An estimation of population doses from a nuclear plant during normal operation

Forskningscenter Risø, Roskilde

Publication date:
1975

Document Version
Publisher's PDF, also known as Version of record

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Risø - M - 1808

Title and author(s)

An Estimation of Population Doses from a Nuclear Power Plant During Normal Operation

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Date July 1975

Department or group

Health Physics

Group's own registration number(s)

1611200

pages + tables + illustrations

Abstract

In this report a model is presented for estimation of the potential submersion and inhalation radiation doses to people located within a distance of 1000 km from a nuclear power plant during normal operation. The model was used to calculate these doses for people living 200-1000 km from a hypothetical nuclear power facility sited near the geographical centre of Denmark. Two cases of sources are considered for this situation

- unit release of 15 isotopes of noble gases and iodines,
- effluent releases from two types of 1000 MWe Light Water Power Reactors: PWR and BWR.

Parameter variations were made and analyzed in order to obtain a better understanding of the mechanisms of the model.

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ISBN 87 550 0268

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1. INTRODUCTION

With increasing use of nuclear energy for electrical generation considerable attention has been focused on the question of the radiation doses to man and other organisms which might result from use of nuclear facilities in the electric power industry [1,2,3]. The potential impact on the environment from the construction and operation of nuclear facilities includes the radiological impact on man and other biota from routine operation of the facilities and from transportation of radioactive materials (clean fuel, irradiated fuel and wastes).

The proper evaluation of radiation doses to people and other organisms from environmental radiation sources requires the summation of dose contributions from all nuclides and possible exposure pathways in question. Frequently the relative importance of a particular pathway-nuclide combination cannot be judged without calculating its contribution to the total dose. The pathways by which man and other organisms in the environment could be exposed to radiation are shown in figures 1-1 and 1-2 respectively.

The exposure pathways for man can be classed as those associated with:

a) gaseous effluents - air pathways

b) liquid effluents - water pathways

c) external radiation from the nuclear power plant or from transportation of radioactive materials to or from the plant - direct radiation pathways.

The principal air pathways from nuclear power plant are the following:

- air submersion
- external exposure to deposited material
- inhalation
- ingestion of food crops
- ingestion of animal products.

The principal water pathways from nuclear power plant are the following:

- water immersion and water surface
- external exposure to shoreline
- ingestion of water
- ingestion of fish, shellfish and waterfowl
- ingestion of irrigated food crops
- ingestion of products produced by animal fed irrigated foods.

The principal direct radiation pathways from nuclear power plant are the following:

- direct radiation from facility
- exposure during transport of wastes
- exposure during transport of fuel.

Many of the pathways of exposure for organisms other than man are similar to those for man. These pathways include ingestion of water and aquatic foods, submersion in air, immersion in water and exposure to sediments and shorelines. Other pathways such as inhalation and direct radiation from air deposition of radionuclides on soils are not considered significant in the total dose to such organisms.

