion. The lapse concentration may be underestimated by a somewhat larger amount, but the area of comparable exposure is so limited that the inversion case remains the one of concern. While this study serves to indicate the inherent uncertainties, the use of typical meteorological data is justified on the basis that such data are representative for site analysis.

Dispersion by Atmospheric Diffusion from an Elevated Source

Dispersions of activity released from the stack of the NS "Savannah" at an elevation of approximately 90 ft above ground level were analyzed in the manner described below. The fraction of the activity emerging from the stack that arrives at a distance x is expressed as either (1) the concentration χ at x,y ($z = 0$), for continuous release, or (2) the total integrated accumulated "concentration" χ (or dose) for instantaneous release. The value of χ/Q was calculated from

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[5] Personal communication to G. D. Schmidt from D. Pack, U.S. Weather Bureau, Washington, D.C. (April 1959).

[6] "Meteorological Estimates for Philadelphia, Pennsylvania – Camden, N.J. Area," prepared by Special Projects Section, Office of Meteorological Research, U.S. Weather Bureau, Washington, D.C. (April 1958).

[7] Note that these are *probable limits*. Concentrations for more common but still conservative conditions are derived in the following sections of this appendix.

[8] *Meteorology and Atomic Energy*, AECU-3066, p 47, Eq. 4.51 (July 1955).

Sutton's dispersion equation (for dry weather, neglecting fallout and decay):

$$\frac{\chi}{Q} = \frac{2}{\pi C_y C_z \bar{U} x^{2-n}} \exp\left(-\frac{h^2}{C_z^2 x^{2-n}} - \frac{y^2}{C_y^2 x^{2-n}}\right) . \tag{1}$$

The downwind values of χ/Q at $y = 0$ are listed in Table A.2 and are shown graphically in Fig. A.1 for typical lapse and inversion conditions and are compared with corresponding values of χ/Q with rainfall.

Dispersion by Atmospheric Diffusion from a Ground-Level Source

For the calculation of dispersion from a ground-level source, the Sutton equation is used with $h = 0$:

$$\frac{\chi}{Q} = \frac{2}{\pi C_y C_z \bar{U} x^{2-n}} \exp\left(-\frac{y^2}{C_y^2 x^{2-n}}\right) ,$$

or, directly downwind ($y = 0$),

$$\frac{\chi}{Q} = \frac{2}{\pi C_y C_z \bar{U} x^{2-n}} ,$$

which may be conveniently plotted by the expression

$$\log \frac{\chi}{Q} = (n - 2) \log x + \log \frac{2}{\pi C_y C_z \bar{U}} .$$

As may be seen, χ/Q for a ground-level source equals that for an elevated source divided by

$$e^{-h^2/C_z^2 x^{2-n}} .$$

Dispersion from Ground-Level Release Point or by Looping from an Elevated Release Point

In looping,[9] at locations where the center of the cloud temporarily is in contact with the

[9] Discussed under paragraph 2.6 (b), p 50, Eq. (4.51), with exponential term = 1.000, and in Chap. 5 of *Meteorology and Atomic Energy*, AECU-3066 (July 1955).

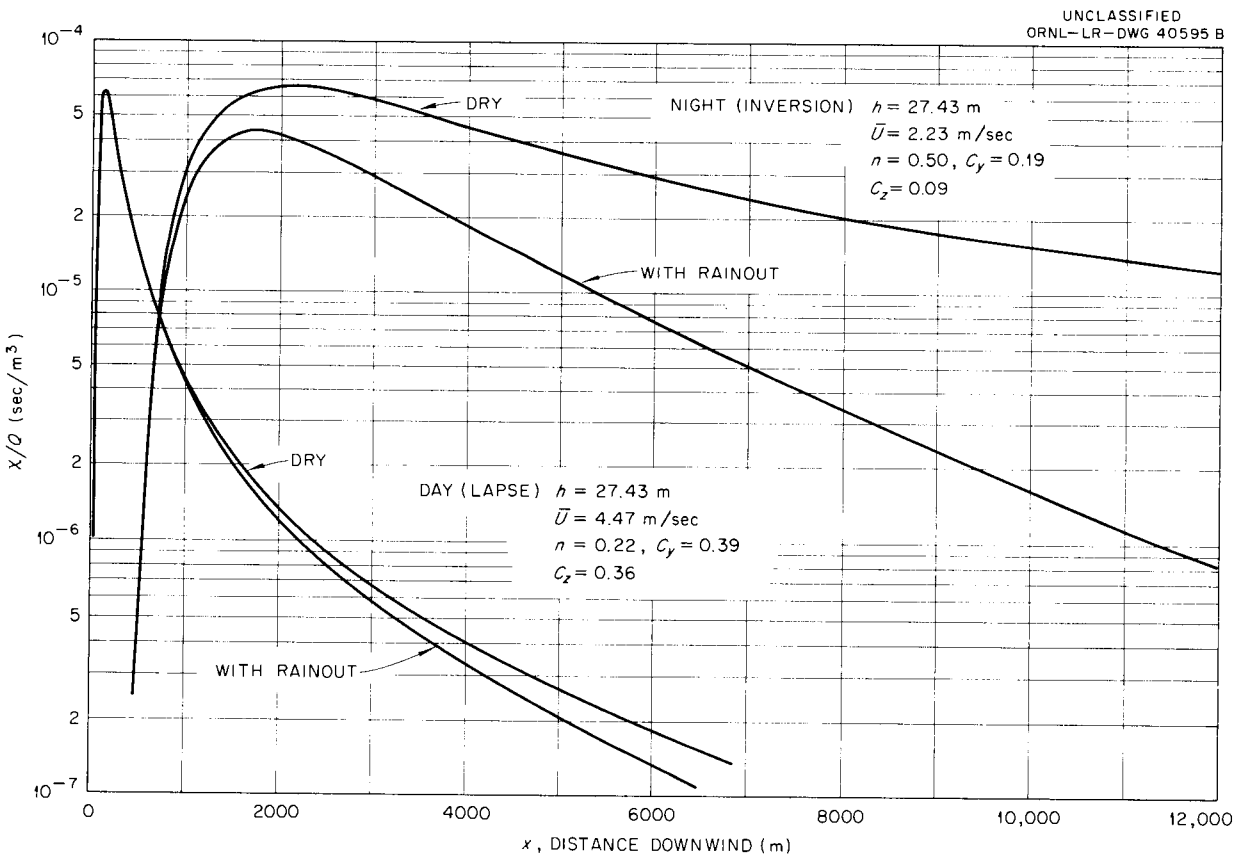

Fig. A.1. Atmospheric Downwind Dispersion from Elevated Source.

Table A.2. Dispersion Downwind from Continuous Elevated Source

$h = 27.43$ m

Meteorological Condition	x (m)	χ/Q	
		Dry	With Rainout
Inversion ($\bar{U} = 2.24$ m/sec)	250	2.65×10^{-13}	2.63×10^{-13}
	500	3.67×10^{-7}	3.28×10^{-7}
	600	2.06×10^{-6}	1.80×10^{-6}
	800	1.22×10^{-5}	1.02×10^{-5}
	900	2.00×10^{-5}	1.64×10^{-5}
	1,000	2.76×10^{-5}	2.21×10^{-5}
	1,250	4.60×10^{-5}	3.48×10^{-5}
	1,500	5.80×10^{-5}	4.15×10^{-5}
	2,000	6.57×10^{-5}	4.20×10^{-5}
	2,050	6.60×10^{-5}	4.40×10^{-5}
	2,500	6.33×10^{-5}	3.62×10^{-5}
	3,500	5.09×10^{-5}	2.33×10^{-5}
	5,000	3.63×10^{-5}	1.18×10^{-5}
	6,000	2.94×10^{-5}	7.70×10^{-6}
	7,000	2.43×10^{-5}	5.10×10^{-6}
	8,500	1.88×10^{-5}	2.80×10^{-6}
	10,000	1.52×10^{-5}	1.62×10^{-6}
	12,500	1.11×10^{-5}	6.74×10^{-7}
	15,000	8.64×10^{-6}	3.01×10^{-7}
	20,000	5.71×10^{-6}	6.51×10^{-8}
	22,000	4.96×10^{-6}	3.62×10^{-8}
Lapse ($\bar{U} = 4.5$ m/sec)	50	3.95×10^{-6}	3.94×10^{-6}
	100	5.65×10^{-5}	5.63×10^{-5}
	150	6.40×10^{-5}	6.40×10^{-5}
	250	3.50×10^{-5}	3.50×10^{-5}
	500	1.45×10^{-5}	1.42×10^{-5}
	1,000	4.51×10^{-6}	4.31×10^{-6}
	1,500	2.22×10^{-6}	2.08×10^{-6}
	2,500	9.02×10^{-7}	8.06×10^{-7}
	5,000	2.64×10^{-7}	2.11×10^{-7}
	10,000	7.69×10^{-8}	4.92×10^{-8}

ground, the concentration at ground level is described by

$$\frac{\chi}{Q} = \frac{2}{\pi C_y C_z \bar{U} x^{2-n}} ,$$

which also describes dispersion from a ground-level source. For the conditions assumed at Camden, this becomes, during lapse conditions, $\chi/Q = 1.014/x^{1.78}$, which has the following values:

Distance from Source (m)	$x^{1.78}$	χ/Q
30	4.3×10^2	2.38×10^{-3}
100	3.6×10^3	2.79×10^{-4}
1,000	2.19×10^5	4.6×10^{-6}
10,000	1.32×10^7	7.7×10^{-8}

During inversion conditions $\chi/Q = 16.66/x^{1.50}$, which has the following values:

Distance from Source (m)	$x^{1.50}$	χ/Q
30	1.64×10^2	1.014×10^{-1}
100	1.000×10^3	1.67×10^{-2}
1,000	3.16×10^4	5.3×10^{-4}
10,000	1.000×10^6	1.67×10^{-5}

A plot of χ/Q vs x for lapse and inversion conditions is presented in Fig. A.2. The hazard from looping depends critically on local meteorological conditions, as discussed in ref 9.

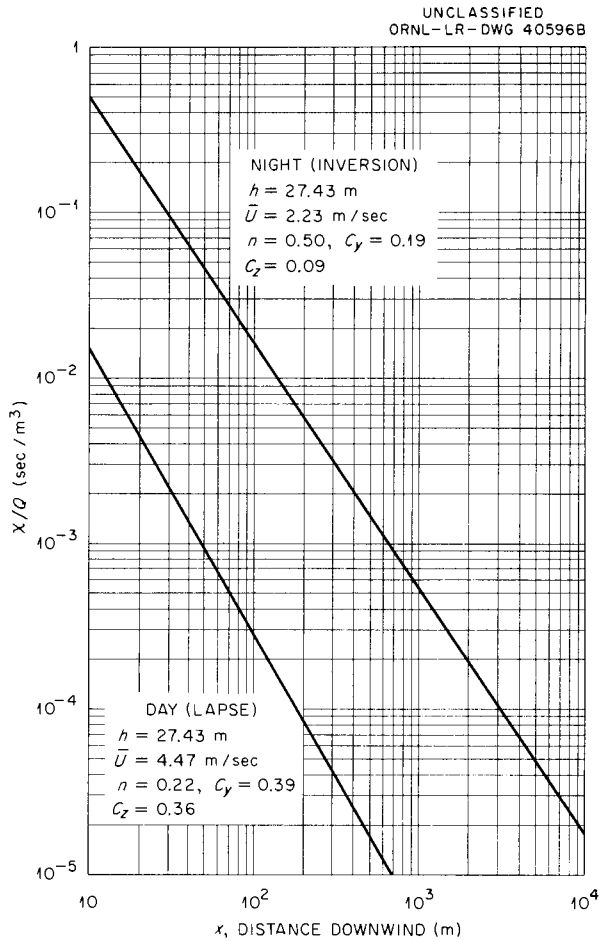

Fig. A.2. Atmospheric Downwind Dispersion from Ground-Level Source (Looping from Elevated Source).

Dry Deposition of Activity (Gravity Fallout)

It may be shown[9] that the maximum settling rate due to gravity of any particulate radioactive material released is so low (<1 cm/sec) that it is small compared with vertical turbulence; that is, the vertical atmospheric motions are much larger than the rate of descent of the particles. There would be some fallout which would not be negligible if the activity release continued for a long period of time. However, the fallout which could accumulate during the 24-hr period postulated for the MCA is negligible.

Rainout of Activity

The activity concentrations remaining in the air at essentially ground level at locations x,y were calculated from

$$\frac{\chi}{Q} = \frac{2}{\pi C_y C_z \bar{U} x^{2-n}} e^{-h^2/C_z^2 x^{2-n}} e^{-y^2/C_y^2 x^{2-n}} e^{-\Lambda x/\bar{U}} ,$$

in which the term $e^{-\Lambda x/\bar{U}}$ is the effect of the rain; Λ is the fraction of isotopes (other than noble gases) removed by rain per second. By using Fig. 7.5, p 95, of ref 9 and assuming small particle sizes,[10] Λ is approximately 1×10^{-4} sec^{-1} for a rainfall rate of approximately 0.1 in./hr, and

$$e^{-\Lambda x/\bar{U}} = e^{-1\times 10^{-4} x/\bar{U}} = e^{-1\times 10^{-4} t} ,$$

where t is in seconds. Using the other parameter values as they were used above for nondeposition calculations, the χ/Q values for rainout are obtained by applying the factor

$$\exp\left(-1 \times 10^{-4}\, x/\bar{U}\right)$$

as follows:

Condition	$\bar{U}$	$1 \times 10^{-4}/\bar{U}$	Factor
Lapse	4.5	2.24×10^{-5}	$\exp(-2.24 \times 10^{-5}\, x)$
Inversion	2.4	4.5×10^{-5}	$\exp(-4.5 \times 10^{-5}\, x)$

The results of these calculations are presented in Table A.2 and Fig. A.1.

The rates of deposition, ω, or the total deposition (for instantaneous release) on the ground downwind from the release point were calculated from

$$\frac{\omega}{Q} = \frac{\Lambda e^{-\Lambda(x/\bar{U})}}{\pi^{1/2} C_y \bar{U} x^{(2-n)/2}} .$$

The results are presented in Table A.3 and Fig. A.3.

Total Instantaneous Washout

In the case of total instantaneous washout, it is assumed that all fission products except xenon and krypton are instantaneously removed from the air and deposited on the ground directly below. Since these isotopes are removed instantly, continuation of the washout will not increase the deposit on the ground except at zero distance from the emission point (stack).

[10] *NARF Progress Report, 1 June through 30 November 1958*, NARF-58-54P, p 77.

Table A.3. Deposition Caused by Rainout

x (m)	ω/Q (m^{-2}) Typical Lapse	ω/Q (m^{-2}) Typical Inversion
1	3.22×10^{-5}	1.32×10^{-4}
10	4.15×10^{-6}	2.35×10^{-5}
10^2	5.35×10^{-7}	4.17×10^{-6}
10^3	6.73×10^{-8}	7.09×10^{-7}
10^4	7.12×10^{-9}	8.45×10^{-8}
10^5	1.23×10^{-10}	2.86×10^{-10}

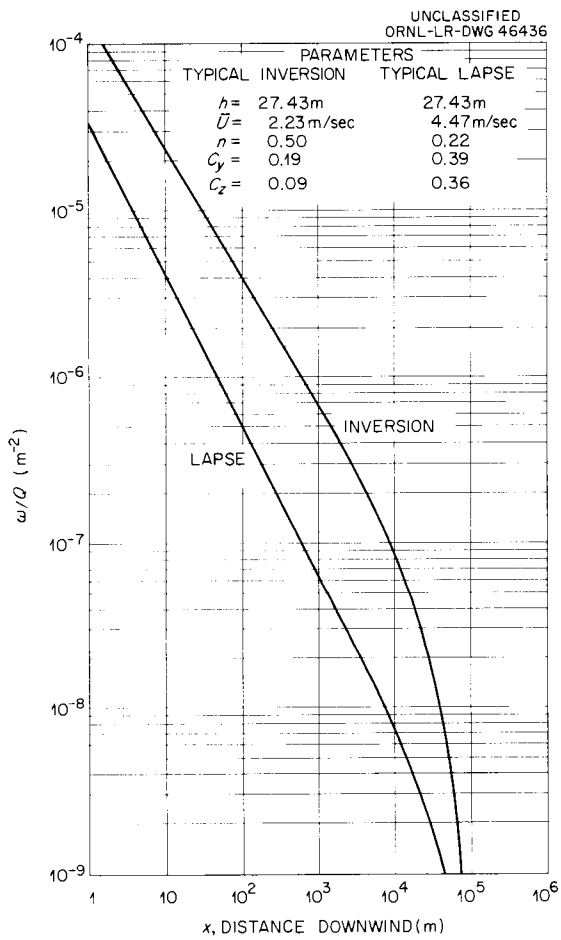

Fig. A.3. Rainout from Continuous Source (0.1-in./hr Rainfall).

The equation for washout from a continuous source after semiequilibrium has been reached is[11]

$$\frac{\omega}{Q} = \frac{1}{\sqrt{\pi}\, C_y\, \bar{U} x^{(2-n)/2}} ,$$

where Q is curies released from the stack in unit time, and ω is total curies deposited per unit area. The calculated deposit for this condition is given in Table A.4 and Fig. A.4.

Areas Affected by Atmospheric Activity Releases

Isopleths (lines of constant χ/Q) are shown for the inversion (nighttime) case in Fig. A.5. Since it is apparent from Fig. A.1 that inversion conditions are controlling, isopleths for lapse conditions were not calculated. The χ/Q values for lapse conditions are at least an order of magnitude smaller than for inversion conditions at distances greater than 1200 m. Lapse and inversion depositions were equal at about 700 m.

In the calculation of the isopleths plotted in Fig. A.5, F_x was determined for $y = 0$ and F_y was determined for the given values of x. The product $F_x \cdot F_y$ is the F defined on p 72 and shown in Fig. A.5. The term F_x is the ratio of χ/Q at any value of x to $(\chi/Q)_{max}$ and may be determined from Fig. A.1:

$$F_x = \frac{(\chi/Q)_x}{(\chi/Q)_{max}} .$$

The term F_y may be determined from Eq. (1) of this appendix as follows:

$$F_y = \frac{(\chi/Q)_y}{(\chi/Q)_{y=0}} = e^{-y^2/C_y^2 x^{2-n}} .$$

Values of the term F_y are plotted as a function of x and y in Fig. A.6. For the inversion case,

[11] *Meteorology and Atomic Energy*, p 98, Eq. 7.23, AECU-3066 (July 1955).

Table A.4. Deposit from Total Instantaneous Washout (Continuous Source)

Meteorological Condition	Downwind x (m)	ω/Q (sec/m^2)
Typical lapse	10	4.17×10^{-2}
	10^2	5.35×10^{-3}
	10^3	6.88×10^{-4}
	10^4	8.87×10^{-5}
	10^5	1.14×10^{-5}
Typical inversion	10	2.37×10^{-1}
	10^2	4.21×10^{-2}
	10^3	7.47×10^{-3}
	10^4	1.33×10^{-3}
	10^5	2.38×10^{-4}

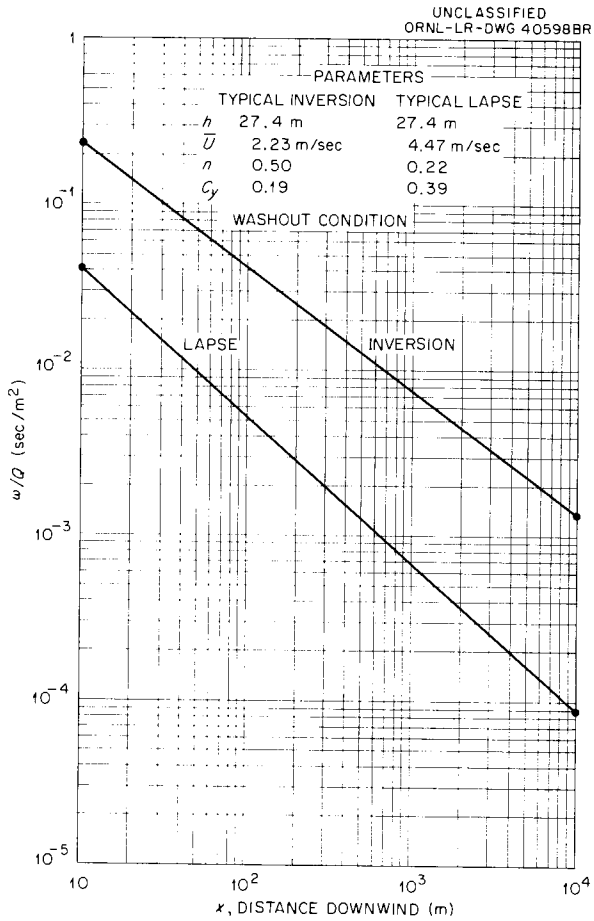

Fig. A.4. Washout from an Elevated Source.