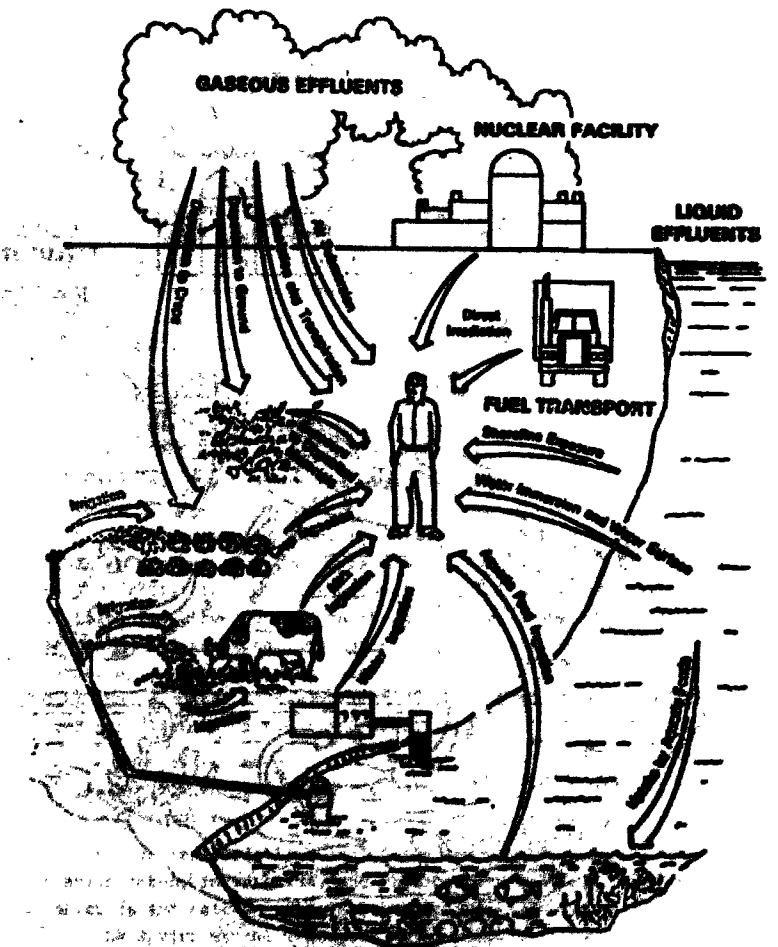


FIGURE 1.1 EXPOSURE PATHWAYS TO MAN

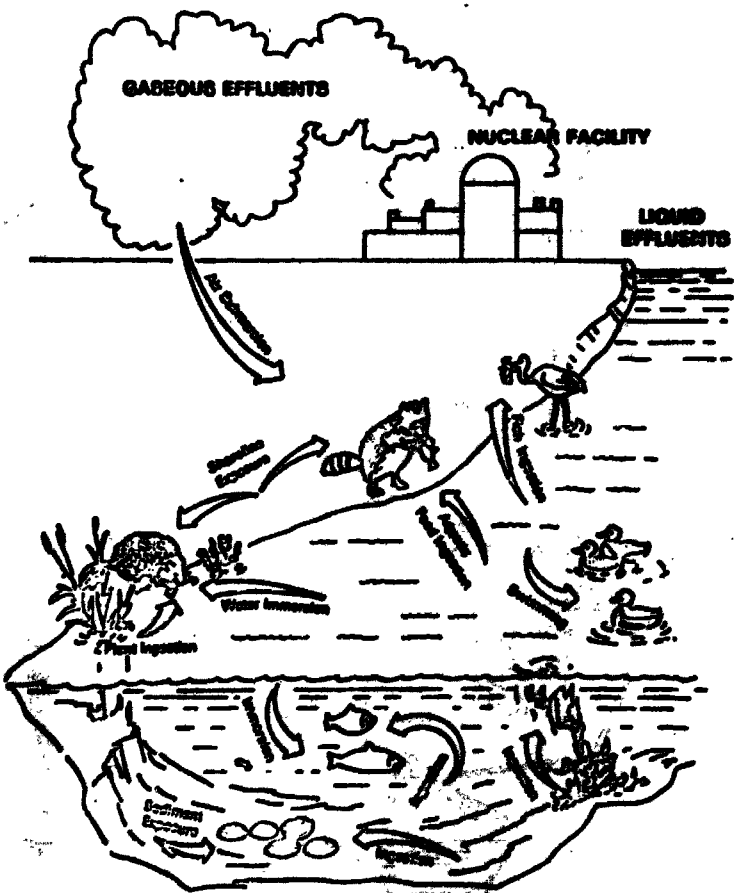


FIGURE 1.2 EXPOSURE PATHWAYS TO ORGANISMS OTHER THAN MAN

2. DOSE TO MAN - GENERAL CALCULATION SCHEME

The report analyses the radiation potentially received by the population located up to 1000 km from a nuclear power plant during its normal operation. Two air pathways are considered for 15 isotopes of noble gases and iodines: air submersion and inhalation of air.

Releases of radioactivity to the environment during normal operation of a nuclear power plant result in exposure of the population to ionising radiation. The assessment of the exposure of the population is dependent upon the types of nuclear facilities and radioactive waste treatment systems assumed, on the uncertainties in the role of various processes in transporting radionuclides through the environment leading to human exposure, and on the approximations required in the mathematical modelling of these processes [2].

In a general study as this it is very difficult to take into account all possible variations. However, sensitivity studies were performed to evaluate the effects of uncertainties in the parameters believed to be most significant in their effects on the dose. Moreover, the doses received by individuals in the vicinity of the nuclear power plant are subject to a wide variation depending on location, age, dietary and other habits, and other statistical factors. More generally this can be expressed in a dose distribution in the population. The area under the distribution curve represents the total population dose. The assessment of the total population dose that may result from normal operation of a particular nuclear power plant is dependent upon a number of assumptions. The calculational models used are generally categorized as follows:

- Source term models
- Environmental transport models
- Dose models.

Source term modelling includes assessment of pollutant generation rates, inventories, and physical and chemical characteristics and release rates to the atmospheric carrier.

The Environmental transport model permits an estimate of the air concentration at a particular point in the space-time

continuum.

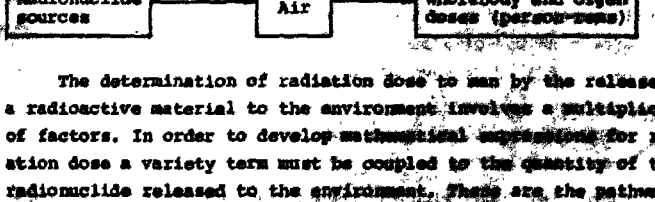
The Dose Model allows an estimate of the energy deposition and biological effectiveness from exposure to the air concentration of radionuclides.

The general calculation scheme of the population dose is presented in table 1.

Table 1

Model for estimating the population doses from a nuclear power plant

Source Term Models	Environmental Transport Models	Dose Models
Radioactive half-lives	Dispersion	Submersion dose
Chemical and physical behaviour of radionuclides	Wet and dry depletion	Inhalation dose
Production rates	Radioactive Decay	Distribution of population
Release rates		



The determination of radiation dose to man by the release of a radioactive material to the environment involves a multiplicity of factors. In order to develop mathematical expressions for radiation dose a variety term must be coupled to the quantity of the radionuclide released to the environment. These are the pathway transfer function (T) and dose conversion factor (F). These terms may differ depending upon the radionuclide (i), pathway (k), body organ (j), and group of people (n) under consideration. In addition, the pathway transfer function will in general be a function

of geographical location and of time.

The fundamental equation for calculation of radiation doses to man from two air pathways (submersion and inhalation) is given in Equation (1).

$$D_{i,k,j,n}(x,\theta,d) = Q_i \cdot T_i(x,\theta,d) \cdot F_{i,k,j,n} \qquad (1)$$

where

$D_{i,k,j,n}(x,\theta,d)$ = The dose rate to organ j of the individuals in the group n located at a point x from the source in a direction d averaged over a sector width of θ radians from nuclide i via pathway k, mrem/year

Q_i = Release rate for nuclide i, pCi/S

$T_i(x,\theta,d)$ = Relative concentration relating quantity of radionuclide i released to its concentration in the air at a point x from the source in a direction d averaged over a sector width θ radians, $pCi/m^3/pCi/S$

$F_{i,k,j,n}$ = Dose conversion factor relating concentration of a radionuclide i in the air to a resultant dose to n-th group of people for organ j via pathway k, $mrem/y \text{ per } pCi/m^3$

k = index of pathway; this report analyses two air pathways:
- submersion in air
- air inhalation

i = index of radionuclides; this report considers 15 radionuclides for submersion in air and 5 radionuclides for air inhalation

j = index of organs; this report considers 2 organs (skin and total body) for submer-

sion and 2 organs for inhalation (thyroid and total body)

n = index of group of people; this report considers three groups of people (children, teenagers and adults) for inhalation and one group for submersion

x = the distance from the source; this report considers distances up to 1000 km from the source

d = the direction from the source; this report examines 12 sectors around the nuclear power plant

θ = the sector width; in this case the sector width is $\frac{\pi}{6}$, i.e. a 12-point compass rose.

The above equation yields the yearly (mrem/y) dose to specific organ j-th individuals in the group n located at a point x from the source, in a direction d, averaged over a sector width of θ radians from nuclide i via pathway k. The population dose in man-rem/year to a specific organ j for individuals in the group n from nuclide i, via pathway k, is determined by multiplying the individual dose to the same organ j, of the same group of people n, from the same nuclide i, via the same pathway k, by the number of the population group n located within the sector in question. Values of the dose at the point (x,θ,d) are assumed to be applicable to all individuals located in that sector (d,θ) from distance $x-\Delta x$ to $x+\Delta x$.

3. SOURCE TERM MODELS

Since Light Water Reactor Plants (LWR) are by far the predominant type of nuclear power plants being purchased and installed in the world [1,4,5] at this present time, they are the major subject of this report. The two predominant types of Light Water Power Reactors currently in use are the Boiling Water Reactor (BWR), so called because it generates steam by direct boiling of water in the reactor core, and the Pressurized Water Reactor (PWR) in which water coolant is not allowed to bulk boil, but produces steam in an external steam generator. The nuclear components of both types are similar. To-day the nuclear fuel used in commercial power reactors of the BWR and PWR types consists of uranium dioxide (UO_2) fuel pellets encapsulated in zircaloy or stainless steel cladding [1].

3.1. Sources and Amounts of Radioactivity Confined in Light Water Power Reactors

The radioactive substances that accumulate in the reactors are primarily the result of three processes

- fission which occurs within the uranium dioxide (UO_2) fuel pellets during reactor operation,
- fission of tramp uranium which occurs outside the fuel cladding,
- neutron activation which is the process in which neutrons are captured by the various non-radioactive atomic nuclei throughout the reactor core region which then becomes radioactive.

Of the three processes, fission within the fuel pellets is by far the most predominant source of radioactivity. Under typical operating conditions the quantity of radioactivity contained in the fuel of a 1000 MWe plant is nearly 1000 times greater than the quantity of radioactivity in activation products throughout the core region of the plant, as well as fission products of tramp uranium [3,4].

The inventory of radioactivity in any given core is a complicated function of the operating history of the reactor, the power level, core configuration, etc.

3.2. Radioactive Effluents from LWR

3.2.1. Introduction

During normal operation of a LWR there are three kinds of radwaste:

- Gaseous radwaste
- Liquid radwaste
- Solid radwaste

In this report only gaseous radwaste is considered and only some isotopes of iodines and noble gases which constitute the major radiation hazards in gaseous radwaste [4,5,6].

LWRs require equipment for the control of gaseous radioactive materials. The gaseous radwaste treatment systems presented in this report illustrate the methods used to control the effluent gases to the environment. They range from minimal treatment with attendant relatively high releases to advanced and complex treatment systems for which the releases are very low.

In all 16 conceptual gaseous radwaste systems are presented [4,5] to cover the range of the state-of-the-art treatment technology for BWR and PWR systems considering 7 cases for BWR Gaseous Radwaste Treatment Systems and 9 cases for PWR. The cases in each category show the effects of varying the types and degree of waste treatment provided. Case No. 1 in each category is intended to provide a basis for comparison to demonstrate the effectiveness of the subsequent treatment system. The succeeding cases were developed to evaluate modifications in radwaste systems to reduce radioactive emissions.

In considering the discharge of gaseous radioactive effluents from a LWR it is necessary to consider certain distinctions between BWR and PWR design features.

3.2.2. Origin of the Gaseous Radwaste

3.2.2.1. BWR Systems. In all BWRs the coolant is circulated through the reactor core where steam is produced. The steam is then routed through the turbine, condensed, and the condensate returned to the core. Separate side streams of primary coolant are withdrawn from the primary system, processed through the reactor cleaning system, and returned to the reactor.

The principal mechanism that affect the concentrations of radioactive materials in the primary coolant are

- fission product leakage to the coolant because of defects in the fuel cladding,
- activation products in the core.

The vast majority of the radionuclides produced by fission are retained within the pellets until the fuel is eventually removed from the reactor and reprocessed. Some of the more volatile (krypton, xenon and iodines) fission products diffuse out of the fuel pellets and normally occupy the annular space between the fuel and cladding. During reactor operation cladding defects can result from mechanical or thermal stresses, corrosion and other causes and allow escape of small amounts of the volatile fission products into the primary coolant. Fission products also enter from the tramp uranium on the cladding surfaces, while activation products are generated in the reactor core.