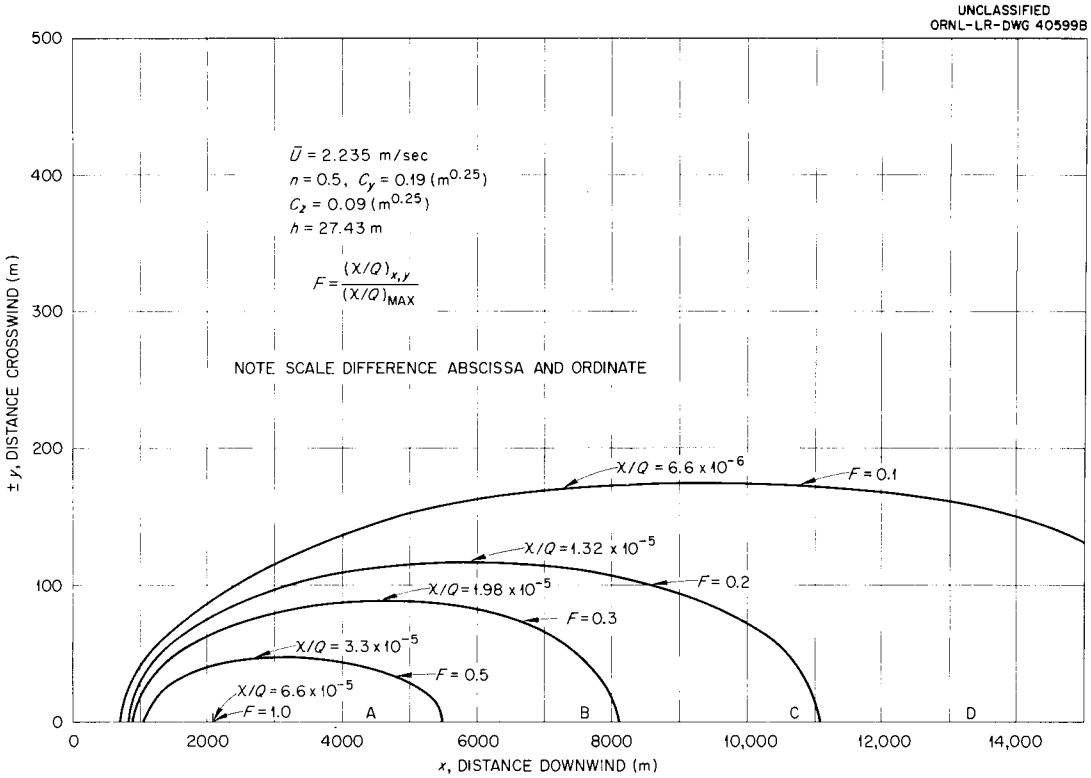

Fig. A.5. Isopleths for Typical Inversion.

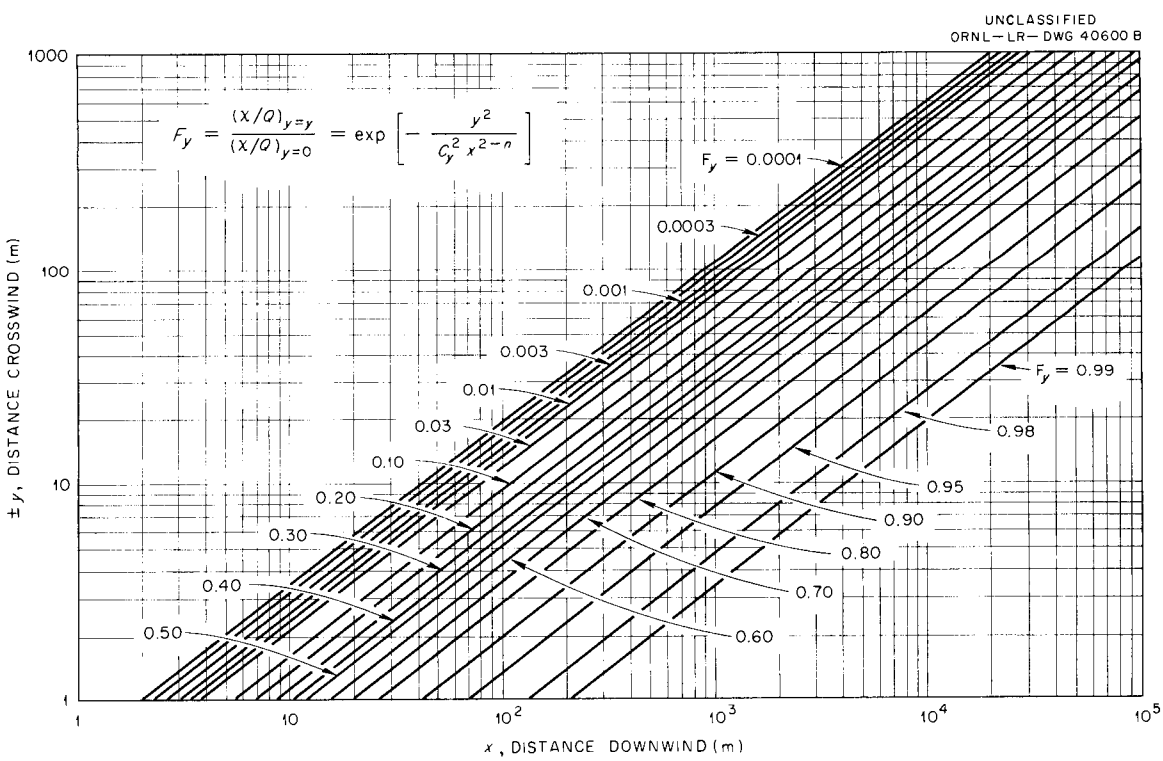

Fig. A.6. F_y as a Function of Downwind and Crosswind Distances.

$C_y = 0.19\ m^{n/2}$, where $n = 0.5$, and for the lapse case, $C_y = 0.39\ m^{n/2}$, where $n = 0.22$.

For the typical inversion conditions assumed at the Camden site, the maximum χ/Q ($= 6.6 \times 10^{-5}$) occurs at 2050 m downwind from the stack of the NS "Savannah." By using Fig. A.6, a plot of isopleths for these conditions, and assuming elliptical shapes for the areas enclosed by the isopleths, the areas in which $F_i = (\chi/Q)_i/(\chi/Q)_{max}$ lies within the ranges 0.5 to 1.0, 0.3 to 0.5, 0.2 to 0.3, and 0.1 to 0.2 were calculated. The results are given below:

F Range	Area (sq miles)
0.5–1.0	0.125
0.3–0.5	0.263
0.2–0.3	0.338
0.1–0.2	0.353

Appendix B
SITE METEOROLOGY

This appendix consists of excerpts from an unnumbered report prepared by the Special Projects Section, Office of Meteorological Research, U.S. Weather Bureau, Washington, D.C., in April 1958 entitled "Meteorological Estimates for Philadelphia, Pennsylvania – Camden, New Jersey Area."

SUMMARY OF SALIENT WEATHER FACTORS

Predominant winds are from the northwest sector in winter and from the southwest sector in summer. Precipitation winds are predominantly from the northeast and southeast sectors. Low-level inversions will be most frequent during the summer and fall months, forming after sunset and breaking up after sunrise. Stagnation periods are most frequent during August, September, and October. Inversion winds during stagnation periods will be predominantly from the northeast or southwest sectors. Precipitation occurs mostly in association with showers and thunderstorms in summer and in association with storm systems (cyclones) in winter. The geographical location of the harbor offers ample protection to shipping from coastal storms.

LOCATION AND TOPOGRAPHY

The Philadelphia-Camden metropolitan area is located on the Delaware River about 101 miles from the mouth of Delaware Bay. The state of New Jersey lies between the Delaware River and the Atlantic Ocean; the ocean is about 50 miles to the east of the Camden shipbuilding area. The first ridges of the Appalachian Mountains lie about 65 miles to the northwest of the dock area. These mountains are oriented northeast-southwest and rise from Coastal Plain elevations of about 300 ft to ridges of about 1500 to 3000 ft. The terrain between Philadelphia and the Atlantic Ocean, including the Delaware Bay area, is comparatively low and flat, with elevations of 50 to 250 ft in the immediate vicinity of Philadelphia that slope to sea level at the immediate coastal areas.

CLIMATOLOGY

General

The Delaware Valley area has a temperate climate that is characterized by warm humid summers and moderately cold winters. Average monthly temperatures vary from about 34°F in January to about 77°F in July. Temperature extremes range from 106 to −11°F; however, below-zero and over-100°F temperatures are rare. The region has a relatively equable distribution of precipitation, averaging about 42 in./year. Snow can be expected from November through early April and averages about 21 in./year. Freezing rain and sleet storms are not uncommon during the winter months. Thunderstorms may occur at any time during the year; however, their occurrence is most frequent during the summer months, with thunderstorms occurring on about 27 days/year.

Diffusion Climatology

Winds. – Data on the seasonal winds are presented below as percentages of time the wind is calm and from the indicated quadrant:

	Seasonal Wind Direction Frequencies (%)				
	Calm	NNE-E	ESE-S	SSW-W	WNW-N
Winter	7	16	10	28	38
Spring	7	19	15	26	33
Summer	12	14	16	34	25
Fall	12	17	13	30	29

Wind speeds average about 7.6 mph for the months of July, August, and September, compared with about 11.0 mph from December through April. Higher prevailing wind speeds can be expected at the immediate coastal areas in all seasons, as well as at the Delaware Bay headwaters. The highest frequency of occurrence of light winds (<4 mph and including calms) can be expected from late May through mid-November.

Inversions. – Vertical temperature lapse rate data from New York City and Washington, D.C., permit a general assessment of inversion frequencies in the Delaware Valley area. Low-level stability will be realized predominantly from radiational effects during the summer and fall seasons and from advection effects during the winter and spring seasons.

Low-level inversions will exist on most nights during the spring and summer months when relatively clear skies and light winds permit

radiational cooling near the ground. Such inversions will form shortly after sunset and will be readily dissipated by solar heating shortly after sunrise. During the winter and spring seasons, low-level inversion formation will depend primarily upon advection of warm air over the colder ground.

In general, about 80% of the evenings from July through mid-November will have inversions based at or near the ground which will be readily dissipated shortly after sunrise. During the colder months, inversion frequency at night will be considerably less.

The existence of a water-to-air temperature difference on and immediately adjacent to the river and bay areas may impose modifications upon the vertical temperature lapse rate at the low (<500 ft) levels. It would be expected that during the summer and fall, when the water temperature is usually cooler than the air temperature, stabilization will be improved over the river and bay. However, this stabilizing effect will be more pronounced at the wider expanse of the bay than at the relatively narrower river in the immediate vicinity of the port area. Conversely, during the winter and spring, when the water is usually warmer than the ambient air, low-level mixing over the water would be increased. The effects of the air-to-water temperature difference will be most pronounced during periods of light wind speeds, since relatively high wind speeds tend to establish adiabatic lapse rates and more thorough mixing at the lower levels.

Precipitation. – Rain may be expected to fall on about 16 to 20 days/month from December through May. During these months, precipitation winds will be predominantly from the northeast and southeast sectors. Precipitation occurrence is likely to persist for periods of 6 to 24 hr during this period, reflecting the influence of storm systems that originate either off Cape Hatteras or in the Great Plains region.

From June through November precipitation occurs mostly as showers and thunderstorms, with a resultant higher frequency of precipitation winds from the southwest and northwest quadrants. The shower type of precipitation results in lower frequencies of longer periods of continuous rain and fewer precipitation days, which average about 15 days/month in the summer and 11 days/month in the fall. However, it is during the summer and fall months that the heaviest precipitation can be expected within a 24-hr period, resulting from heavy thunderstorm activity of occasional hurricanes that move up the East Coast.

LAND-SEA BREEZE REGIME

The Philadelphia-Camden area lies far enough inland from the Atlantic Ocean that diurnal land-sea breeze effects are not of consideration.

SEVERE WEATHER

Hurricanes

The Philadelphia area rarely receives the full impact of hurricanes that affect the East Coast area. The inland location of the harbor area affords ample protection from all coastal storms. On rare occasions, hurricanes deviate from their normal path off the East Coast and move inland. Such storms that pass immediately to the west of the Philadelphia area, or directly over the region, constitute the major hazard to the port. Hurricane Hazel (October 1955), which was such a storm, caused winds in excess of 75 mph and damaging high tides. However, hurricanes of this destructive nature have been recorded in the Philadelphia area on only three occasions during the last 75 years.

The hurricane season exists from June through October, although hurricanes affecting the area are most probable from late August through October. The southern regions of the Delaware Bay and Delaware Peninsula are more susceptible to destructive hurricane effects.

An average of one hurricane every two years can be expected to cause gale-force winds and heavy rains in the Philadelphia area.

Tornadoes

Tornadoes or tornado-type winds have been reported in the Philadelphia area, although very infrequently. Past records indicate that localized destructive winds have been associated with squall lines and/or active cold fronts that pass over the area during the summer months. Brief wind gusts of more than 50 mph are not uncommon in association with thunderstorms; however, tornado frequency in the region is not sufficient to warrant serious consideration. Severe-weather warnings for the metropolitan area are issued by the Philadelphia Weather Bureau Office at International Airport.

Coastal Storms

A more frequent occurrence of coastal storms is experienced in the area, particularly during the winter and early spring months. Storms that move north or northeastward up the Atlantic Coast will produce periods (usually exceeding 24 hr) of heavy rains and winds of 20 to 40 mph from the northeast. Such storms are usually termed "northeasters." These storms are responsible for the occasional heavy snows that affect the Philadelphia area. Such storm systems may give the area 10 to 20 in. of snow within a 36-hr period during the winter months.

CONCLUSIONS

The conventional meteorological data that have been summarized and analyzed permit a tentative analysis of meteorological factors influencing diffusion at the Philadelphia-Camden port area. Additional data, particularly from Mustin Field, only 1 to 2 miles from the shipyard, will be available for more detailed analyses of wind flow.

It is important to note that, due to weather variability, no definite information can be given on the weather that will exist during dockside tests and sea trials. For such information, current and forecast meteorological service will be required.

Typical values of the meteorological parameters were selected for the dispersion calculations (Appendix A) on the basis of the area meteorology that were consistent with values recommended in the general literature.[1–5] They were selected to result in ground concentrations somewhat higher than average, and their use was subsequently deemed by area meteorologists[6] to be reasonable for this analysis.

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[1] *Meteorology and Atomic Energy*, AECU-3066 (July 1955).

[2] *Theoretical Possibilities and Consequences of Major Accidents in Large Nuclear Power Plants*, WASH-740 (March 1957).

[3] J. Korshover, *Synoptic Climatology of Stagnating Anticyclones East of the Rocky Mountains in the United States for the Period 1936–1956*, U.S. Weather Bureau, Washington, D.C., 1958.

[4] *Meteorological Analysis Applicable to Operation of a Nuclear Powered Vessel*, U.S. Weather Bureau, Washington, D.C., 1957.

[5] *Climatology of the United States No. 30-36 (Philadelphia, Pennsylvania)*, U.S. Weather Bureau, Washington, D.C., 1956.

[6] Personal communication from D. Pack, U.S. Weather Bureau, Washington, D.C., to G. D. Schmidt (April 1959).

Appendix C
EXPOSURE CRITERIA

The criteria for the exposure of persons to radioactivity from both routine and accidental releases are essential to the evaluation of the practicality of any site location. Unfortunately, these criteria are not defined for all conditions of interest, and considerable judgment is involved in designating a particular exposure as acceptable for certain conditions. While such criteria are particularly lacking for emergency exposures, maximum permissible concentrations for continuous occupational exposures in air and water have been established for several years[1] and have only recently been revised.[2] Even starting with these criteria, however, considerable interpretation is involved with regard to the implications for reactor operation. Specific exposure criteria for the NS "Savannah" and the reasoning which led to the use of these criteria are described here.

NORMAL RELEASE OF ACTIVITY TO AIR AND WATER

NBS Handbook 69 establishes the MPC for continuous occupational exposure and also supports the contention that the MPC for continuous exposure to a member of the public living in the neighborhood of nuclear plants should be one-tenth of the occupational exposure,[3] as advocated by the International Commission on Radiological Protection (ICRP).[4] The ICRP report states that it is the presence of children in the public group which requires that the exposure criterion be reduced by a factor of 10 from the permissible occupational levels.

Although the public exposure levels have thus been established, in any particular situation the activity producing a given concentration at any location may come from many sources. In order to allow for the growth of the nuclear industry, it is proposed that, in instances where the resultant concentration may be cumulative, the continuous releases from any one source not routinely exceed one-tenth of the public concentration (or 1/100 of the occupational concentration). However, since the maximum ground concentrations from nearby stacks are seldom additive and the point of maximum ground concentration is not fixed, allowable stack release rates may be established on the basis of not exceeding the maximum permissible public exposure at the point of maximum ground concentration for the typical inversion. In view of the conservative features in establishing the release rate for the continuous discharge of activity from a stack, it is consistent to expect that this release rate may be further increased during favorable meteorological conditions.

As applied to the operation of the NS "Savannah," the above criteria would permit the release of some gaseous activity. While these criteria might be presumed to be valid for release to the river water, this is not the case, since the processes by which fish and other biota might concentrate such activity are not fully understood. Therefore, although it is not anticipated that this concentration process will be harmful at the proposed concentration levels, the NS "Savannah" will not intentionally release any activity to the water until such time as the consequences of such release are better defined.

ACCIDENTAL RELEASE OF ACTIVITY

The criteria for the permissible accidental or emergency dose of 25 r of whole-body exposure have been established for several years.[5,6] These criteria are specified for radiation workers to occur only once in the lifetime of a person and are assumed to have no effect on the radiation status of that person. At this exposure there are no detectable medical effects. Although ref 6 specifies that the exposure is from external radiation, a total-body exposure to the same dose from internal activity should be equivalent. Internal exposures

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[1] *Maximum Permissible Amounts of Radioisotopes in the Human Body and Maximum Permissible Concentrations in Air and Water*, NBS Handbook 52 (Mar. 20, 1953).

[2] *Maximum Permissible Body Burdens and Maximum Permissible Concentrations of Radionuclides in Air and in Water for Occupational Exposure*, NBS Handbook 69 (June 5, 1959).

[3] *Ibid.*, pp 3,8.

[4] Recommendation of the International Commission on Radiological Protection, *Radiation Protection*, adopted Sept. 9, 1958, Pergamon Press, New York.

[5] *AEC Contract Policy and Operations*, p 19, U. S. Government Printing Office (1951).