Gaseous radwastes are removed from the primary coolant to the atmosphere by the following ways (which are shown in figure 3-1):

- steam-jet air ejectors
- turbine gland seal system
- reactor building ventilation system
- turbine building ventilation system
- mechanical vacuum pump
- radwaste building ventilation system.

3.2.2.2. PWR Systems. In PWRs the primary coolant circulates in a closed circuit, steam being generated in a secondary circuit. The steam expands through the turbine and is then condensed and returned to the steam generators. The primary coolant water flows back to the reactor core.

For PWRs the gaseous radioactive wastes are classified as follows:

- Primary coolant: Primary coolant gases consist of the gases that are stripped from the plant liquid during normal operations, from the reactor coolant during shutdown, and from the volume control tank for the cover gas supply

- Secondary coolant: Secondary coolant gases consist of the gases vented from the steam generator blowdown flash tank and from the steam-jet air ejector exhaust.

- Building ventilation: Gaseous wastes released from the building ventilation system consist of the gases that are volatilized when the primary coolant leaks into the reactor containment building, or into the auxiliary building which contains the radwaste treatment equipment. Gases containing radioactive material are also released from steam leakage into the turbine building.

Primary Coolant

The principal mechanisms that affect the primary coolant activity are the same as for the BWRs

- fission product leakage to the coolant and fission product generation in tramp uranium
- generation of the activation products in the core.

The primary coolant is continuously purified by the passing of a side stream through filters and demineralizers in the reactor coolant treatment systems (RCTS). Radioactive gases stripped from the primary coolant by degassification are normally collected in pressurized storage tanks and held for radioactive decay prior to release to the environment. Alternative treatment methods include charcoal delay, cryogenic destillation and cover gas recycle system.

Due to leakage through valve stems and pump shaft seals some coolant escapes into the containment and into the auxiliary buildings. A portion of the leakage evaporates, thus contributing tc the gaseous source term. The amount of leakage entering the gaseous phase is dependent upon the temperature and pressure at the point where the leakage occurs. Most of the noble gases enter the gas phase whereas iodine partitions into the gaseous and liquid phases.

Secondary Coolant

Leakage of primary coolant into the secondary coolant in the steam generator is the only source of radioactivity in the secondary coolant system. Steam leakage from the secondary systems pro-

vides significant inputs to the gaseous radwaste treatment systems. For the reactors considered in this evaluation a primary-to-secondary leakage rate of 50 kg/day was assumed [4,5]. Sources of radioactive wastes from the secondary system are the offgases from the turbine condenser, vent gases from the turbine gland seal and vent gases from the steam generator blowdown. The radwaste effluents from PWRs are shown schematically in figure 3-2.

3.2.3. Gaseous Radwaste Treatment Processes

Gaseous Radwaste Treatment systems are designed to control, measure and reduce the amounts of radioactive material in gaseous effluents from a nuclear power plant. The degree of treatment should be based on a cost analysis balancing treatment requirements against the costs of alternative treatment processes.

Several treatment methods are used to reduce radioactivity materials in gaseous effluents:

- holdup of the waste to permit radioactive decay
- reducing the source of radioactivity entering the effluent steam
- selectively removing radioactive materials prior to discharge.

One of the methods used to reduce radioactivity in gaseous effluents is to delay the release of a gaseous stream to permit the radionuclides to decay to an acceptable level. In this report systems with holdup times ranging from 2 minutes to 90 days have been considered [4,5]. Holdup pipes providing a 2-minute delay are used for BWR gland seal vent releases. The main condenser off-gas holdup line for a BWR is designed for a 30-minute holdup.

The 30-minute holdup line used in early BWR facilities provided little reduction of radioactive gaseous effluents with half-lives exceeding a few minutes. Similarly, the PWR base case utilizes a 7-day pressurized holdup tank to delay primary system gases. The practical difference in delay times between the BWR and PWR cases is the result of the difference in the volumetric flow rates. BWR off-gas flow is approximately 340 m^3/h whereas PWR primary system gas stripping flow is approximately 0.17 m^3/h [4].

In the PWR cases evaluated, pressurized storage tanks are

used to provide up to a 60-day delay for primary system gases. Alternative treatment systems, i.e. cryogenic destillation, cover gas recycle and charcoal systems, were used to provide longer delay times and to reduce the volumetric requirements of holdup tanks.

For BWR off-gas systems additional treatment processes are necessary to increase holdup times from a few minutes to hours or days. In evaluation of off-gases from the steam-jet air ejector a catalytic recombiner is used to decrease the BWR off-gas volumetric flow rate from 340 m^3/h to 34 m^3/h to reduce the size of components used for subsequent treatment [4]. Treatment processes range from charcoal adsorbers to large charcoal delay systems and cryogenic distillation systems to holdup the noble gases and to provide almost complete removal of iodine. Charcoal delay trains and cryogenic distillation units provide delay times up to 90 days [4].

Another method used to reduce radioactive gaseous releases is to reduce gaseous leakage into a building atmosphere. In the early BWR facilities (e.g. BWR Gas Case No. 1) the radioactive material released into the turbine building ventilation air was insignificant as compared with the total radioactive gases released from the facility [4,5]. In the BWR facilities employing more advanced treatment systems (e.g. BWR Case No. 5) the radioactive materials present in the turbine building ventilation become significant. The radioactivity released into the turbine building ventilation air can be reduced either by treatment prior to discharge or taking measures to reduce the radioactivity entering the building atmosphere. The steam leakage and thus the radioactive gas leakage can be reduced by using more efficient seals on valve stems in steam service [4].

Treatment equipment with the capability of selectively removing specific radionuclides may also be used. Charcoal adsorbers are effective for the removal of radioiodine from air streams. The charcoal adsorbers considered in this report are deep-bed units capable of reducing the iodine concentrations by a factor of 10 [4]. Charcoal decay systems are large charcoal beds which removes iodine and selectively delay the flow of noble gases. Their performance is dependent upon:

- the flow rate
- the temperature
- the moisture content of the stream.

The performance is also influenced by the type, mass, and physical characteristics of the charcoal used, the impurities in the carrier gas, the system pressure and the carrier gas velocity.

The length of time a nuclide is delayed increases with (1) the amount of charcoal used, (2) decreasing temperature and humidity of the charcoal bed, (3) decreasing carrier gas flow rate.

In the cases considered in this report the holdup times were changed by

1) reducing gas flow rate by recombining the hydrogen with the oxygen into water
2) reducing the temperature and relative humidity of the carrier gas.

In this report charcoal delay systems provide nearly complete removal of iodine, a delay of 1 to 2 days for Kr and a delay of 13 to 35 days for Xe [4].

A cryogenic distillation unit may be used to selectively remove radionuclides. In a cryogenic system the waste gas stream temperature is reduced to approximately -195°C with liquid nitrogen. The Kr, Xe and I are separated from the carrier gas by distillation. These liquefied radionuclides are stored for radioactive decay prior to release. Catalytic recombiners are used to reduce process volumes and increase operating safety by forming water from hydrogen and oxygen.

A summary of the variables for BWR and PWR gaseous radwaste treatment systems is presented in table 3-1 (BWR-7 cases) and table 3-2 (PWR-9 cases). The flowsheets in figures 3-3 through 3-9 show how the BWR gaseous wastes are treated for seven cases considered. The flowsheets in figures 3-10 through 3-18 show how the PWR gaseous wastes are treated for nine cases considered.

3.2.4. Principal Parameters Used in the Source Term Calculation

It is necessary to obtain basic parameters when calculating the radioactive source terms expected from a nuclear power reactor. The parameters assumed in this report are identical with those used

in licensing evaluations of radioactive waste treatment systems in the U.S. [4,5]. The source term parameters are based on available operating reactor data, laboratory data and on field testing combined with judgement as to the most practical application of the available information. When necessary, theoretical considerations and engineering judgement have been applied. In general parameters which provide realistic radioactive source terms based on state-of-the-art technology have been presented [1,4,5].

The estimation of release rates (pCi/s) of 10 isotopes of noble gases and iodines in gaseous effluents for a 1000 MWe reactor - type BWR and PWR - is presented in table 3-3. The values are given for seven BWR Gaseous Radwaste Treatment cases and nine PWR Gaseous Radwaste Treatment cases [4,5]. The total annual costs of particular radwaste systems are also presented in the table 3-3 [5]. These costs are stated in terms of early 1973 dollars, no attempt has been made to include the effect of inflation.

Table 3-1

Summary of variables for BWR gaseous radwaste treatment systems[a]

Principal sources	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7
Steam-jet air ejector	30-min holdup HEPA filter, 100-meter stack	Catalytic recombiner, 30-min holdup, charcoal adsorber, 100-meter stack	Catalytic recombiner, 30-min holdup, charcoal delay system, 13-day Xe, 18-hr Kr	Catalytic recombiner, 30-min holdup, charcoal delay system 13-day Xe, 18-hr Kr	Catalytic recombiner, 30-min holdup, charcoal delay system, 13-day Xe, 18-hr Kr, 100-meter stack	Catalytic recombiner, 30-min holdup, charcoal delay system, 52-day Xe, 3-day Kr	Catalytic recombiner, 30-min holdup, cryogenic distillation 90-day holdup tank
Turbine gland seal system	Primary steam, 2-min holdup, 100-meter stack	Primary steam, 2-min holdup 100-meter stack	Clean steam	Clean steam	Clean steam	Clean steam	Clean steam
Reactor building ventilation	No treatment	100-meter stack	Charcoal adsorber	Charcoal adsorber	Charcoal adsorber 100-meter stack	Charcoal adsorber	Charcoal adsorber
Turbine building ventilation	No treatment	No treatment	Clean steam on valves 24 inches in dia. and larger	Clean steam on valves 2-1/2 inches in dia. and larger, internal recirculation, charcoal adsorber	100-meter stack	Clean steam on valves 2-1/2 inches in dia. and larger	Clean steam on valves 2-1/2 inches in dia. and larger, internal recirculation, charcoal adsorber

[a] All gaseous effluents released through roof or building vent unless a stack is indicated.

Table 3.2

Summary of variables for PWR gaseous radwaste treatment systems[a]