[6] *Permissible Dose from External Sources of Ionizing Radiation*, NBS Handbook 59 (Sept. 24, 1954).

by either ingestion or inhalation are somewhat more complicated to deal with, inasmuch as the removal of the source of contamination (usually water or air) does not terminate the exposure because of the activity already within the body. The dose from this activity within the body must be integrated over its effective life in the body, which is a function of both the radiological half life and the biological half life.

The exposure to various parts of the body is a function of the isotope in question, as well as concentration, exposure time, breathing rate, mass of body organ, etc. Since the various elements are selectively absorbed by different parts of the body, the resulting exposure from internal sources is most frequently a localized rather than a total-body exposure. Inasmuch as the ICRP has established a relationship between the maximum permissible exposures to different parts of the body and the whole body as a consequence of continuous exposure to all significant fission product isotopes, it is proposed that the emergency exposures to different parts of the body be obtained as a ratio of these data and the whole-body emergency dose of 25 r. Although the 25-r criterion was established for radiation workers, it is felt that its use as the controlling public exposure is justified for an accident with as low a probability as the MCA for the same reasons that justified its use with radiation workers.

The ICRP recommendations establish the 13-week maximum exposure as the maximum single dose limit for occupational workers. Since the permissible continuous exposure to the public has been established as one-tenth of the permissible continuous occupational exposure, it is proposed here that the exposure to the public from accidents less severe than the MCA (but which may be expected to occur more frequently than once in a lifetime, but less than once a year) should be less than one-tenth of the 13-week occupational exposure limit.

For occupational workers, the ICRP report,[4] which provides the basis for NBS Handbook 69,[2] establishes the following maximum exposures from internally deposited nuclides:

"1. The dose to the gonads or total body during any 13-week period shall not exceed 3 r.

"2. The dose to the skin and thyroid shall not exceed 8 r in any 13-week period (or 30 r in one year).

"3. The dose to the bone in any 13-week period shall not exceed the dose due to the body burden of 0.1 μc of Ra^{226} (this is equivalent to a dose rate of 0.56 r/wk or 7.3 r in the 13-week period).

"4. The dose to any single organ of the body (except gonads, bone, skin, and thyroid) shall not exceed 4 r in any 13 weeks or 15 r in 1 year."

It is therefore concluded that the limits of exposure allowable from radiation incidents may be those given in Table C.1. Maximum allowable exposures to occupational workers as a consequence of the MCA cannot be established. Although the nuclear industry has established one of the best safety records of any major industry,[7] it is conceivable that accidents resulting in the death of occupational workers may occur.

[7] K. Z. Morgan, *Maximum Permissible Exposure to the Population at Large to Sources of Ionizing Radiation*, paper presented before the Special Subcommittee on Radiation, May 7, 1959, p 9.

Table C.1. Accidental Exposure Limits

Part of Body Exposed	13-Week Maximum Exposure for Less than MCA		MCA Exposure to Public Residing near Controlled Areas (r)
	Exposure to Occupational Workers (r)	Exposure to Public Residing near Controlled Areas (r)	
Bone	7.3	0.73	61
Skin and thyroid	8	0.8	67
Total body and gonads	3	0.3	25
Other organs	4	0.4	33

While the limits given in Table C.1 are proposed as the maximum that the respective individuals should be allowed to received in the situations considered, there are other limits which must be taken into account, namely, the number of persons affected, their integrated exposure, and the resulting implication for the population as a whole. These limits are derived from the desire to restrict the exposure of the population as a whole so that the genetic burden does not become excessive.[4] The ICRP report further proposes that the permissible genetic dose (average dose per person from conception to 30 years of age) should not exceed 5 rems exclusive of natural background and medical exposure. Although no firm recommendations for apportioning the 5 rems are made by the ICRP, they give the following apportionment as an illustration: 1.0 rem, exposure of occupational groups; 0.5 rem, exposure of special groups (principally the public living in the neighborhood of reactors); 2.0 rems, exposure of the population at large; and 1.5 rems, reserve. A recent recommendation of the National Committee on Radiation Protection reads, "The maximum permissible dose to the gonads for the population of the United States as a whole from all sources of radiation, including medical and other man-made sources, and background shall not exceed 14 million rems per million of population over the period of conception up to the age of 30, and $\frac{1}{3}$ that amount in each decade thereafter."[8] These two statements are completely consistent, since the estimated exposures to the United States population from natural background and medical effects are 4 and 5 r per person, respectively, and $14 - (4 + 5) = 5$.

In a paper[9] presented at the Health Physics Society Annual Meeting, 1959, C. R. McCullough proposed 2,000,000 man-rems as the limit on the population exposure from a single reactor MCA. If it is assumed that there may eventually be one such accident every year and the population is 2×10^8, the resulting genetic dose is

$$\frac{2 \times 10^6 \times 30}{2 \times 10^8} = 0.3 \text{ r} .$$

This dose is appreciably less than either that allocated by the ICRP for the population at large or the reserve. However, since significant portions of these allocations may be required for routine public exposures, the selection of a value as low as 0.3 r for the genetic exposure from MCA's has considerable merit for planning purposes, although it is somewhat conservative at the present time.

This population exposure may be compared with that recently proposed by the British Medical Research Council[10] for application in Great Britain, in which a value of 10 r whole-body exposure would be permitted in instances where the population is small compared with $\frac{1}{50}$ of the total population. "Small" is not defined in this report, but the calculated genetic dose to age 30 for $\frac{1}{50}$ of the population to receive 10 r would be 6 r if one accident per year in a population of 5×10^7 were assumed. If 10% may be considered a "small" fraction, the resulting genetic dose would still be twice that proposed by McCullough, even though the emergency exposure specified by the British is a factor of 2.5 less than that suggested here.

Accidental Release to the Atmosphere

The consequences of the accidental release of activity to the atmosphere must be evaluated in terms of the resulting maximum individual exposure and the total population exposure. The exposure in the case of a reactor accident may result from an instantaneous puff, a semicontinuous source, or some combination of both. Where the total exposure is integrated over some significant time interval, various means of reducing the exposure may be employed, either toward the end of removing the population from the source (evacuation) or toward decreasing the intensity of the source (water spray, for example). In any case it would be expected that inhalation exposures following reactor accidents would be, in general, short term, inasmuch as the most significant fraction of the exposure would be received in the first 24 hr. The calculation of the total exposure following a single short period of activity release to the atmosphere has been described by Burnett.[11]

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[8] As included in the AEC Manual, chap. 0524, "Permissible Levels of Radiation Exposure," TN-0000-198, effective Feb. 1, 1958.

[9] Submitted for publication in *Health Physics*.

[10] "Maximum Permissible Dietary Contamination After the Accidental Release of Radioactive Material from a Nuclear Reactor," *Brit. Med. J.* 1959, I, 967–69.

[11] T. J. Burnett, *Nuclear Sci. and Eng.* 2, 382–93 (1957).

Accidental Release to the Hydrosphere

As opposed to the inhalation process, which for the purposes of this discussion may be considered to be continuous, the ingestion process is discontinuous and in an emergency could be forsaken for one day or more by the majority of the population without lasting deleterious effects. Thus, although the same exposure criteria apply, the alternative of not ingesting contaminated water always exists.

Once a water supply becomes contaminated, it frequently remains contaminated for long periods of time. This is particularly true where the water supply is a reservoir or, in the case of the lower Delaware River, where the body of water is a tidal estuary in which the effective half life of contamination may be several weeks. In such instances, some steps may be taken to reduce the activity level, such as filtration in water treatment plants[12] or the addition of flocculating agents in the river or reservoir,[13] although it has not been demonstrated that it is practical to reduce the water contamination by a significant factor through either of these techniques.

In any event, if ingestion of contaminated water is the only source of exposure, the allowable exposures are the same as previously defined. If the cause of the contamination were a weapons explosion, the obvious recourse would be to limit the consumption of the water in such a fashion that neither the individual nor the genetic dose was exceeded (unless the alternative were of greater consequence). As far as reactor accidents are concerned, it would appear to be necessary to design to a condition in which neither the individual nor the genetic exposure would be exceeded in the course of the accident. The exposure, as previously noted, may have a duration of weeks or even months. The method for calculating the resulting dose from a single exposure was derived by Morgan *et al.*[14]

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[12] R. A. Lauderdale and R. F. Eliassen, *The Removal of Radioactive Fallout from Water by Municipal and Industrial Water Treatment Plants*, NYO-4441 (Mar. 1, 1956).

[13] *Report of the Joint Program of Studies on the Decontamination of Radioactive Waters*, ORNL-2557 (Feb. 9, 1959).

[14] K. Z. Morgan *et al.*, *Maximum Permissible Concentration of Radioisotopes in Air and Water for Short Period Exposure*, International Conference on Peaceful Uses of Atomic Energy, paper No. 547, August 1955.

Appendix D

HYDROLOGY OF DELAWARE RIVER BASIN

The New York Shipbuilding Corporation yard is located on the Delaware River at Camden, New Jersey, above Newton Creek, 101 miles above the mouth of the river where it flows into the Atlantic Ocean (see Figs. 2.1 and 2.2). The flow in the Delaware River is influenced, as in the case of all other tidal streams, by the rainfall on the drainage area of the river, the runoff from the land surfaces, the stage of the river, whether the stream is recharging ground-water aquifers or is being recharged by ground water, the elevations and range of the tide, winds, and barometric pressure, or anything that changes the hydrostatic head of the ocean relative to that of the river.

The Delaware River is 296 miles long and drains an area of 12,765 square miles. The area of particular concern is the tidal portion of the stream from Trenton, New Jersey, to the mouth, a distance of 134 miles. The drainage area below Trenton is 5965 square miles. Any contaminant introduced into the tidal section of the river will appear, more or less diluted, in every other portion of the tidal section because of the reversal in direction of flow when the tide changes. In a nontidal river, water flows continuously downstream, diluting and flushing out any contaminant that may be introduced into the river. In a tidal river, however, the flow regime is far more complex. A contaminant introduced into the river during flood tide is carried upstream, where it is mixed and diluted with both the fresh water and the ocean water. When the tide reverses, most of the contaminant is swept downstream with the mixture of fresh water and ocean water. Once again, when the tide reverses, some of the contaminant is swept upstream and is further diluted by the incoming tidal water and the upstream fresh water.

The rate of movement of a contaminant downstream is directly affected by the fresh-water flow in the river. The fresh-water flow in the Delaware River is at a maximum during January to May because of the higher rate of runoff of the precipitation that falls on the land. As shown in Fig. D.1, the precipitation is actually highest during the summer and fall months, but runoff is greatly reduced by the high rates of evaporation from the indigenous flora. As may also be seen in Fig. D.1, the ocean level outside Delaware Bay is highest during August through October, thus favoring increased flushing times, and lowest during December to February, favoring decreased flushing times, since the river water has less head to work against.[1] The range in the tidal height is far greater than seasonal height changes and consequently has a far greater effect upon the flushing of a contaminant from a tidal estuary. In fact, the average river flow and the tidal height are two of the most important factors influencing the flushing characteristics of a stream.

The fresh-water flow in the stream may be influenced by the recharge to, or inflow from, ground-water aquifers. In the lower Delaware Basin, because of heavy pumping for domestic and industrial uses, the ground-water table has fallen below the level of the river, and consequently the river is recharging the ground-water aquifers. The principal ground-water aquifers being recharged are the Raritan and Magothy formations, which outcrop through the river bed in the reach between Trenton and Wilmington.[2] Below Wilmington the river intersects the outcrops of other aquifers. The river water is being depleted by ground-water withdrawals by an estimated 40 million gallons per day (mgd) for public water supplies and 65 mgd for industrial water uses.[3] The river water also is being depleted by surface-water withdrawals of an estimated 4300 mgd for industrial purposes (about 4000 mgd of which is returned to the river) and about 200 mgd for public water supplies.[3] One million gallons

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[1] B. Cohen, *Salinity of the Delaware Estuary*, U.S. Geological Survey open-file report (1957).

[2] H. C. Barksdale *et al.*, *Ground Water Resources in the Tri-State Region Adjacent to the Lower Delaware River*, State of New Jersey, Department of Conservation and Economics Development, Division of Water Policy and Supply, Special Report No. 13 (1958).

[3] S. M. Lang, C. N. Durfor, and R. H. Tice, *Hydrology of the Delaware River and Aquifers in the Camden-Philadelphia Area*, U.S. Geological Survey (July 1958).

per day is equal to 1.54 cfs, so the total depletion by ground- and surface-water withdrawals is negligible during periods of average flow (approximately 16,000 cfs) but can amount to as much as 25% of the flow during low flow periods. Even though the flow in the Delaware River is regulated to some extent by the Delaware River Master, low flows of 1500 cfs have been recorded. In terms of contaminant control this withdrawal can be of major importance, particularly the withdrawal of surface and ground water for drinking-water supplies.

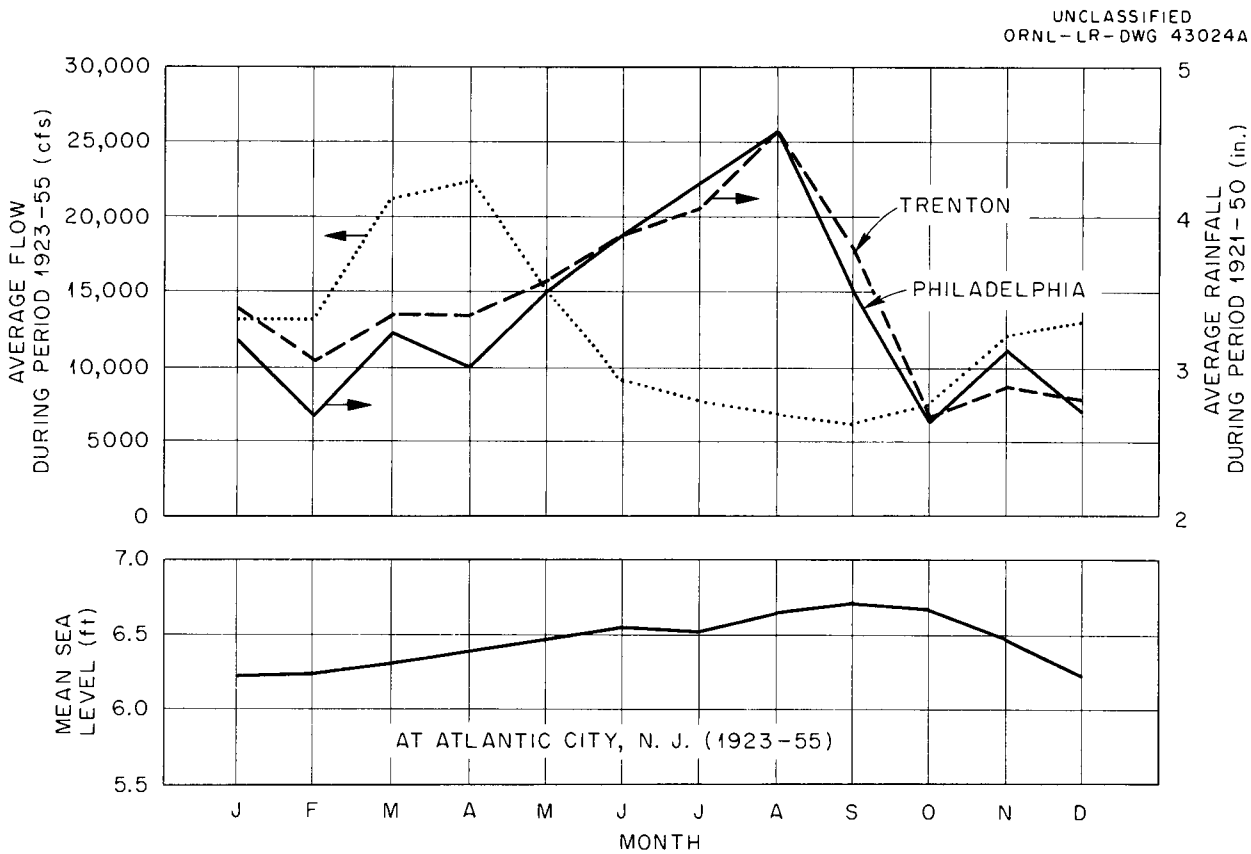

Fig. D.1. Hydrological Data on Delaware River Basin. Points are connected by straight lines for clarity. Between the points the interpolations are not necessarily correct.

Appendix E

DISPERSION OF RADIOACTIVITY IN DELAWARE RIVER BASIN

Once radioactive material enters a stream the main processes affecting the subsequent path of the material are convection, diffusion, sorption, sedimentation, and radioactive decay.

CONVECTION

In a nontidal stream, convection terms can be readily obtained from velocity profiles of the stream. In a tidal stream, however, the situation is far more complex, since there is convection both upstream and downstream, alternately. Measurements in the field are extremely difficult to make in the tidal sections of the river, as is evidenced by the fact that the U.S. Geological Survey, the official stream gaging organization, does not measure flows in the tidal portion of the stream, although it does measure the velocities. The usual method of determining flow in a tidal stream is to measure the flow in the nontidal portions and then assume the same net inflow per unit of drainage area in the tidal portion as in the nontidal portion. Another method is to simulate the stream by a physical model, complete with tides and stream velocities, and determine from the model the actual flow and the dispersion of the contaminant in the stream.

DIFFUSION

The contaminant is dispersed in a stream by diffusion. The diffusion process includes both molecular and turbulent eddy diffusion. Molecular diffusion is the result of the thermal motion of individual molecules and is extremely slow in liquids and gases because the mean free path of molecules is so short. Turbulent diffusion may be much faster, since it is due to the mass transfer of molecules in eddies of various sizes throughout the entire volume. Molecular diffusion is essentially submicroscopic in movement, while turbulent diffusion is macroscopic.

The radioactive material is presumed to behave dynamically in the same way as the transporting medium, water. The radioactive substance is treated as radioactive water dispersed in water of no radioactivity. Many experiments support the validity of this assumption.[1]

The differential equation for diffusion is relatively simple if the diffusion coefficient remains constant throughout the region of flow:

$$\frac{\partial c}{\partial t} = a^2 \frac{\partial^2 c}{\partial x^2} , \qquad (1)$$

where

c = concentration,

a = molecular diffusion coefficient,

x = length,

t = time.

The standard formulation of the diffusion law is commonly known as Fick's law. Eddy diffusion has been found to vary from 1000 to 1,000,000 times greater than molecular diffusion in water.[2] Therefore molecular diffusion can be ignored.

In the ocean, turbulent diffusion in large areas may be taking place in numerous ways within the same areas. Large- and small-scale eddies within them induce various rates of mixing. The extreme randomness of the process makes it a very difficult phenomenon to formulate, and it is only recently with the application of statistical methods to the problem that some ideas of its fundamental nature are being uncovered. At present it is only possible to approximate the magnitude of the diffusion rate.

The earliest work on turbulent diffusion was that of Reynolds, who differentiated in turbulent flow between the primary and secondary characteristics of the motion. The separation of turbulent velocity into two components is accomplished by assuming the mean velocity along the direction of travel as the primary component and a superimposed turbulent velocity having a temporal mean velocity of zero as the secondary component. This can be carried to an extreme by making the time and length scales small enough so that even laminar flow would appear to be turbulent.

Prandtl provided the next advance in turbulence theory by relating the intensity of turbulent flow

[1] F. L. Parker, *Trans. Am. Geophys. Union* 39, 434–39 (1958).

[2] H. U. Sverdrup, M. W. Johnson, and R. H. Fleming, *The Oceans, Their Physics, Chemistry, and General Biology*, p 91, Prentice Hall, New York, 1942.

to a parameter of distance. The "mixture length" of Prandtl represents the average distance a small mass of fluid will travel before it loses its increment of momentum to the region into which it comes. The work of Prandtl, however, bore no close relationship to the physical nature of turbulence. Taylor next applied the concept of the transfer of vorticity rather than momentum but still retained the concept of mixture length, which here represents the transverse path in the vorticity transfer. This formulation accorded better with experimental results; Von Karman attempted to improve those efforts with his thesis of turbulent similitude, based upon the assumptions that the mechanism of turbulence is independent of viscosity, except in the immediate neighborhood of the flow boundaries, and that the pattern of secondary flow is statistically similar from point to point, varying only in time and length scales. These assumptions led to equations of the same form as Prandtl's and Taylor's, but with the mixture length a function of the velocity distribution of the mean flow. A difference between momentum transfer and vorticity transfer is that in momentum transfer the eddy coefficient is a function of a mixing length and the transverse velocity of the stream, while in vorticity transfer the eddy coefficient is independent of the secondary velocity.

These methods lead to relatively simple and semiempirical solutions, which are widely used in engineering applications. For more adequate theoretical treatment and closer representation of the physical reality, they are not sufficiently accurate to enable fundamental research into turbulent flow to proceed. The fundamental problems of turbulence are best approached through statistical analysis, and Taylor produced the first study of turbulence by statistical methods. The ideas introduced by Taylor in the investigation of isotropic turbulence resulted in the correlation between two fluctuating quantities in the turbulent flow, the study of the decay of turbulence, and the study of spectrum of turbulence (i.e., the distribution of energy among eddies of different sizes). The above devices are means to solve the main question of the joint probability distribution of the displacement of any marked particles. In this study both convection and turbulence were investigated with a physical model of the Delaware River.

SORPTION

Some of the radioactive salts introduced into an aqueous medium tend to dissociate into their ionic forms. Once the radioactive material becomes cationic and anionic, it is more likely to be sorbed on the organic and clay particles suspended in the stream and on the river bottom. Clay materials have a particular affinity for cationic materials, including most of the hazardous fission products.[3] In a series of experiments, Carritt and Goodgal determined the percentage of sorption of P^{32}, I^{131}, Sr^{89}, Cu^{64}, Fe^{59}, and S^{35} on Chesapeake Bay surface sediments (top 6 in. and 6 in. at 9 ft).[4] The composition of the sediments was approximately 5% kaolinite, 30% illite, 40% chloritelike montmorillonite, 15% amorphous silica, and 10% quartz.

For the conditions to be expected in estuaries, the uptake of phosphorus was less in sea water than in fresh water, but in both systems it approached 100% removal within 1 hr. Iodine showed no significant uptake, but most of the strontium which was not precipitated was sorbed on the muds in less than 30 min. It is reasonable to assume that an appreciable fraction of radiostrontium waste will become associated with naturally suspended solids. Copper was almost completely removed in less than 24 hr, but iron and sulfate were not removed at all.

In general, therefore, it may be said that alkali metals (group IA), alkaline-earth metals (group IIA), and transition-group IIIA elements in the periodic table are sorbed quite easily on the sediments, while the elements of the transition groups VIIA, VIII, IB, and IIB, the nonmetals (group VIB), and the halogens (group VIIB) are sorbed only with difficulty. These are only general conclusions and for specific instances depend upon the chemical form of the radioactive material and conditions in the receiving waters (such as pH, temperature, concentration, and ionic strength).

In addition to sorption on the muds, there can be considerable sorption and concentration in the biota. The organisms that sorb the isotopes

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[3] K. E. Cowser and F. L. Parker, *Health Phys.* 1, 152–63 (1958).

[4] D. E. Carritt and S. H. Goodgal, *The Sorptive and Zeolitic Properties of Natural Water Borne Silts ... in Natural Waters*, NYO-4591 (October 1953).

from the water take the elements into their system to the degree required to satisfy that system. Therefore radioactive isotopes can be concentrated many times by particular organisms and in a particular part of the organism. There are wide variations in these factors between organisms, but approximate concentration factors are shown in Table E.1.[5]

SEDIMENTATION

The sedimentation of the materials attached to the clay particles and dead organic matter will also remove radioactive contamination in water. Wherever any of the elements exceed the solubility product, they will precipitate and settle out. In general, when fresh water enters salt water, some colloidally dispersed solids flocculate and settle.

The sedimentation process can be further increased artificially by applying flocculating agents to the water. A group at the Armour Research Foundation has studied the potentialities of such processes by using aluminum and ferric hydroxide systems.[6] Since the radioactive materials will disperse in the ocean quite rapidly, only a system that immediately operates upon the introduced contaminant can be effective.

All the systems described above interact with each other, and the efficiency and effectiveness of any one system is also a function of the

[5] L. A. Krumholtz, E. D. Goldberg, and H. A. Boroughs, *The Effects of Atomic Radiation on Oceanography and Fisheries*, Natl. Acad. Sci.–Natl. Research Council, Publ. No. 551, chap. 7, p 74 (1957).

[6] J. Rosinski, *Scavenging of Particulate Matter in Connection with Nuclear-Powered Ships*, ARF Project C-119, Report No. 6 (February 1959).

Table E.1. Approximate Concentration Factors of Different Elements in Members of the Marine Biosphere

Concentration factors are based on live weight

Element	Form in Sea Water	Concentration in Sea Water (μg/liter)	Concentration in Noncalcareous Algae (μg/liter)	Concentration Factors			
				Invertebrates		Vertebrates	
				Soft	Skeletal	Soft	Skeletal
Na	Ionic	10^7	1	0.5	0	0.07	1
K	Ionic	380,000	25	10	0	5	20
Cs	Ionic	0.5	1	10		10	
Ca	Ionic	400,000	10	10	1,000	1	200
Sr	Ionic	7,000	20	10	1,000	1	200
Zn	Ionic	10	100	5,000	1,000	1,000	30,000
Cu	Ionic	3	100	5,000	5,000	1,000	1,000
Fe	Particulate	10	20,000	10,000	100,000	1,000	5,000
Ni*	Ionic	2	500	200	200	100	
Mo	Ionic-particulate	10	10	100		20	
V	?	1	1,000	100		20	
Ti	?	1	1,000	1,000		40	
Cr	?	0.05	300				
P	Ionic	70	10,000	10,000	10,000	40,000	2,000,000
S	Ionic	900,000	10	5	1	2	
I	Ionic	50	10,000	100	50	10	

*Data from T. Laevastu and T. G. Thompson, *J. conseil, Conseil permanent intern. exploration mer* 21, 125–43 (1956).

others. For example, when the contaminant precipitates and settles it comes into contact with other suspended solids and may sorb them and thus scavenge more material than the original precipitation.

RADIOACTIVE DECAY

All these mechanisms are, of course, subject to radioactive decay, which will change the concentration of the isotopes in the water, muds, and biota over a period of time.

Appendix F

DELAWARE RIVER BASIN MODEL TESTS

As outlined in Appendix E, the analytical determination of diffusion and convection in the field for an area the size of the Delaware River Basin is quite difficult. An easier solution is to build a physical model to represent the field conditions and to determine the dispersion of a contaminant from the model. Fortunately, a large-scale model of the Delaware River had been built by the Corps of Engineers at the U.S. Army Waterways Experiment Station, Vicksburg, Mississippi, in 1948, based upon a 1942 hydrographic survey, for studies of salinity intrusion, shoaling, and the flushing of wastes discharged into the estuary.[1] The model is 750 ft long and 130 ft wide at its widest point and covers an area of 30,000 ft^2, which is equivalent in the prototype to 1000 square miles. Because of the large area covered and the relatively small depths, it has been necessary to use a distorted model so that the depths of water in the model will be great enough to minimize the influence of surface tension. This model, like most open-channel models, is scaled by the Froude number, $v/(gl)^{1/2}$, where v is a velocity term, g is the gravitational acceleration, and l is a length term. The Froude number is used to scale models where gravitational forces predominate, rather than the Reynolds number, which is used to scale models where the viscous forces are dominant. No model can, of course, reproduce the effects in the prototype, since the viscous forces, surface tension, and elastic compression of the water do play a role in the flow regime; only the gravitational forces are scaled. The Delaware model is scaled 1:1000 horizontally and 1:100 vertically. The model scale factor for velocity is 1:10, since by the Froude scaling

$$\frac{v_m}{v_p} = \left(\frac{gl_m}{gl_p}\right)^{1/2} = \frac{1}{10} ,$$

where the subscript m refers to the model and p to the prototype. Similarly, the model-to-prototype discharge ratio is 1:1,000,000 and the model-to-prototype volume ratio is 1:100,000,000. Inasmuch as the flow time is distance divided by velocity, the time ratio between the prototype and the model is 1:100. Thus the mean flow time for the same (scaled) distance is 100 times as long in the river as in the model. This is of particular importance in that the normal tidal cycle of 12 hr 25 min may be reproduced in the model in 7.45 min. The salinity scale ratio is 1:1.

Prior to using any model, it is necessary to make sure that the model is not only geometrically similar to the river, but that the velocity, tidal heights and elevations, and salinity profiles are also similar. The scaled reproduction is accomplished by varying the roughness of the model. The hydraulic agreement between the Delaware model and the prototype is considered to be excellent. The prototype representation of tidal heights was considered to be accurate to within 0.1 ft, velocity to within 0.5 fps, and salinity to within 5% of actual values measured in the river.

MODEL TESTS OF 1952

A series of tests was run in the model in 1952 to determine the effects of a pollutant introduced into the Delaware Estuary. In three of the tests the contaminant was introduced into the main channel opposite the Philadelphia Naval Shipyard, Delaware River mile (DRM) 96.6. The pollutant was introduced at high-water slack in the center of the channel, and samples were taken at high-water slack from the center of the channel. During the first test, methylene blue dye, used as the contaminant, was instantaneously released at mean tide and mean river flow (12,350 cfs at Trenton) and during the second test at low river flow (3000 cfs at Trenton).[2]

This study is concerned with the effects of release of a radioactive contaminant during startup operations at the New York Shipbuilding Corporation outfitting docks 22,500 ft upstream (DRM 101) from the dosing site. Since this is only about one-half of a tidal excursion upstream, it was felt that no serious error would be introduced by transposing the dosing site upstream.

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[1] Technical Memorandum No. 2-337, Report No. 1, U.S. Army Waterways Experiment Station, 1956.

[2] D. W. Pritchard, *A Study of Flushing in the Delaware Model*, Technical Report No. 7, ref 54-4 (April 1954).

The main difference in the results will be caused by the fact that the Schuylkill River enters the Delaware River just below the original dosing point at the U.S. Naval Shipyard, and thereby provides greater dilution and turbulence on the first ebbing of the tide after dosing. Therefore the assumption made here will be on the unsafe side.

Six cases have been studied, including three different dosing programs at each of two different river flows: (1) the instantaneous single dose, (2) equilibrium values of an instantaneous dose at each tidal cycle, (3) equilibrium values of an instantaneous dose every other tidal cycle (approximately once each day), at mean flows of 12,350 cfs at Trenton and low water flows of 3000 cfs at Trenton. The dosing conditions are not typical of those that might occur in the Camden outfitting basin because the accident, if one occurs, would most likely occur at the dockside rather than at the center of the stream. The resulting spread of contamination would then be slower by a considerable amount because of less mixing and turbulence near the shore. The model dosing also covered one-third of the width of the stream to facilitate the dispersion. All these changes are on the unsafe side in the eastern half of the river. On the safe side is the fact that the accident would most likely not occur directly on high-water slack, and therefore it would occur under more turbulent conditions than those of the test. Although the contaminated stretch will be farther upstream when the dosing is done at low-water slack, it is obvious from a study of the dye dispersion that the difference in dispersion between dosing at high- and at low-water slack is inconsequential after one or two tidal cycles. The increased area in the cross sections at high tide is only 20% greater than the area at low tide. The concentration of the contaminant decreases by a factor of 100 after just one tidal cycle and by a factor of 1000 in three tidal cycles at mean flow.

The results of the model study are applicable only to a conservative contaminant, that is, one in which there is no decay or removal by physical or biological mechanisms. The decrease in concentration is due only to the diffusion and dispersion in the liquid phase. A radioactive contaminant in the river, on the other hand, is a nonconservative contaminant in that it is accumulated in destructive fashion in the river and decays with its own characteristic half life in the sediments, flora, and mud. All these facts make the results based on the model study extremely conservative. This, of course, must be balanced against the unsafe assumptions enumerated above, but in general it is possible to say that the results based on the model study are conservative, particularly for the short-half-life isotopes.

The most serious accident that could occur in the river would take place if the Torresdale Filter Plant (DRM 114), which is about 12 miles above the NYS outfitting basin and which supplies Philadelphia with about half its water, should become contaminated. Model studies indicate that this is not likely, but they are somewhat deceiving in that the minimum detectable concentration of the methylene blue used as the contaminant in the model study is far above the hazardous concentration of some radioactive isotopes. For example, the limit of detection of methylene blue was 0.01 ppm or 0.01 mg/liter; and 0.01 mg of Sr^{90} per liter is equal to 1.43×10^{-3} curie/liter (1.43×10^{7} times the MPC value of 1×10^{-10} curie/liter) or, at 10% counting efficiency, equal to 3.2×10^{5} $\text{counts}\cdot\text{min}^{-1}\cdot\text{ml}^{-1}$. The limit of detection of unconcentrated Sr^{90} is, of course, a function of the counting equipment and sample preparation, but it may be said that 10 to 15 $\text{counts}\cdot\text{min}^{-1}\cdot\text{ml}^{-1}$ is easily detectable; there is therefore a factor of 10^4 difference in the ease of detection. This large difference might be an excellent reason to consider the use of radioactive isotopes rather than dye in future tests.

In order to correlate the results of the model tests with the results from an accident, it is assumed that 1 ppm is equivalent to 1 mg/liter. The dosing device has a volume at high tide in the prototype of 1.7×10^{7} ft^3 $[(740)^2(\pi/4)(40)]$, and, with an initial dose of 1000 ppm, this is equivalent to 4.9×10^{8} g of methylene blue dosed. If, as above, it is assumed that the dose in curies and the contaminant in millicuries per liter will be proportional to the quantity of dose in grams and milligrams per liter of contaminant, the maximum contamination for different accidents may be obtained. Correspondence between milligrams of dye and milligrams of isotopes and linearity of response to greater doses are the two important assumptions in using the model data.

For example,

$$\frac{4.9 \times 10^{11} \text{ mg dosed}}{\chi_m \text{ mg/liter found}} = \frac{Q \text{ curies dosed}}{\chi_p \text{ curies/liter found}} .$$

The maximum concentration found in the model at Benjamin Franklin Bridge for a single dose at NYS at high-water slack was 2.5 ppm, and, assuming 10^4 curies dosed,

$$\frac{4.9 \times 10^{11} \text{ mg}}{2.5 \text{ mg/liter}} = \frac{10^4 \text{ curies}}{\chi_p \text{ curies/liter}} ,$$

or

$$\chi_p = \frac{10^4 \times 2.5}{4.9 \times 10^{11}} = 5.1 \times 10^{-8} \text{ curie/liter}$$

$$= 5 \times 10^{-5} \ \mu\text{c/ml} .$$

The total dose received by anyone drinking or swimming in this water can be obtained by integrating the concentration over the tidal cycles affected if long-lived isotopes are involved. For shorter-half-life isotopes, the nuclear decay must be considered.

MODEL TESTS OF 1958

The Delaware River was subjected to a detailed hydrographic resurvey in 1954 of the area between Chester, Pennsylvania (Darby Creek) and Pennsville, New Jersey (DRM 88.5–DRM 70.5), and the model was revised accordingly.

At the request of the Nuclear Projects Office of the Maritime Administration, tests were run on the revised model for a 3-hr and a 20-tidal-cycle dose at low-water slack at the NYS outfitting basin during both mean and low flows of fresh water. In addition, a test was run in which half the dose was discharged in 3 hr at low-water slack and the remainder over 20 tidal cycles at low water flow.[3] The dosing was at low-water slack, since this would tend to give the highest concentrations of contaminant at the Torresdale water intake. If dosing had been done at high-water slack, the contaminant would have been swept downstream prior to being swept upstream and thus would have been diluted and dispersed to a considerable extent prior to reaching Torresdale.

The model data concentrations are scaled to the prototype concentrations by the ratio of volumes (1 to 10^8). The model data give the sample concentration χ_m as a percentage P of the initial concentration χ_0, where the dose of dye was a volume $V_0 = 6$ liters at a concentration $\chi_0 = 1000$ ppm (or 1×10^{-3} mg/cm^3). The dispersion $(\chi/Q)_m$ in the model is then

$$\left(\frac{\chi}{Q}\right)_m = \frac{\chi_{0,m} P/100}{V_{0,m} \chi_{0,m}} = \frac{10^{-2} P}{V_{0,m}} ,$$

and, since $V_{0,m} = 6 \times 10^3$ cm^3,

$$\left(\frac{\chi}{Q}\right)_m = 1.67 \times 10^{-6} P \text{ cm}^{-3} .$$

However,

$$\left(\frac{\chi}{Q}\right)_p = \left(\frac{\chi}{Q}\right)_m \times 10^{-8} ,$$

and therefore

$$\left(\frac{\chi}{Q}\right)_p = 1.67 \times 10^{-14} P \text{ cm}^{-3} ,$$

where P is defined above and is the experimental model value.[3]

The results of the model tests are plotted in Figs. F.1 and F.2, where they are compared with the results of the computed values from the 1952 model tests[2] and shown to be in fair agreement. The earlier tests[2] were used to approximate a continuous release by assuming an instantaneous release to occur once each tidal cycle. The increment of concentration from each new addition was added to the (dispersed) accumulated concentrations from the previous additions.

Similar calculations can be made for any other section of the river or taken from the data of the second set of model experiments. These give the concentrations and the times at which they exist at any particular river station for a conservative contaminant. Based on the hypothesized accident, it is possible then to determine the distribution of isotopes in the river, assuming that they act as conservative contaminants. Then, since the half lives are known for each isotope, the decay factors can be incorporated in the calculations to show what fraction of each isotope still remains at the station of interest. The other two factors, sorption

[3] *Hydraulic Model Investigation*, Miscellaneous Paper No. 2-332, Report No. 1, U.S. Army Waterways Experiment Station, 1959.