Principal sources	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8	Case 9
Primary system gases	7-day holdup pressurized storage tanks, HEPA filters	45-day holdup pressurized storage tanks, HEPA filters	45-day holdup pressurized storage tanks, HEPA filters	60-day holdup pressurized storage tanks, HEPA filters	Catalytic recombiner, charcoal delay system, pressurized storage tanks -total holdup 60 days Xe 31 days Kr	Catalytic recombiner cryogenic distillation, 90-day holdup pressurized storage tanks	45-day holdup pressurized storage tanks, HEPA filters	Cover gas recycle 90-day holdup pressurized storage tanks	60-day holdup pressurized storage tanks, HEPA filters 100-meter stack
Secondary system gases									
Condenser air ejector	No treatment	No treatment	Charcoal adsorber	Charcoal adsorber	Charcoal adsorber	Charcoal adsorber	No treatment	Charcoal adsorber	Charcoal adsorber 100-meter stack
Steam generator blowdown tank	Vent to atmosphere	Vent thru condenser	Vent thru condenser	Vent thru condenser	Vent thru condenser	Vent to condenser	No blowdown (once-through steam generator)	Heat exchanger blowdown tank, ion exchange	Vent thru condenser 100-meter stack
Containment purge									
Internal cleanup	No treatment	4,000-cfm charcoal adsorber	20,000-cfm charcoal adsorber	20,000-cfm charcoal adsorber	20,000-cfm charcoal adsorber	No treatment	20,000-cfm charcoal adsorber	20,000-cfm charcoal adsorber	20,000-cfm charcoal adsorber
Purge vent	No treatment	No treatment	No treatment	Charcoal adsorber	Charcoal adsorber	Charcoal adsorber	Charcoal adsorber	Charcoal adsorber	Charcoal adsorber
Auxiliary building ventilation	No treatment	No treatment	No treatment	Charcoal adsorber	Charcoal adsorber	Charcoal adsorber	Charcoal adsorber	Charcoal adsorber	Charcoal adsorber 100-meter stack
Turbine building ventilation	No treatment	No treatment	No treatment	Clean steam on valves 2-1/2 inches in dia. and larger	No treatment	No treatment	No treatment	No treatment	Charcoal adsorber 100-meter stack

[a]All gaseous effluents released through roof or building vent unless a stack is indicated.

Table 3.3

Radionuclide release rates for 1000 MWe light water power reactor, pCi/a

Nuclide	Boiling water reactor							Pressurised water reactor								
	I	II	III	IV	V	VI	VII	I	II	III	IV	V	VI	VII	VIII	IX
^{85m}Kr	3.65 (9)	3.65 (9)	2.11(8)	2.11(8)	2.11(8)	1.91(6)	9.66(5)	3.13(5)	3.13(5)	3.13(5)	3.13(5)	2.61(5)	3.13(5)	$3.13 \cdot 10^5$	2.61(5)	3.13(5
^{85}Kr	4.01 (7)	2.01 (7)	2.01(7)	2.01(7)	2.01(7)	2.01(7)	1.96(7)	2.53(7)	2.53(7)	2.53(7)	2.53(7)	2.53(7)	2.53(7)	2.53(7)	2.51(7)	2.53(7
^{87}Kr	8.87 (9)	8.87 (9)	1.51(6)	7.31(5)	1.77(6)	2.61(5)	2.48(6)	1.83(5)	2.09(5)	2.09(5)	1.57(5)	2.09(5)	1.57(5)	2.09(5)	1.57(5)	2.09(5
^{88}Kr	1.12(10)	1.12(10)	1.26(8)	1.26(8)	1.26(8)	3.87(5)	3.13(6)	5.74(5)	5.74(5)	5.74(5)	5.74(5)	4.70(5)	5.74(5)	5.74(5)	4.70(5)	5.74(5
^{131m}Xe	1.75 (7)	1.75 (7)	8.09(6)	8.09(6)	8.09(6)	2.22(6)	7.83(4)	1.17(7)	1.64(6)	1.67(6)	9.4 (5)	1.83(6)	5.22(5)	1.67(6)	3.13(5)	9.4 (5
^{133m}Xe	2.43 (8)	2.43 (8)	4.44(6)	4.44(6)	4.44(6)	>2.61(4)	2.61(4)	4.44(6)	7.05(5)	7.05(5)	7.05(5)	1.57(5)	7.05(5)	7.05(5)	1.57(5)	7.05(5
^{133}Xe	6.79 (9)	1.31 (9)	1.31(9)	1.31(9)	1.31(9)	1.31(8)	6.06(7)	1.11(9)	7.05(7)	7.05(7)	6.26(7)	1.31(7)	6.26(7)	7.05(7)	1.02(7)	6.26(7
^{135}Xe	1.91(10)	1.92(10)	1.10(7)	1.10(7)	1.15(7)	9.66(6)	1.15(7)	9.92(5)	9.92(5)	9.92(5)	9.92(5)	6.26(5)	9.92(5)	9.92(5)	6.26(5)	9.92(5
^{131}I	3.92 (5)	1.02 (4)	7.05(3)	7.05(3)	8.87(3)	1.8 (3)	4.18(2)	1.11(4)	8.61(3)	1.41(3)	7.81(2)	1.31(3)	2.09(3)	1.46(2)	1.15(3)	7.31(2
^{133}I	2.24 (6)	5.76 (4)	3.92(4)	3.92(4)	4.96(4)	1.02(4)	1.33(3)	1.54(4)	4.96(3)	9.92(2)	5.74(2)	9.14(2)	9.14(2)	1.7 (2)	8.09(2)	5.74(2
Annual fuel cycle costs a) thousands	138	358	657	943	820	715	1130	68	90	244	442	289	745	264	400	731

a) These annual costs are applicable for 1200 MWe BWR or PWR radwaste system.