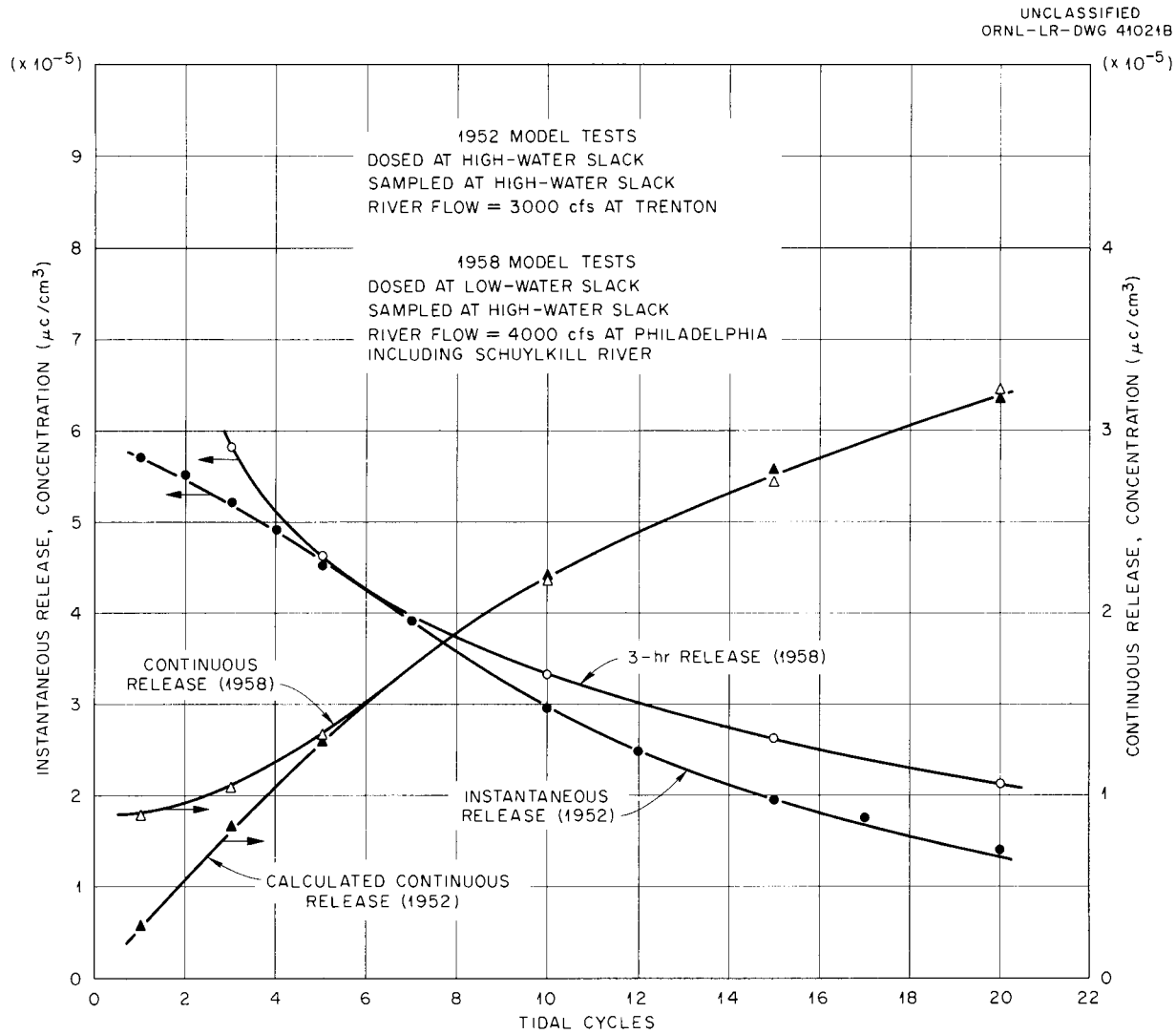

Fig. F.1. Concentration at Benjamin Franklin Bridge for Dose of 10^4 Curies at NYS Outfitting Basin as a Function of Time in Tidal Cycles.

and sedimentation, may also be taken into account since the contaminant is nonconservative. The sorption and the sedimentation coefficients are extremely uncertain and difficult to predict. They vary widely from species to species and from isotope to isotope. The problems are so numerous that the Committee on Oceanography of the National Academy of Sciences–National Research Council stated:

"In arriving at recommended disposal rates the interaction of a contaminant with suspended solids and bottom sediments has been neglected. It was found impossible to make a quantative estimate of the magnitude of this reaction. Neglecting this factor puts a certain factor of safety in the recommendations, as sorption onto bottom sediments within the disposal area will provide additional containment, thus allowing for further destruction of the contaminant by radioactive decay."[4]

However, for the purpose of this study, it was felt that these effects should be evaluated with the best data presently available. It is recognized that the values used are not definitive and may be off by orders of magnitude. However, an estimate

[4] *Radioactive Waste Disposal into Atlantic and Gulf Coastal Waters*, Natl. Acad. Sci.–Natl. Research Council, Publ. No. 655, p 2 (1959).

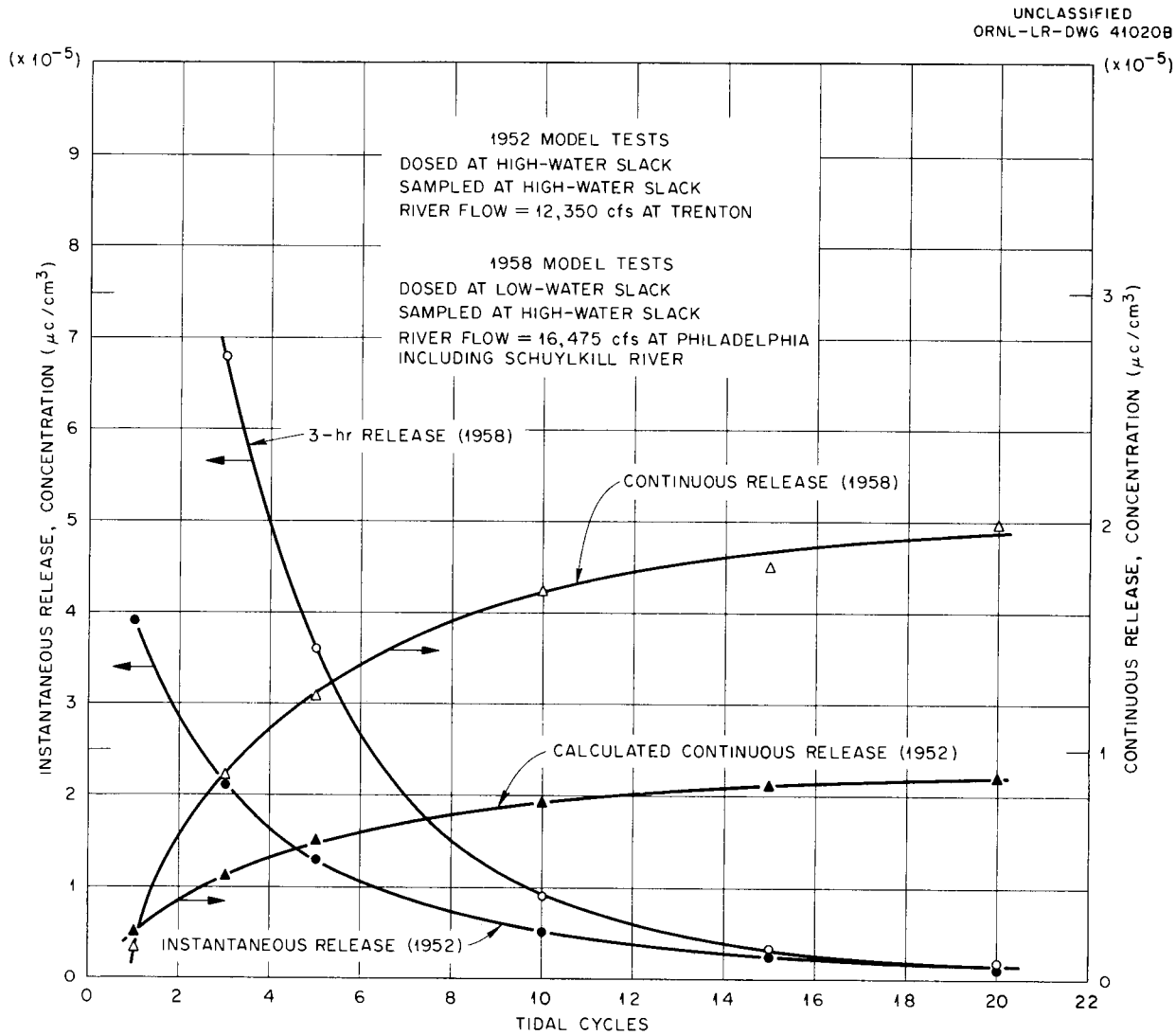

Fig. F.2. Concentration at Benjamin Franklin Bridge for Dase of 10^4 Curies at NYS Outfitting Basin (Mean River Flow) as a Function of Time in Tidal Cycles.

of the effects can be made once some values are assigned to the sorption and sedimentation coefficients. Since they are both so indefinite, a combined coefficient, λ (hr^{-1}), was used: for I^{131}, $\lambda = 0$; for Sr^{90}, Cs^{137}, and Ce^{144}, $\lambda = -0.7$; and for all other isotopes, $\lambda = -0.1$. The values chosen were based upon the works of Carritt and Goodgal,[5] Ketchum and Bowen,[6] and Pendleton and Hanson.[7] Since the sorption and sedimentation are to some extent concentration-dependent, it was felt that an exponential decay would best express mathematically what was taking place physically and would also parallel the reduction in concentration caused by radioactive decay and eddy diffusion and convection. For these values the calculations show that all the isotopes except I^{131} can be neglected after a very short period of time.

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[5] D. E. Carritt and S. H. Goodgal, *The Sorptive and Zeolitic Properties of Natural Water Borne Silts ... in Natural Waters*, NYO-4591 (October 1953).

[6] B. H. Ketchum and V. T. Bowen, *Biological Factors Determining the Distribution of Radioisotopes in the Sea*, A-Conf. 15/P/402, 1958.

[7] R. C. Pendleton and W. C. Hanson, *Absorption of Cesium-137 by Components of an Aquatic Community*, A-Conf. 15/P/392, 1958.

It is, of course, also necessary to consider what happens to the sorbed, concentrated, and precipitated isotopes. For a continuous discharge over long periods of time, the reconcentration could lead to hazardous amounts of isotopes in the biota and muds. However, for the short period of discharge in an accidental release and the limited number of curies released, it is difficult to reach hazardous conditions. For example, for 24 curies of Sr^{90} per tidal cycle, a maximum concentration of 5.8×10^{-8} $\mu c/ml$ in the water phase, and a maximum reconcentration by a factor of 10 in the edible portions, even under the most hazardous conditions, a person would have to eat 4×10^7 g or 1×10^5 lb before reaching the permissible body burden. It should also be recognized that the maximum concentration is available to the biota for a very short period of time and decreases quite rapidly (see also Appendix C).

Scaling Factors

The factor used in converting the model dye concentration to the prototype contamination concentration was 10^8, as indicated by the scaling factor for volume. This is true for the 1952 and 1958 model tests, in which the prototype dosing schedule was the same as that of the model. The 10^8 scaling factor can be correctly used for an instantaneous dose. If, however, the dosing in the prototype is carried out over a different period of time from that in the model, the scaling factor of 10^8 is not correct. Mathematically, physically, and intuitively it is realized that using a 10^8 factor for a 3-hr dose or a 20-cycle dose is equivalent to saying that the resulting concentrations are independent of the rate of introduction, and this is patently false. The extreme case would be to introduce the contaminant at such a small rate that it could not be detected. The other boundary value would be to assume that the concentration of the contaminant was proportional to the flow, that is, a scaling factor of 10^6. This is also patently false. The extreme case of this is to assume that the contamination continues forever. The true scaling factor lies somewhere between. The concentration in the prototype is a function of the total dose and the rate of dosing, but this could only be determined experimentally for each rate of dosing not used in the model.

Plotting the results of the model experiments and the calculated values on log-log paper shows that the slopes of the lines are not significantly different (Fig. F.3). The concentration at Benjamin Franklin Bridge has been extrapolated from the 1952 model tests by assuming a continuous source to be represented by an instantaneous release once each tidal cycle. The concentration at Torresdale is taken directly from the 1958 model test data. This would indicate that the concentration for a one-cycle dose would be only 20% (0.026/0.13, see Fig. F.3) of the concentration for an instantaneous dose. The equation for the concentration at Torresdale (Fig. F.3) would be

$$P = 0.026t^{-0.241} ,$$

where P is the percentage at Torresdale of concentration dosed, and t is the number of tidal cycles over which the dose was injected.

Critical Stations

The Torresdale water plant was chosen as the most critical site to investigate, since the calculations showed that submersion doses were negligible (except for a short period of time at locations adjacent to the dosing point) and that the dose from ingested material would be more important. Torresdale is the nearest surface intake for public water supplies, and therefore the concentrations should be greater there than at any other surface water supply. In determining the concentrations of isotopes in the drinking water, no allowance was made for the decontamination by conventional water treatment practices. A series of studies on

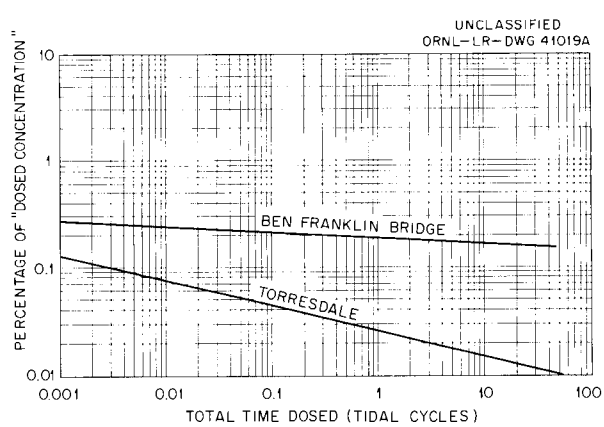

Fig. F.3. Maximum Concentration at Benjamin Franklin Bridge and Torresdale Inlet in Per Cent of Dosed Concentration as a Function of the Total Time over Which the Contaminant Was Added.

this point has shown that about 50% gross removal can be expected, although the strontium decontamination can be as great as 90% for lime-soda softening treatment. A conservative factor of 50% could be used.[8]

There is also the possibility that the contaminant could reach public water supplies obtained from ground water. Because of the clays that overlie the ground-water aquifers in the area of the outfitting basin, there is very little recharge on the Philadelphia side, as shown on the water table maps of the U.S. Geological Survey, but there is recharge on the New Jersey side above Camden. The velocities of the ground water in this area and at the Philadelphia Naval Base are 1.7 and 1.0 ft/day, respectively; thus 17 and 43 years, respectively, will be required for river water to reach the wells. At that time Sr^{90} and Cs^{137} would be the major isotopes left, because of radioactive decay of the others. Extensive work has shown that these two isotopes are sorbed on clays, even in the presence of heavy concentrations of competing ions. Contaminants will reach some of the Camden wells in shorter times, within $2\frac{1}{2}$ months in the city of Camden and as quickly as $1\frac{1}{3}$ months in Beverly, New Jersey. The wells in Beverly are the closest to the river and take approximately 100% river water. Here, too, the same reasoning holds, and the decrease in activity due to radioactive decay alone is 99.8%. A more severe hazard could develop if there should be a buildup on the soils which could be suddenly released. Such a sudden release would have to be caused by a major change in the composition and pH of the water. This would necessitate changing drastically the composition and pH of the river water in the entire reach, and this is practically impossible. Therefore it may be concluded that the surface water supply at Torresdale is the most critical water to examine.

[8] R. A. Lauderdale and R. Eliassen, *The Removal of Radioactive Fallout from Water by Municipal and Industrial Water Treatment Plants*, NYO-4441 (March 1956).

Appendix G

ACTIVITY RELEASE FROM MAXIMUM CREDIBLE ACCIDENT DURING OPERATION[1]

The data on activity release rates, fission product inventories, and containment leakage rates used in these environmental studies were obtained from calculations by Babcock & Wilcox. The results of the calculations are presented in Figs. G.1–G.5 and Table G.1. A sample calculation is included in this appendix to demonstrate the manner in which the curves and the table were used. With the information in this basic form, a large degree of flexibility is available in the variation of parameters and assumptions, depending upon the particular point of interest.

The assumptions for the MCA in the early stages of nuclear power operation are identical with those discussed in the preliminary safeguards report,[2] with one exception. During the early stage of reactor operation there is essentially no increase in the gas pressure within the fuel rods from the formation and internal release of fission product gases. Consequently, fission gas pressure does not cause the fuel rod cladding to fail, and failure does not occur until the cladding temperature approaches the melting point. Figures G.1–G.3 show the percentage of the gaseous activity released for various operating times, power levels, and shutdown times.

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[1] This appendix was prepared by the Babcock & Wilcox Company and transmitted by J. H. MacMillan of that company to W. B. Cottrell on April 8, 1959.

[2] J. H. MacMillan (ed.), *Nuclear Merchant Ship Reactor Preliminary Safeguards Report*, BAW-1117, vol I (rev) (Dec. 22, 1958); vol II (Nov. 3, 1958).

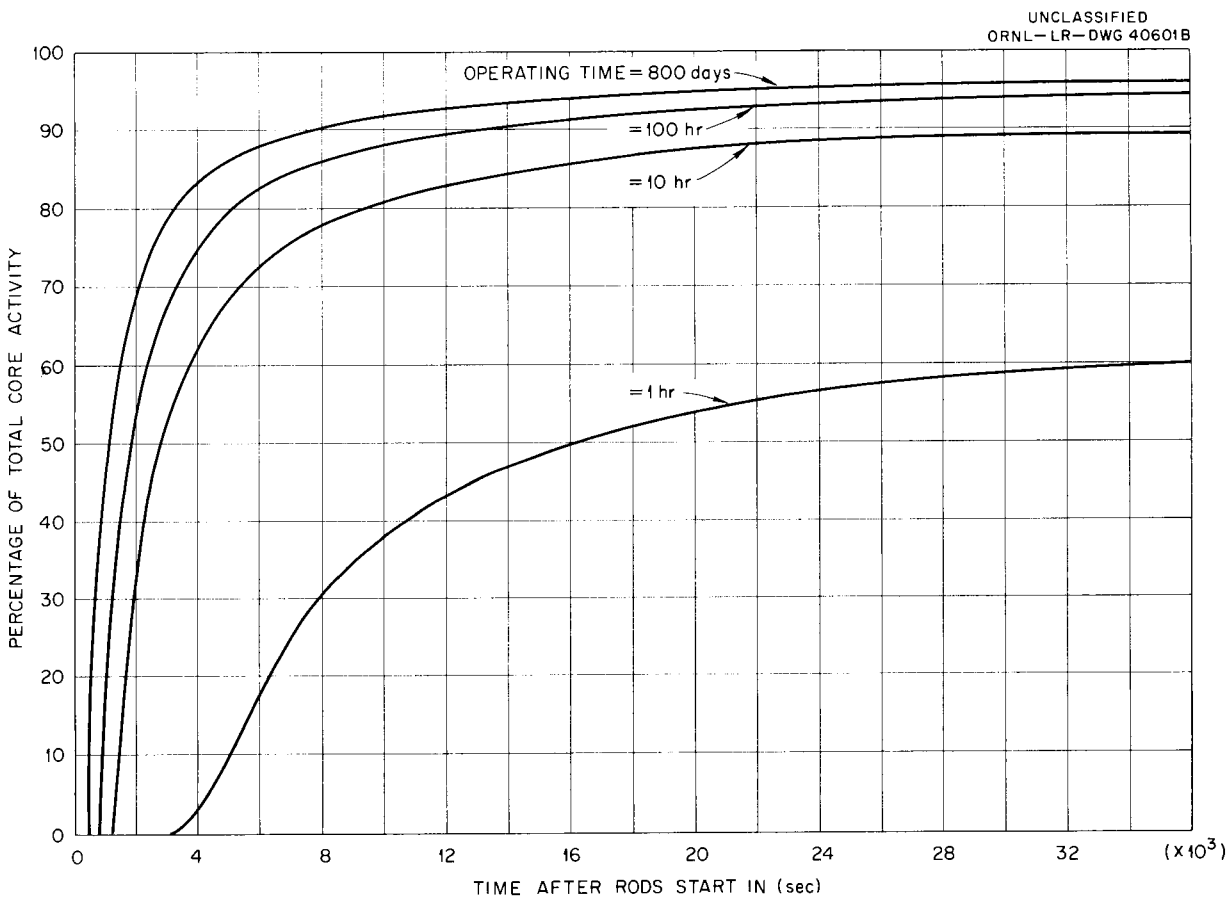

Fig. G.1. Per Cent of NMSR Fission Gas Activity Released as a Function of Time After Start of MCA (Reactor Power Before Accident = 100%).

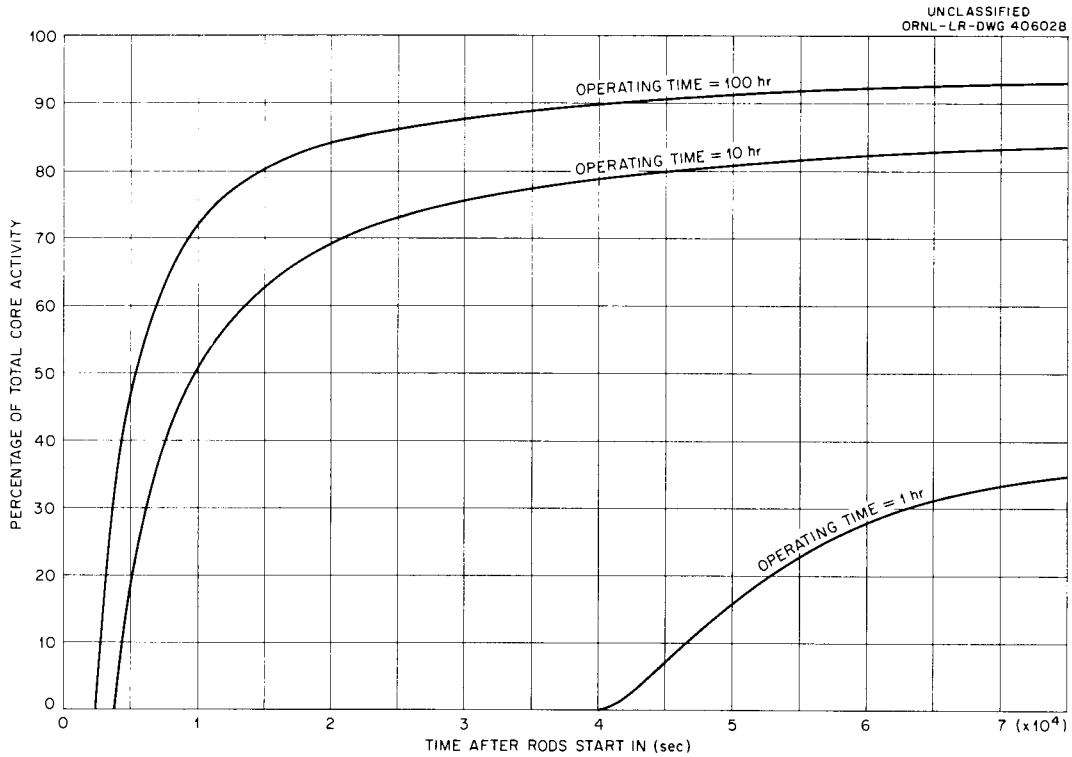

Fig. G.2. Per Cent of NMSR Fission Gas Activity Released as a Function of Time After Start of MCA (Reactor Power Before Accident = 50%).

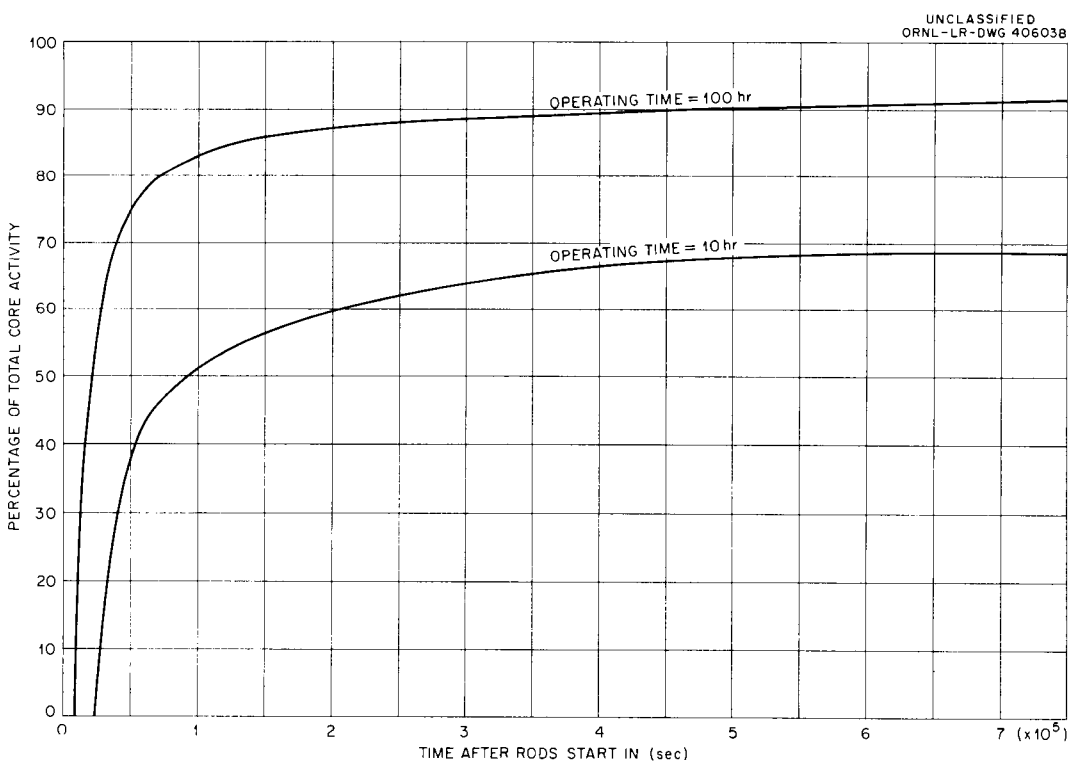

Fig. G.3. Per Cent of NMSR Fission Gas Activity Released as a Function of Time After Start of MCA (Reactor Power Before Accident = 20%).

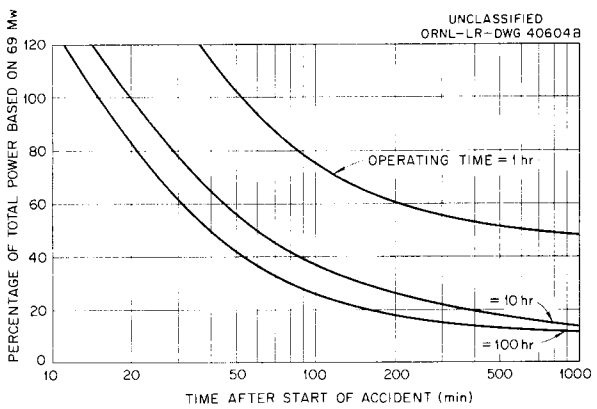

Fig. G.4. Time to Onset of Core Melting Following the MCA as a Function of Operating Power and Time.

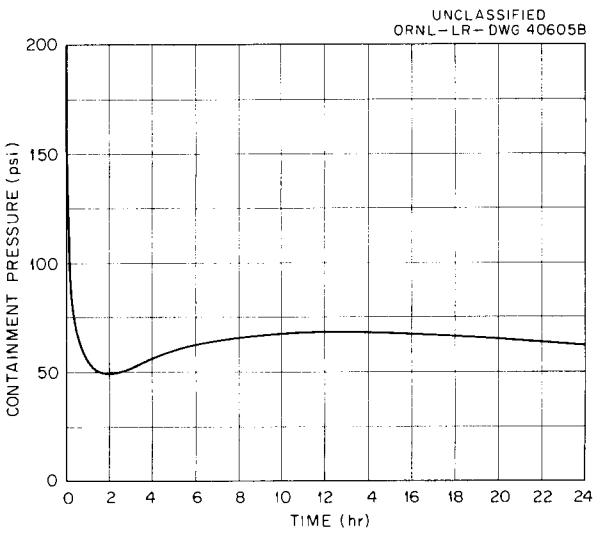

Fig. G.5. Pressure Inside the Containment Vessel as a Function of Time After Initiation of the MCA.

The following items summarize the assumptions used in the analysis:

1. The accident is initiated by a major rupture in the largest primary coolant pipe, with the system initially at 1750 psi and 508°F.
2. Pressure equilibrium between the reactor pressure vessel and the containment vessel is reached in approximately 30 sec.
3. There is no heat loss from fuel rods after pressure equilibrium is attained.
4. The fuel rod cladding fails when the temperature reaches 2550°F.
5. All fission gases generated within a fuel rod are released when the cladding at any point on the rod reaches 2550°F.
6. The distribution of decay heat and fission products in the core is based on a $J_0(\mu E)$ radial power distribution and a cosine vertical (axial) power distribution.
7. The gaseous fission products are assumed to diffuse throughout the containment vessel immediately following release from the fuel rod.

Table G.1 gives the results of the calculations, based on a reactor power of 69 Mw for the specified operating period. For lower powers, the activity levels can be scaled in direct proportion to the power level.

The following sample calculation is provided to demonstrate the manner in which the curves and the data of Table G.1 should be used.

PROBLEM

Determine the I^{131} activity release rate from the containment vessel after a primary system rupture under the following conditions:

Initial power	35 Mw (50% of maximum)
Operating period	100 hr
Time after rupture	10 hr

SOLUTION

1. Initial I^{131} activity in entire core. – From Table G.1 for 100 hr at 69 Mw,

$$I^{131} \text{ activity} = 0.0718 \text{ curie per gram of } UO_2 .$$

The quantity of UO_2 in the core is 7980 kg. Therefore

$$\text{Total } I^{131} \text{ activity at 69 Mw} = 5.7 \times 10^5 \text{ curies} ,$$

$$\text{Total } I^{131} \text{ activity at 35 Mw} = 2.9 \times 10^5 \text{ curies} .$$

2. Decay during 10-hr period following shutdown. – From Table G.1,

I^{131} buildup after 600 days

$$= 0.244 \text{ curie per gram of } UO_2 ,$$

I^{131} decay from 600-day buildup in 10 hr

$$= 0.238 \text{ curie per gram of } UO_2 .$$

Table G.1. Results of Fission-Product Study for Reactor Operation at 69 Mw.

Isotope	Half-Life	Activity Buildup (curie/g of UO_2)				Activity Decay After Shutdown from 600-day Buildup (curie/g of UO_2)						Photon Yields per Disintegration per Energy Group					
		In 1 hr	In 100 hr	In 300 days	In 600 days	In ½ hr	In 1 hr	In 10 hr	In 3 days	In 100 days	In 1000 days	Group I (0–0.4 Mev)	Group II (0.4–1.0 Mev)	Group III (1.01–1.50 Mev)	Group IV (1.51–1.80 Mev)	Group V (1.81–2.40 Mev)	Group VI (Above 2.40 Mev)
Se^{83m}	67s	0.0217	0.0217	0.0205	0.0195												
Se^{83}	25m	0.0294	0.0364	0.0385	0.0326	0.0146	0.00636					2.0	2.0				
Br^{83}	2.4h	0.0047	0.0364	0.0385	0.0326	0.0313	0.0312	0.0022									
Kr^{83m}	1.9h	0.00059	0.0364	0.0385	0.0326	0.0325	0.0325	0.0065									
Se^{84}	2m	0.0796	0.0796	0.0755	0.0710												
Br^{84}	32m	0.0582	0.0796	0.0755	0.0710	0.0381	0.0290						0.44			0.51	
Br^{85}	3m	0.109	0.108	0.103	0.0976												
Kr^{85m}	4.4h	0.0149	0.0861	0.103	0.0976	0.091	0.0841	0.0201				1.0					
Kr^{85}	9.9y	0	0	0.00144	0.00216	0.00216	0.00216	0.00216	0.00216	0.00212	0.00179		0.007				
Br^{87}	56s	0.195	0.195	0.187	0.179												0.70
Kr^{87}	78m	0.0796	0.195	0.187	0.179	0.139	0.107	0.0009				0.60	0.11				0.25
Br^{88}	16s	0.210	0.210	0.201	0.193	0											
Kr^{88}	2.8h	0.0591	0.268	0.258	0.246	0.218	0.192	0.0202				0.38			0.15	0.55	
Rb^{88}	18m	0.0372	0.268	0.258	0.246	0.235	0.212	0.0226					0.11			0.21	0.02
Br^{89}	4.5s	0.333	0.333	0.321	0.308												
Kr^{89}	32m	0.333	0.333	0.321	0.308	0.0059											
Rb^{89}	15m	0.317	0.348	0.335	0.326	0.109	0.0284						0.22	1.72	0.05	0.19	0.24
Sr^{89}	54d	0	0.0179	0.330	0.325	0.325	0.325	0.324	0.313	0.0906							
Kr^{90}	33s	0.377	0.377	0.364	0.347												
Rb^{90}	2.7m	0.428	0.427	0.412	0.395	0.00024											
Sr^{90}	28y	0	0	0.0084	0.0164	0.0164	0.0164	0.0164	0.0164	0.0163	0.0153						
Y^{90}	64.5h	0	0	0.0083	0.0163	0.0163	0.0163	0.0163	0.0163	0.0163	0.0153						
Rb^{91m}	1.7m	0.268	0.268	0.258	0.247												
Rb^{91}	14m	0.390	0.413	0.397	0.383	0.0942	0.0214										
Sr^{91}	9.7h	0.0199	0.427	0.412	0.397	0.390	0.378	0.198	0.00234				0.60	0.40			
Y^{91m}	51m	0.00311	0.256	0.247	0.238	0.237	0.235	0.131	0.00154				1.00				
Y^{91}	58d	0	0.0191	0.407	0.406	0.406	0.406	0.405	0.393	0.124				0.003			
Kr^{92}	3s	0.195	0.195	0.191	0.182												
Rb^{92}	80s	0.398	0.398	0.389	0.379												
Sr^{92}	2.7h	0.0976	0.442	0.432	0.420	0.372	0.327	0.0325						1.00			
Y^{92}	3.5h	0.0089	0.442	0.432	0.420	0.417	0.412	0.149					0.23	0.11		0.002	
Kr^{93}	2s	0.0943	0.0943	0.0906	0.0874												
Rb^{93}	Short	0.319	0.319	0.312	0.305												
Sr^{93}	7m	0.463	0.464	0.454	0.445	0.0229	0.00116										
Y^{93}	10h	0.0265	0.471	0.463	0.452	0.442	0.427	0.228	0.00308				1.00				
Kr^{94}	14s	0.0435	0.0435	0.0431	0.0427												
Rb^{94}	Short	0.210	0.210	0.207	0.205												
Sr^{94}	2m	0.420	0.420	0.415	0.408												
Y^{94}	17m	0.429	0.471	0.465	0.457	0.146	0.0414							1.00			
Sr^{95}	Short	0.341	0.341	0.338	0.336												
Y^{95}	10.5m	0.455	0.464	0.461	0.457	0.0632	0.00874										
Zr^{95}	63d	0.00016	0.0207	0.444	0.472	0.472	0.472	0.455	0.443	0.153	0	0.03	0.97				
Nb^{95m}	90h	0	0.00628	0.444	0.472	0.472	0.472	0.472	0.454	0.162	0	1.00					
Nb^{95}	35d	0	0	0.423	0.472	0.472	0.472	0.472	0.472	0.276	0		1.00				
Sr^{97}	Short	0.125	0.125	0.121	0.120												
Y^{97}	Short	0.348	0.348	0.344	0.340												
Zr^{97}	17.0h	0.0179	0.442	0.446	0.442	0.432	0.424	0.294	0.236				1.00				

Table G.1 (continued)

Isotope	Half-Life	Activity Buildup (curie/g of UO_2)				Activity Decay After Shutdown from 600-day Buildup (curie/g of UO_2)						Photon Yields per Disintegration per Energy Group					
		In 1 hr	In 100 hr	In 300 days	In 600 days	In ½ hr	In 1 hr	In 10 hr	In 3 days	In 100 days	In 1000 days	Group I (0–0.4 Mev)	Group II (0.4–1.0 Mev)	Group III (1.01–1.50 Mev)	Group IV (1.51–1.80 Mev)	Group V (1.81–2.40 Mev)	Group VI (Above 2.40 Mev)
Nb^{97m}	1m	0.0175	0.442	0.446	0.442	0.441	0.424	0.294	0.0236				1.00				
Nb^{97}	72m	0.0754	0.442	0.446	0.442	0.441	0.438	0.317	0.0254				1.00				
Nb^{99}	2.5m	0.442	0.442	0.442	0.442	0.000108											
Mo^{99}	67h	0.00431	0.285	0.442	0.442	0.442	0.438	0.399	0.210			1.00	0.13				
Tc^{99m}	6.04h	0	0.0027	0.00443	0.00443	0.00443	0.00443	0.00422	0.0023			1.00					
Mo^{101}	14.6m	0.341	0.362	0.367	0.372	0.0894	0.0216					1.00	0.70				
Tc^{101}	14.0m	0.285	0.362	0.367	0.372	0.213	0.0796					1.00					
Mo^{102}	12m	0.294	0.305	0.311	0.318	0.0562	0.00992										
Tc^{102}	25s	0.294	0.305	0.311	0.318	0.0582	0.0103										
Ru^{103}	41d	0.00015	0.0143	0.218	0.230	0.230	0.230	0.229	0.219	0.0422			0.95				
Rh^{103m}	54m	0.000427	0.0134	0.207	0.220	0.220	0.220	0.218	0.208	0.0402							
Mo^{105}	5m	0.0435	0.0435	0.0517	0.0599	0.00094											
Tc^{105}	Short	0.0651	0.0651	0.0774	0.0894	0.00094											
Ru^{105}	4.5h	0.00862	0.0652	0.0774	0.0894	0.0841	0.0779	0.0194					1.00				
Rh^{105m}	45s	0.0084	0.0652	0.0774	0.0894	0.0841	0.0779	0.0194				1.00					
Rh^{105}	36h	0.00011	0.0541	0.0774	0.0894	0.0894	0.0894	0.082	0.0261			0.30					
Ru^{106}	1.01y	0	0.00022	0.0165	0.0338	0.0338	0.0338	0.0338	0.0337	0.0280	0.00504						
Rh^{106}	30s	0	0.00022	0.0165	0.0338	0.0338	0.0338	0.0338	0.0337	0.0280	0.00504		0.38	0.02	0.002		0.002
Tc^{107}	1.5m	0.0116	0.0117	0.0248	0.0380												
Ru^{107}	4m	0.0145	0.0147	0.0310	0.0476	0.000387											
Rh^{107}	25m	0.0109	0.0147	0.0310	0.0476	0.0264	0.0119										
Rh^{109}	1h	0.00102	0.00209	0.00627	0.0105	0.00738	0.00521	0.00001									
Pd^{109}	13.6h	0.00003	0.00206	0.00623	0.0105	0.0104	0.0103	0.00677	0.00028								
Ag^{109m}	39.2s	0.00003	0.00206	0.00623	0.0105	0.0104	0.0103	0.00677	0.00028			1.00					
Pd^{111}	22m	0.00112	0.00131	0.00238	0.00349	0.00135	0.00053										
Ag^{111}	7.6d	0	0.00041	0.00240	0.00345	0.00345	0.00345	0.0033	0.00262			0.09					
Pd^{112}	21h	0.00003	0.00077	0.00118	0.00157	0.00154	0.00152	0.00713	0.00014								
Ag^{112}	3.2h	0.00003	0.00077	0.00118	0.00157	0.00154	0.00157	0.00130	0.00017				0.55	0.20			
Ag^{113}	5.3h	0.00009	0.00073	0.00107	0.00142	0.00133	0.00125	0.00038									
Cd^{113m}	5.0y	0	0	0.00010	0.00022	0.00022	0.00022	0.00022	0.00022	0.00021	0.00015						
Ag^{114}	2m	0.00073	0.00073	0.00090	0.00107												
Ag^{115}	20m	0.00064	0.00073	0.00088	0.00103	0.00036	0.00013										
Cd^{115m}	43d	0	0	0.00008	0.00009	0.00009	0.00009	0.00009	0.00009	0.00002			1.46	0.27			
Cd^{115}	53h	0	0.00053	0.00087	0.00102	0.00101	0.00100	0.00089	0.00040			0.06	0.94				
In^{115m}	4.5h	0	0.00051	0.00087	0.00102	0.00101	0.00100	0.00096	0.00044			0.94					
Cd^{117m}	2.9h	0.00016	0.00073	0.00083	0.00094	0.00084	0.00074	0.000086					1.00				
Cd^{117}	50m	0.00005	0.00073	0.00083	0.00094	0.00092	0.00087	0.00012									
In^{117m}	1.9h	0.00001	0.00073	0.00083	0.00094	0.00094	0.00094	0.00027				1.00					
In^{117}	1.1h	0	0.00016	0.00018	0.00021	0.00021	0.00021	0.00008				0.10	0.15				
Cd^{118}	3.0m	0.00054	0.00073	0.00082	0.00091	0.00046	0.00023	0									
In^{118}	4.5m	0.00051	0.00073	0.00082	0.00091	0.00054	0.00027	0									
In^{119}	17.5m	0.00066	0.00073	0.00081	0.00090	0.00027	0.00008										
Sn^{119m}	275d	0	0	0.00041	0.00065	0.00065	0.00065	0.00065	0.00064	0.00050	0.00005						
Sn^{121}	27h	0.00003	0.00094	0.00113	0.00125	0.00123	0.00121	0.00097	0.00020								