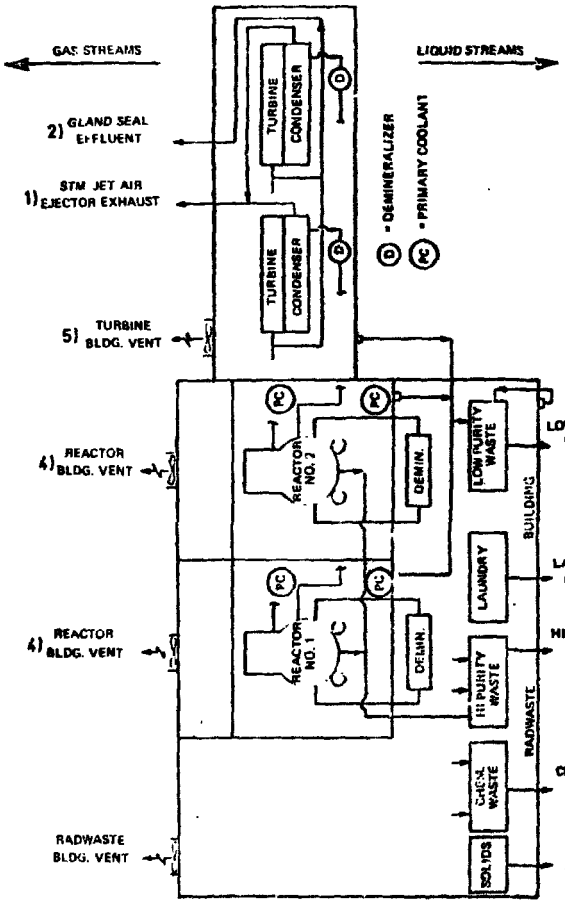


FIGURE 3.1 LIQUID AND GASEOUS RADWASTE EFFLUENTS FROM BOILING WATER REACTORS

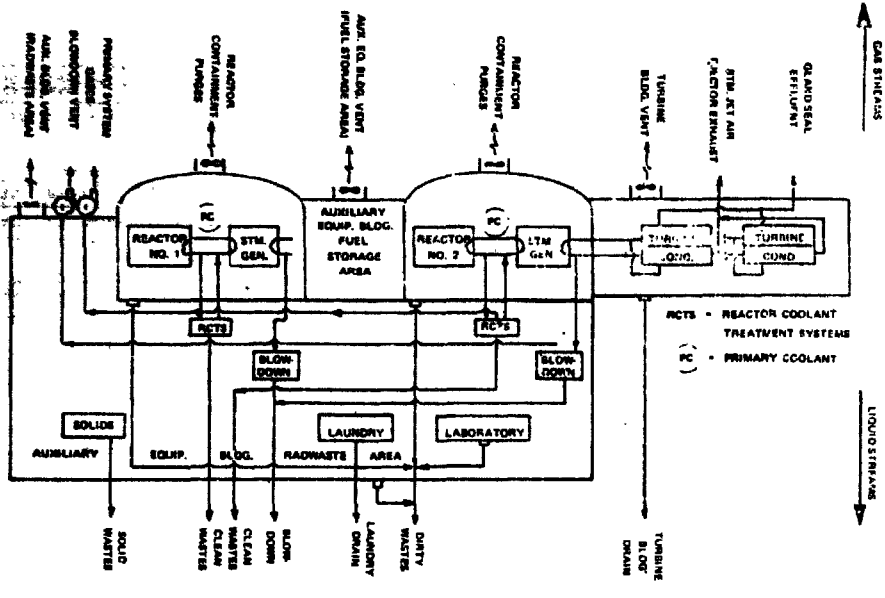


FIGURE 3.2 LIQUID AND GASEOUS RADWASTE EFFLUENTS FROM PRESSURIZED WATER REACTORS

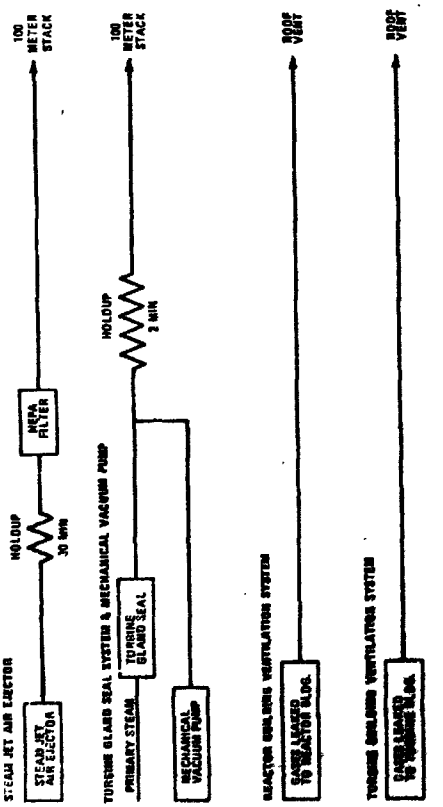


FIGURE 3.3 RADWASTE TREATMENT SYSTEM FOR BWR GAS CASE NO. 1

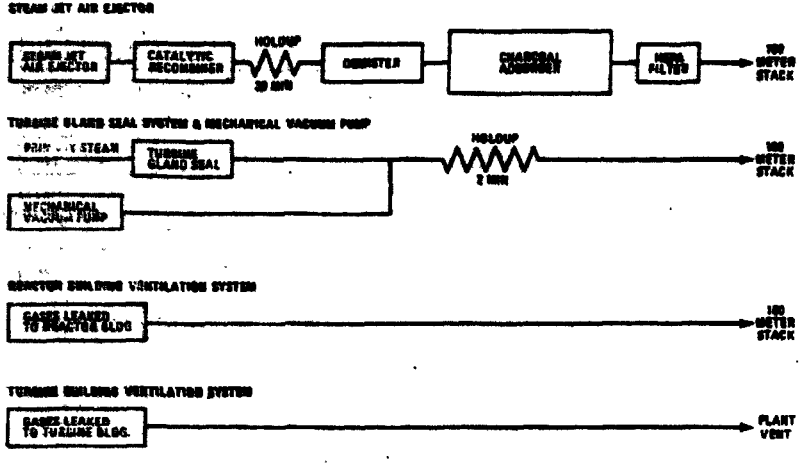


FIGURE 3.4 RADWASTE TREATMENT SYSTEM FOR BWR GAS CASE NO. 2