Table G.1 (continued)

Isotope	Half-Life	Activity Buildup (curie/g of UO_2)				Activity Decay After Shutdown from 600-day Buildup (curie/g of UO_2)						Photon Yields per Disintegration per Energy Group					
		In 1 hr	In 100 hr	In 300 days	In 600 days	In ½ hr	In 1 hr	In 10 hr	In 3 days	In 100 days	In 1000 days	Group I (0–0.4 Mev)	Group II (0.4–1.0 Mev)	Group III (1.01–1.50 Mev)	Group IV (1.51–1.80 Mev)	Group V (1.81–2.40 Mev)	Group VI (Above 2.40 Mev)
Sn^{123}	39.5 m	0.00066	0.00094	0.00117	0.00133	0.00178	0.00046					1.00					
Sn^{125m}	9.5m	0.00079	0.00080	0.00103	0.00127	0.00014	0.00002					1.00					
Sn^{125}	9.4d	0	0.00023	0.00110	0.00134	0.00134	0.00134	0.00130	0.00108							0.05	
Sb^{125}	2.7y	0	0	0.00036	0.00074	0.00074	0.00074	0.00074	0.00074	0.00070	0.00037	0.28	0.72				
Te^{125m}	58d	0	0	0.00004	0.00009	0.00009	0.00009	0.00009	0.00009	0.00010	0.00006	1.00					
Sn^{126}	50m	0.00409	0.00726	0.00701	0.00681	0.00451	0.00296										
Sb^{126}	9h	0.00017	0.00726	0.00701	0.00681	0.00677	0.00665	0.00348	0.00003			1.00	1.00				
Sn^{127}	1.5h	0.00644	0.0174	0.0179	0.0185	0.0147	0.0117	0.00018									
Sb^{127}	93h	0.00003	0.00939	0.0186	0.0191	0.0191	0.0191	0.0180	0.0114								
Te^{127m}	90d	0	0.00006	0.00370	0.00418	0.00418	0.00418	0.00418	0.00414	0.00201		1.00					
Te^{127}	9.3h	0	0.00710	0.0223	0.0203	0.0203	0.0203	0.0160	0.0147	0.00201			0.01				
Sn^{128}	56m	0.0188	0.0365	0.0367	0.0371	0.0258	0.0179										
Sb^{128}	1.1h	0.00537	0.0365	0.0367	0.0371	0.0354	0.0316	0.00034									
Sb^{129}	4.6h	0.0105	0.0726	0.0746	0.0767	0.0709	0.0656	0.0162									
Te^{129m}	33d	0	0.00198	0.0252	0.0260	0.0260	0.0260	0.0259	0.0245	0.00320		1.00					
Te^{129}	72m	0	0.00194	0.0252	0.0260	0.0260	0.0260	0.0259	0.0245	0.00320			0.19	0.10			
Sn^{130}	2.6m	0.139	0.145	0.147	0.149												
Sb^{130}	12m	0.139	0.145	0.147	0.149	0.0337	0.00595										
Sb^{131}	21m	0.168	0.196	0.200	0.203	0.0755	0.0281										
Te^{131m}	30h	0.00403	0.0283	0.0325	0.0331	0.0316	0.0289	0.00369				1.00					
Te^{131}	25m	0.127	0.243	0.244	0.244	0.182	0.0593	0.00427				1.00	0.45				
I^{131}	8.05d	0	0.0718	0.242	0.244	0.243	0.244	0.238	0.170	0		0.85	0.12				
Se^{131m}	12d	0	0	0.00242	0.00244	0.00244	0.00244	0.00244	0.00240	0		1.00					
Sn^{132}	2.2m	0.246	0.246	0.248	0.251	0.0000197											
Sb^{132}	1.9m	0.246	0.246	0.248	0.251	0.000116											
Te^{132}	77h	0.00266	0.190	0.321	0.323	0.322	0.321	0.295	0.168			1.00					
I^{132}	2.4h	0.000328	0.186	0.321	0.323	0.323	0.323	0.304	0.174				2.31	0.13		0.07	
Te^{133m}	63m	0.161	0.333	0.329	0.325	0.234	0.168	0.00045				1.00					
Te^{133}	2m	0.257	0.435	0.429	0.423	0.242	0.173	0.00046					1.70				
I^{133}	21h	0.00705	0.454	0.465	0.458	0.455	0.451	0.341	0.00435				0.99	0.01			
Xe^{133m}	2.3d	0	0.00632	0.0112	0.0110	0.0110	0.0110	0.0108	0.00660			1.00					
Xe^{133}	5.27d	0	0.147	0.465	0.458	0.458	0.458	0.456	0.365	0		1.00					
Sb^{134}	45s	0.217	0.217	0.215	0.211	0											
Te^{134}	44m	0.296	0.486	0.477	0.469	0.294	0.183	0.00004									
I^{134}	52m	0.139	0.550	0.540	0.531	0.478	0.398	0.00885					0.30	0.35	0.35		
Te^{135}	2m	0.304	0.304	0.303	0.302												
I^{135}	6.7h	0.0407	0.428	0.426	0.424	0.0403	0.384	0.150	0.00024					0.40	0.35	0.01	
Xe^{135m}	15.6m	0.00148	0.128	0.128	0.127	0.127	0.126	0.0685	0.00012				1.00				
Xe^{135}	9.13h	0.00266	0.449	0.448	0.446	0.445	0.443	0.353	0.00618			0.97	0.04				
I^{136}	86s	0.228	0.228	0.219	0.214												
Cs^{136}	11.2d	0	0.00087	0.00389	0.00459	0.00459	0.00459	0.00451	0.00392								
I^{137}	22s	0.355	0.355	0.355	0.354												
Xe^{137}	3.9m	0.428	0.428	0.428	0.427	0.00225	0.00001										
Cs^{137}	33y	0	0.00010	0.00734	0.0145	0.0145	0.0145	0.0145	0.0145	0.0144	0.0137		1.00				
Ba^{137m}	2.6m	0	0.00009	0.00673	0.0133	0.0133	0.0133	0.0133	0.0133	0.0133	0.0126		1.00				
I^{138}	59s	0.246	0.246	0.245	0.244												
Xe^{138}	17m	0.364	0.398	0.397	0.396	0.117	0.0345						1.00				
Cs^{138}	32m	0.222	0.420	0.419	0.418	0.321	0.197						0.76	1.00			

Table G.1 (continued)

Isotope	Half-Life	Activity Buildup (curie/g of UO_2)				Activity Decay After Shutdown from 600-day Buildup (curie/g of UO_2)						Photon Yields per Disintegration per Energy Group					
		In 1 hr	In 100 hr	In 300 days	In 600 days	In ½ hr	In 1 hr	In 10 hr	In 3 days	In 100 days	In 1000 days	Group I (0–0.4 Mev)	Group II (0.4–1.0 Mev)	Group III (1.01–1.50 Mev)	Group IV (1.51–1.80 Mev)	Group V (1.81–2.40 Mev)	Group VI (Above 2.40 Mev)
I^{139}	26s	0.130	0.130	0.130	0.130												
Xe^{139}	41s	0.341	0.341	0.338	0.335												
Cs^{139}	9.5m	0.422	0.428	0.425	0.423	0.0500	0.00554										
Ba^{139}	85m	0.134	0.435	0.432	0.430	0.374	0.297	0.00363				0.66	0.19				
Xe^{140}	16s	0.268	0.268	0.265	0.262												
Cs^{140}	66s	0.435	0.435	0.431	0.426												
Ba^{140}	12.8d	0.00100	0.0923	0.452	0.448	0.448	0.447	0.439	0.381	0.00199		0.20	0.30				
La^{140}	40h	0	0.0496	0.453	0.448	0.448	0.448	0.447	0.423	0.00229			0.73		0.94		0.057
Xe^{141}	1.7s	0.131	0.131	0.131	0.130												
Cs^{141}	Short	0.341	0.341	0.393	0.333												
Ba^{141}	18m	0.385	0.428	0.423	0.418	0.132	0.00414										
La^{141}	3.7h	0.0468	0.435	0.430	0.426	0.409	0.380	0.0709						0.05			
Ce^{141}	32d	0.00207	0.0374	0.430	0.426	0.426	0.426	0.424	0.402	0.0488		0.67					
Cs^{142}	2m	0.247	0.247	0.243	0.239												
Ba^{142}	6m	0.406	0.406	0.389	0.393	0.0136	0.00042										
La^{142}	74m	0.161	0.428	0.420	0.413	0.339	0.257	0.00164					1.00				
Cs^{143}	Short	0.138	0.138	0.135	0.132												
Ba^{143}	30s	0.355	0.355	0.354	0.348												
La^{143}	20m	0.397	0.450	0.445	0.440	0.150	0.0504										
Ce^{143}	32h	0.00566	0.397	0.444	0.440	0.438	0.434	0.358	0.0935			0.40	0.14	0.06			
Pr^{143}	13.7d	0	0.0427	0.445	0.440	0.440	0.440	0.440	0.409	0.0311							
Cs^{144}	Short	0.0726	0.0726	0.0710	0.0689												
Ba^{144}	Short	0.254	0.254	0.248	0.243												
La^{144}	Short	0.420	0.420	0.414	0.400												
Ce^{144}	290d	0.00004	0.00439	0.223	0.326	0.326	0.326	0.326	0.325	0.257	0.0301	0.24					
Pr^{144}	17m	0.00004	0.00439	0.223	0.326	0.326	0.326	0.326	0.325	0.257	0.0301		0.03	0.01		0.022	
Cs^{145}	Short	0.304	0.304	0.300	0.296												
Ba^{145}	Short	0.304	0.304	0.300	0.296												
La^{145}	Short	0.304	0.304	0.300	0.296												
Ce^{145}	3.0m	0.304	0.304	0.304	0.296	0.00029											
Pr^{145}	6.0h	0.0331	0.304	0.304	0.296	0.282	0.269	0.0940	0.00007								
Ce^{146}	13.9m	0.220	0.232	0.229	0.226	0.0504	0.0114					1.36					
Pr^{146}	25m	0.155	0.239	0.236	0.233	0.160	0.082						1.22	0.33			
Nd^{147}	11.6d	0.00048	0.00427	0.184	0.183	0.183	0.183	0.179	0.153	0.00040	0	0.15	0.25				
Pm^{147}	2.6y	0	0.00007	0.0350	0.0644	0.0644	0.0644	0.0644	0.0647	0.0619	0.0321	1.00					
Nd^{149}	2.0h	0.0276	0.0915	0.0951	0.0960	0.0808	0.0677	0.00299				1.00					
Pm^{149}	54h	0.00018	0.0672	0.0951	0.0959	0.0959	0.0959	0.0873	0.0396								
Nd^{151}	15m	0.0326	0.0348	0.0361	0.0376	0.00939	0.00235						0.73	0.62			
Pm^{151}	27h	0.00061	0.0333	0.0377	0.0391	0.0389	0.0384	0.0307	0.00644			2.00					
Sn^{151}	73y	0	0.00052	0.0299	0.0369	0.0369	0.0369	0.0369	0.0369	0.0369	0.0363						
Sn^{153}	46h	0.00016	0.0084	0.0119	0.0130	0.0128	0.0127	0.0112	0.00447			0.400	0.0006				
Sn^{155}	23m	0.00186	0.00226	0.00303	0.00380	0.00157	0.00065					2.00					
Eu^{155}	1.7y	0	0.00011	0.00276	0.00358	0.00358	0.00358	0.00356	0.00346	0.00108	0.00218	0.77					
Sn^{156}	10h	0.00006	0.00095	0.00141	0.00187	0.00181	0.00175	0.00935	0.00001								
Eu^{156}	15d	0	0.00014	0.00137	0.00184	0.00184	0.00184	0.00183	0.00165	0.00002						0.60	
Totals		20.6	30.7	36.4	36.3	18.6	16.8	11.6	6.81	1.67	0.150						

Therefore

$$\text{Activity ratio} = \frac{0.238}{0.244} = 0.975 \ .$$

3. Percentage of total activity released to containment vessel 10 hr after rupture. – From Fig. G.2,

$$\text{Percentage released} = 89\% \ .$$

4. Total activity in containment vessel 10 hr after rupture. –

$$\text{Total } I^{131} \text{ activity} = 2.9 \times 10^5 \times 0.975 \times 0.89$$

$$= 2.5 \times 10^5 \text{ curies} \ .$$

5. Leakage rate 10 hr after rupture. – The leakage rate of the containment vessel was taken as 0.2% of the free volume per day. Since the leakage is expressed as being independent of containment vessel pressure and this cannot in fact be true, Babcock & Wilcox has recommended a leak test at 30 psig in order to determine the leakage rate if it is above the lower limit of detectability, which is about 0.2% per day.

It should be mentioned, however, that no detectable leakage is anticipated from the containment vessel. The leakage rates used in environmental studies are based on the minimum value which can be ascertained within the accuracy of the leak tests. The assumption is made that a leak of lesser magnitude than the uncertainty of the leak test could escape notice during the periodic tests. Consequently, the assumed leakage rate for the containment vessel is 0.2% of the free volume in 24 hr.

Data on the containment vessel pressure following a primary system rupture are presented in Fig. G.5. For the first day after the rupture the average containment vessel pressure is estimated to be approximately 60 psi.

For any specific time after the rupture, the maximum leakage rate[3] can be estimated in the following manner:

$$\text{Test leakage rate} = \frac{0.002 \text{ fraction/day}}{24 \times 3600 \text{ sec/day}}$$

$$= 2.3 \times 10^{-8} \text{ fraction of containment vessel volume per second at 30 psi.}$$

From Fig. G.5, the pressure 10 hr after rupture is

$$\text{Containment vessel pressure} = 65 \text{ psi} \ .$$

For this pressure the leakage rate is

$$\text{Assumed leakage rate} = 2.3 \times 10^{-8} \times \frac{65}{30}$$

$$= 5 \times 10^{-8} \text{ fraction/sec} \ .$$

6. I^{131} activity leakage from containment vessel. –

$$I^{131} \text{ leakage} = 5 \times 10^{-8} \times 2.5 \times 10^5$$

$$= 0.012 \text{ curie/sec} \ .$$

[3] This requires that leakage rate checks be repeated frequently enough to ensure that this rate remains a maximum.

Appendix H

ACTIVITY RELEASE FROM MAXIMUM CREDIBLE ACCIDENT AFTER SHUTDOWN[1]

The results of the MCA analysis for the conditions in which the reactor has been shut down for 10 and for 100 hr prior to the major pipe rupture have been calculated. Figures H.1–H.8 present the calculated percentage of the total fission product gaseous activity in the reactor core that is released as a function of time after shutdown. These curves may be used in the manner outlined in Appendix G.

Table H.1 summarizes the effect of cooling time prior to primary system rupture on the time until initial melting of the fuel elements occurs. The containment vessel should not be opened unless sufficient time exists after the primary coolant container failure to replace the hatches before onset of fuel-element failure. For example, Table H.1 indicates that 3 hr will elapse between the primary system rupture and initial melting when the reactor has been shut down for 10 hr following operation at 50% power for 100 hr.

[1] This appendix was prepared by the Babcock & Wilcox Company and transmitted by J. H. MacMillan of that company to W. B. Cottrell on May 12, 1959.

Table H.1. Time Between Rupture of a Major Pipe and the Initiation of Melting of Fuel Elements

Time of Rupture After Shutdown (hr)	Time Reactor Operated Prior to Shutdown (hr)	Time of Initiation of Fuel-Element Melting After Rupture (hr) if Reactor Had Been Operating at Indicated Power Level		
		100% Power	50% Power	20% Power
0	10	0.33	1	6
	100	0.25	0.65	3
10	10	4.7	15	118
	100	1.5	3.2	17.8
100	10	72	230	1790
	100	5.5	22	67

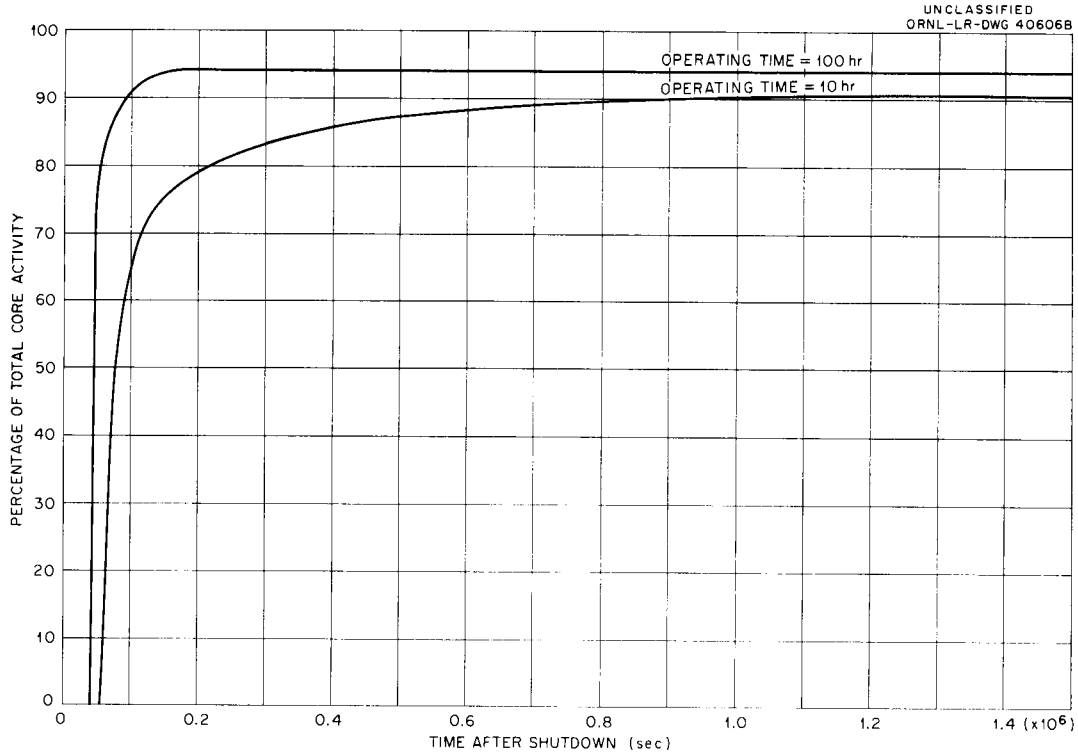

Fig. H.1. Rate of Activity Release Following MCA for MCA Occurring 10 hr After Shutdown (Reactor Power Before Shutdown = 100%).

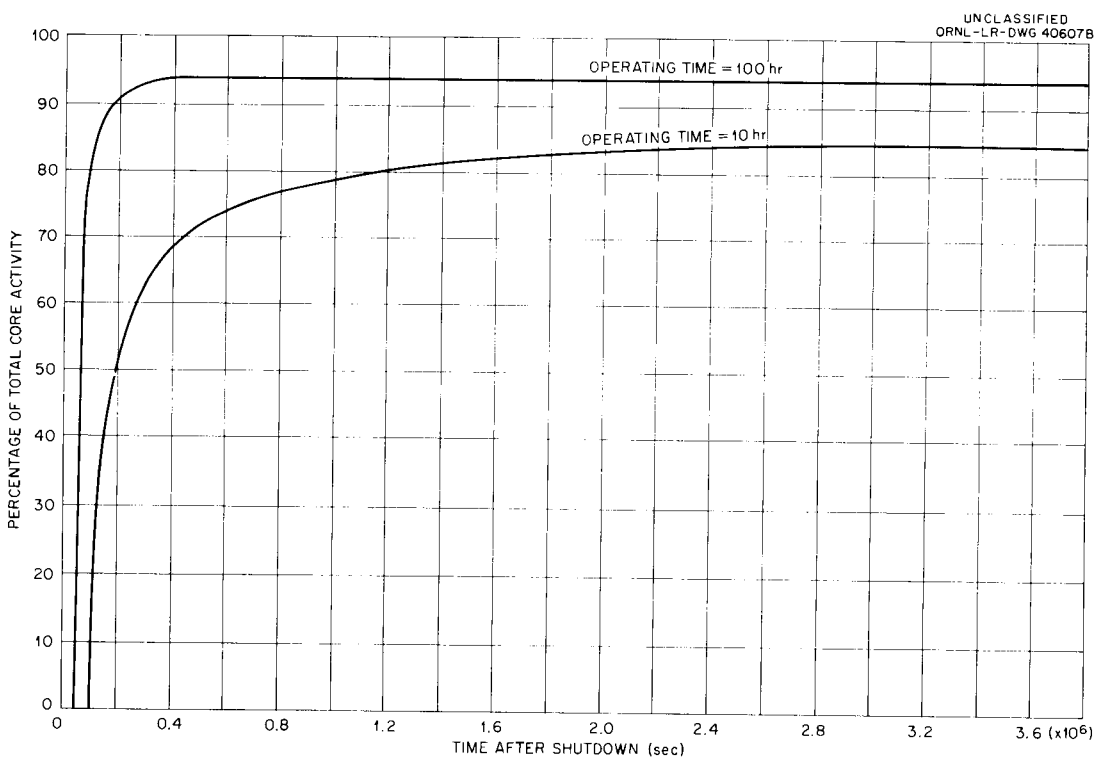

Fig. H.2. Rate of Activity Release Following MCA for MCA Occurring 10 hr After Shutdown (Reactor Power Before Shutdown = 50%).

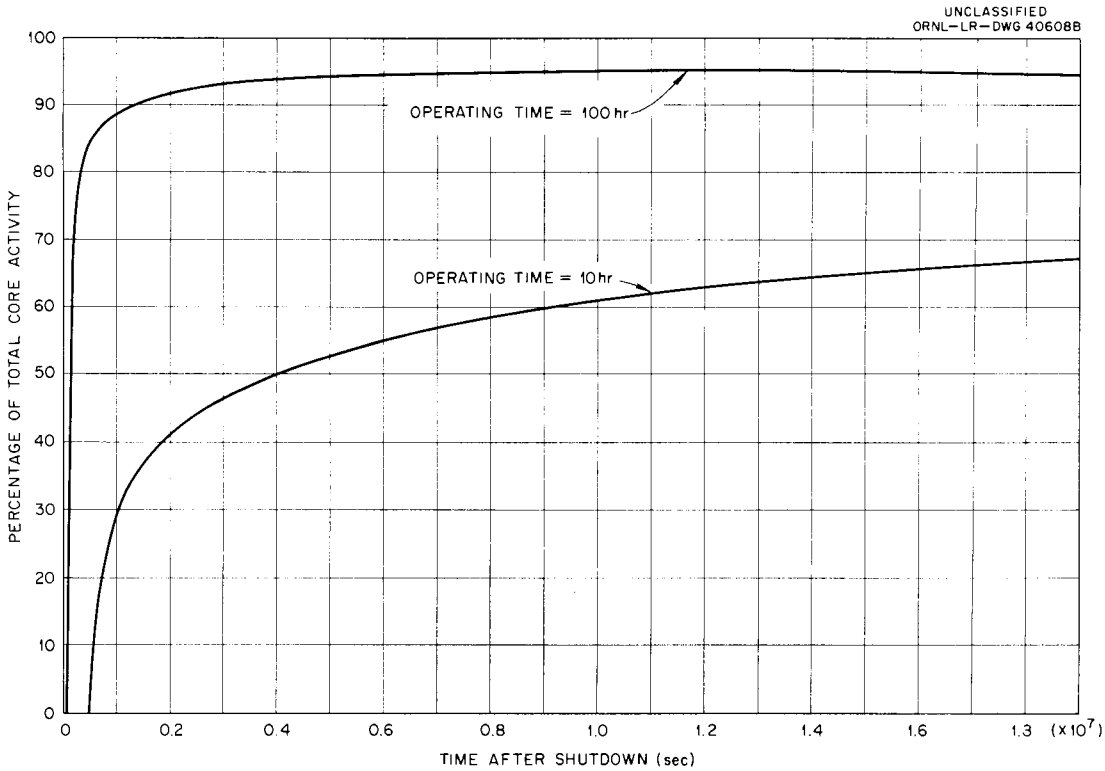

Fig. H.3. Rate of Activity Release Following MCA for MCA Occurring 10 hr After Shutdown (Reactor Power Before Shutdown = 20%).

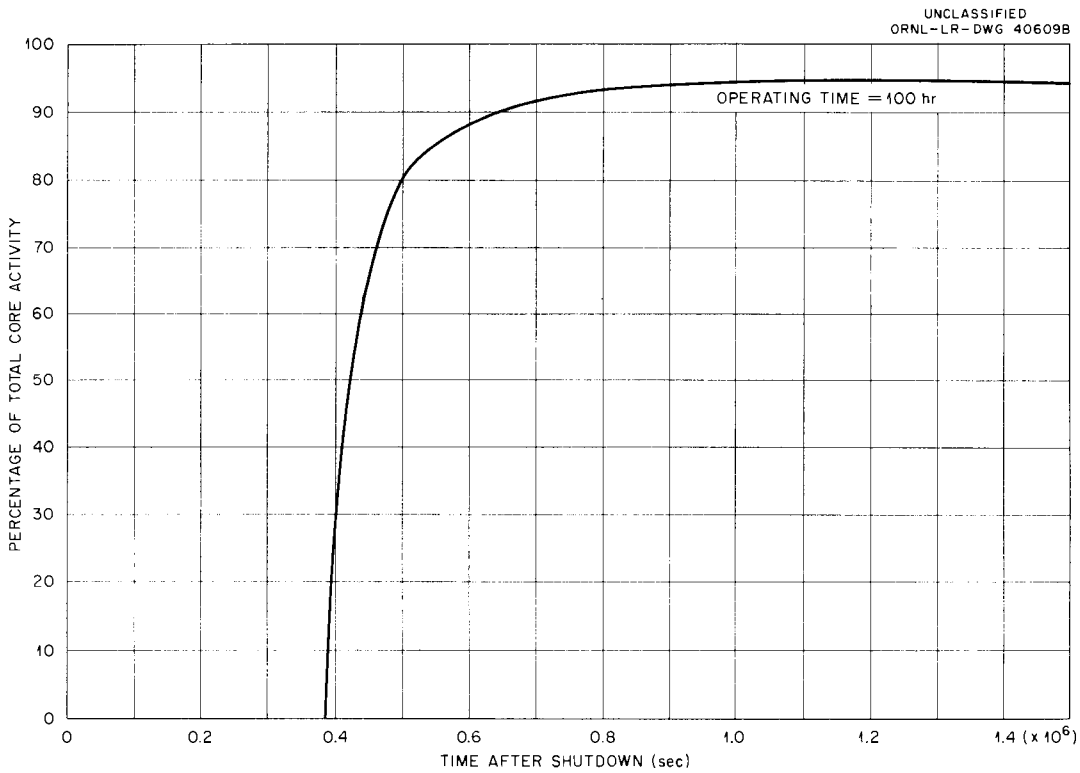

Fig. H.4. Rate of Activity Release Following MCA for MCA Occurring 100 hr After Shutdown (Reactor Power Before Shutdown = 100%).

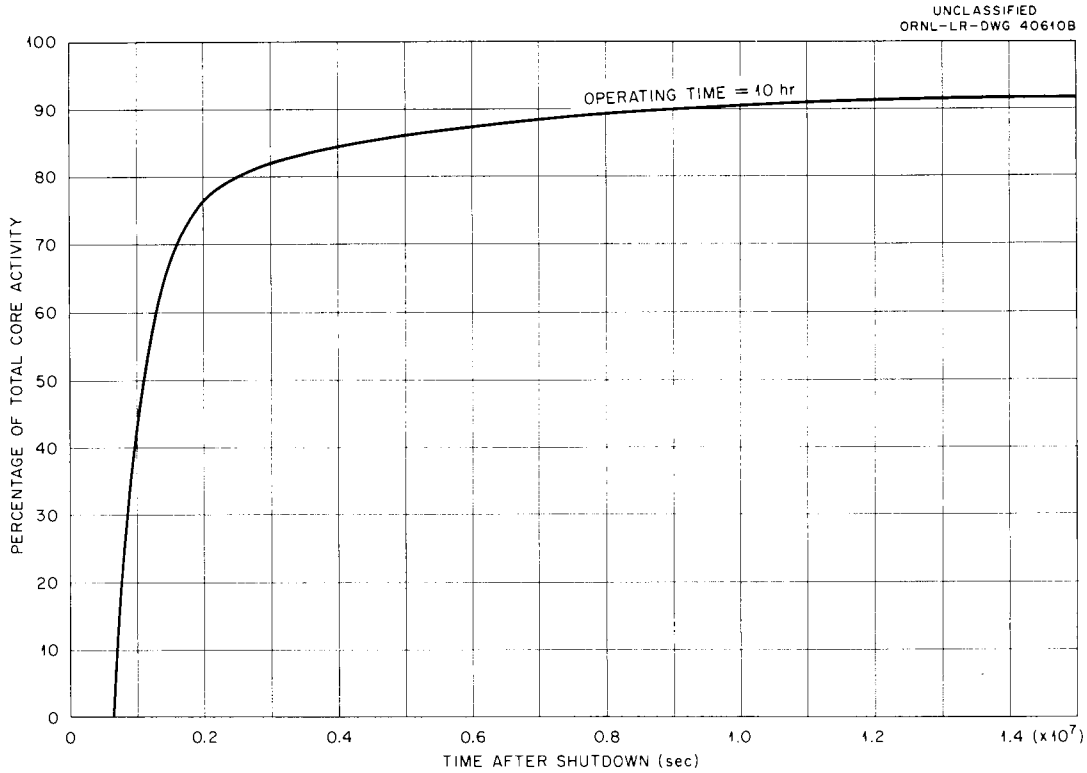

Fig. H.5. Rate of Activity Release Following MCA for MCA Occurring 100 hr After Shutdown (Reactor Power Before Shutdown = 100%).

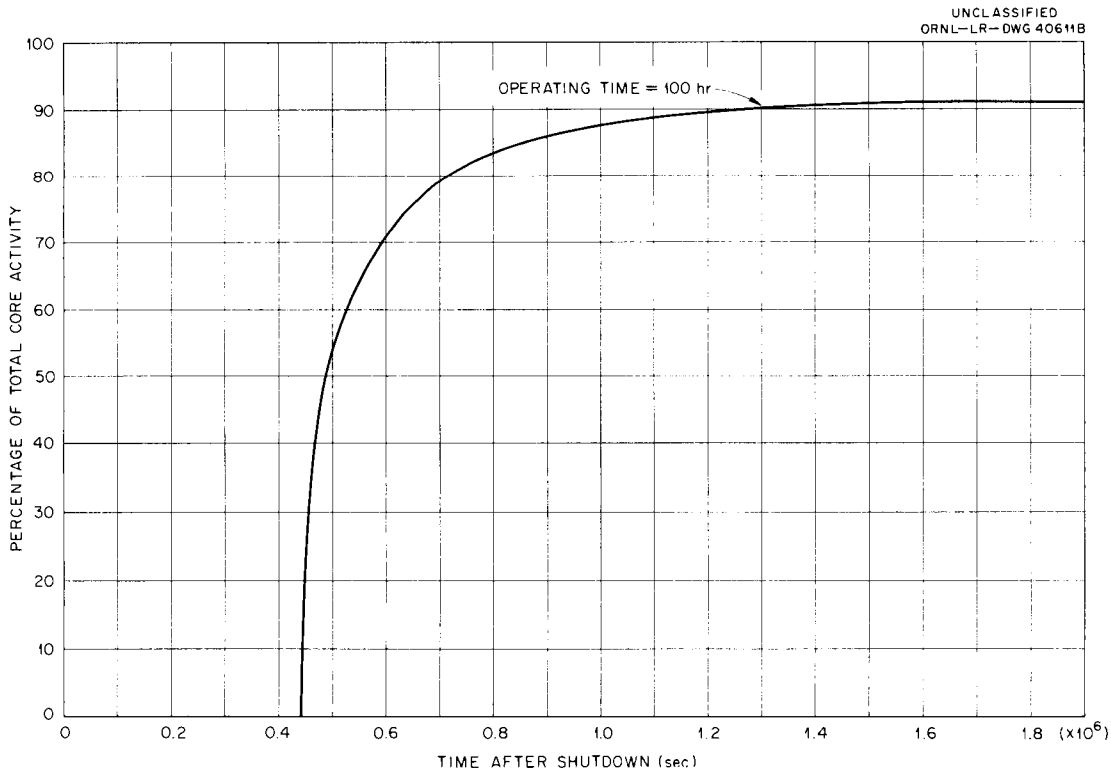

Fig. H.6. Rate of Activity Release Following MCA for MCA Occurring 100 hr After Shutdown (Reactor Power Before Shutdown = 50%).

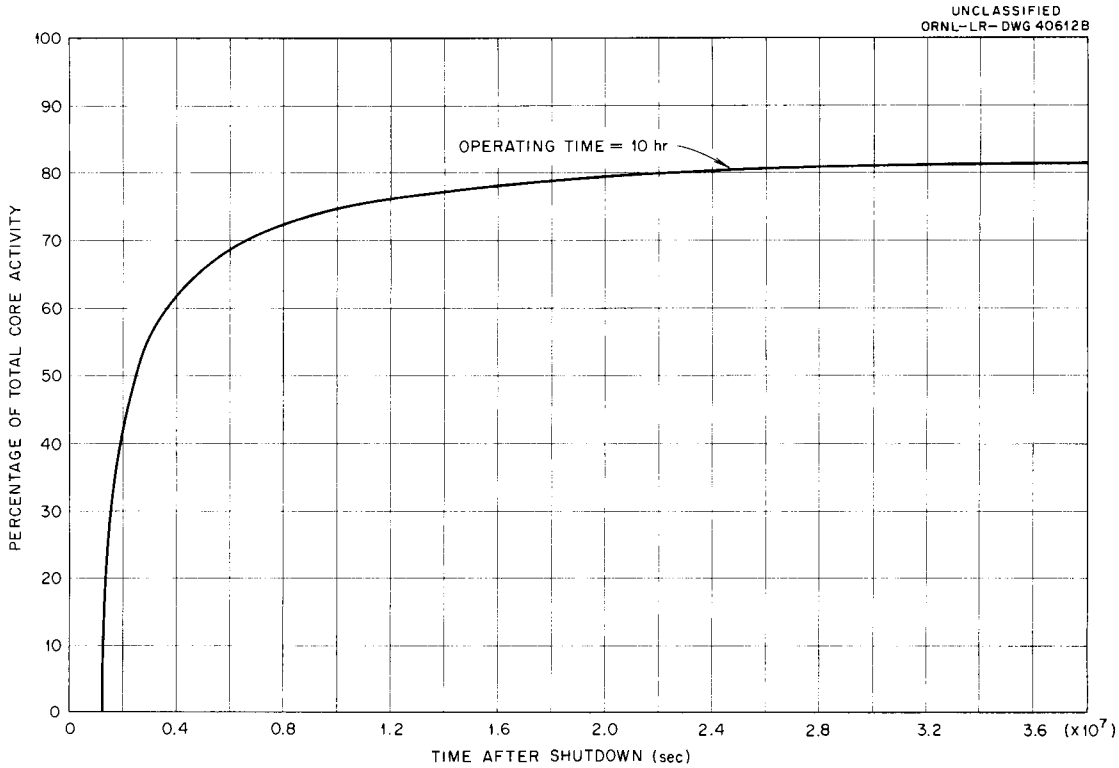

Fig. H.7. Rate of Activity Release Following MCA for MCA Occurring 100 hr After Shutdown (Reactor Power Before Shutdown = 50%).

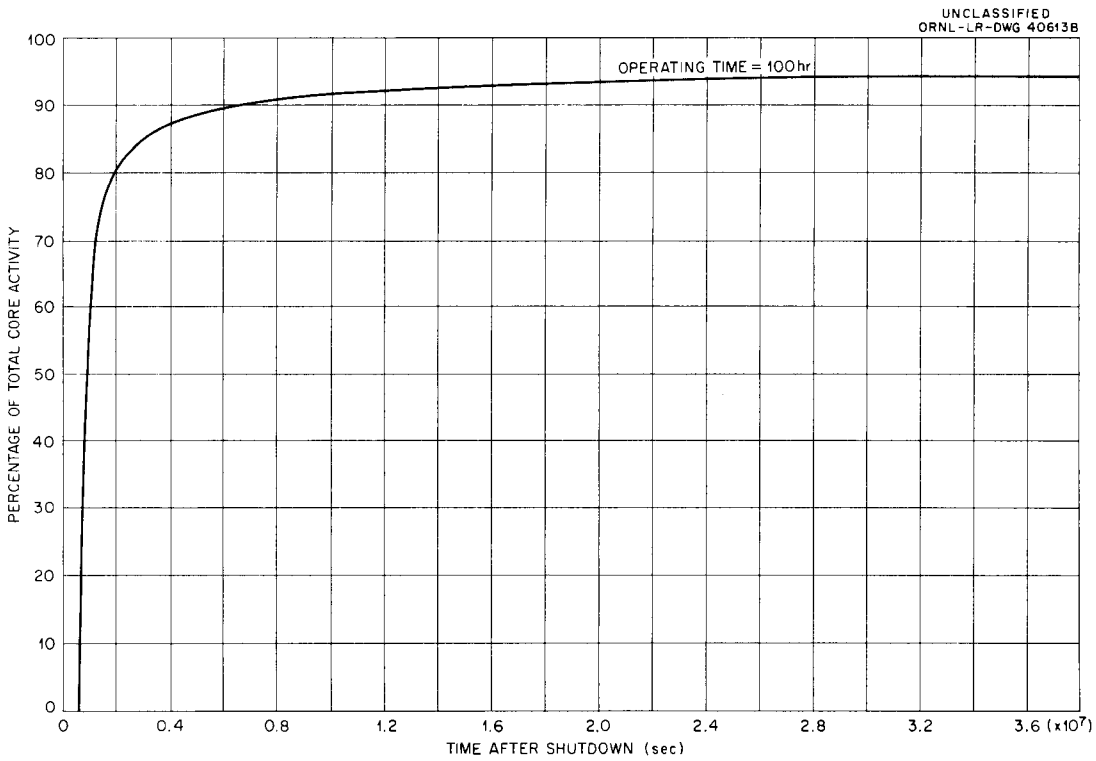

Fig. H.8. Rate of Activity Release Following MCA for MCA Occurring 100 hr After Shutdown (Reactor Power Before Shutdown = 20%).

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