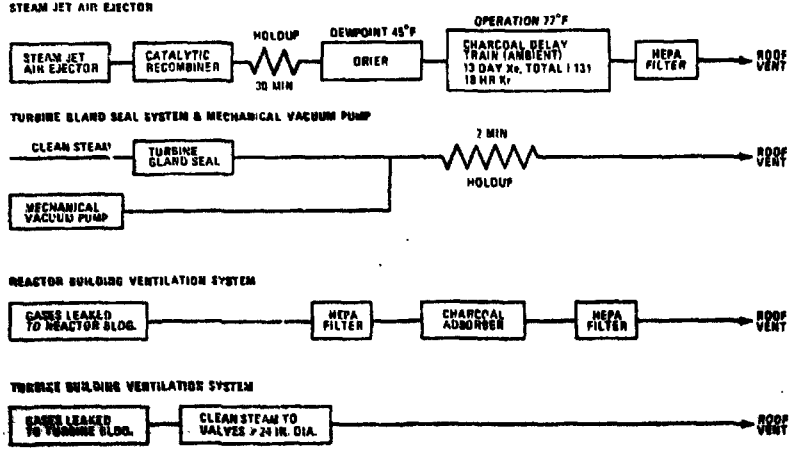


FIGURE 3.5 RADWASTE TREATMENT SYSTEM FOR BWR GAS CASE NO. 3

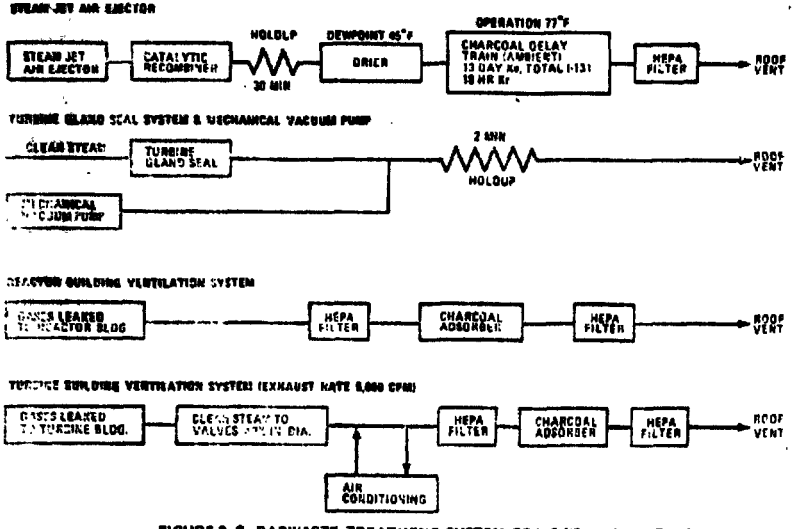


FIGURE 3.6 RADWASTE TREATMENT SYSTEM FOR BWR GAS CASE NO. 4

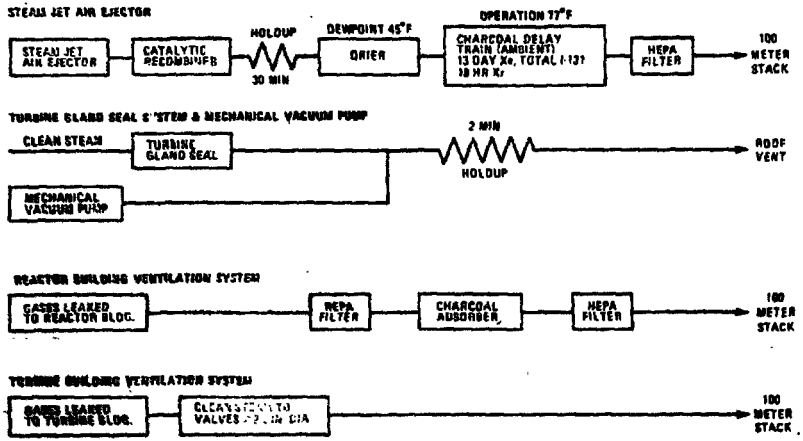


FIGURE 3.7 RADWASTE TREATMENT SYSTEM FOR BWR GAS CASE NO. 5

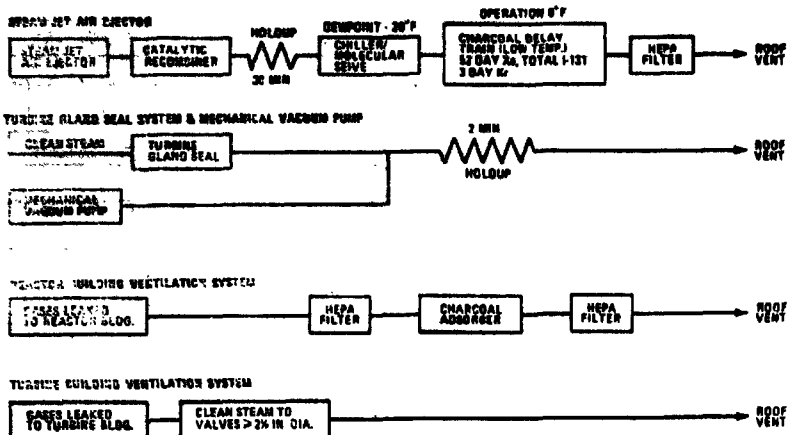


FIGURE 3.8 RADWASTE TREATMENT SYSTEM FOR BWR GAS CASE NO. 6

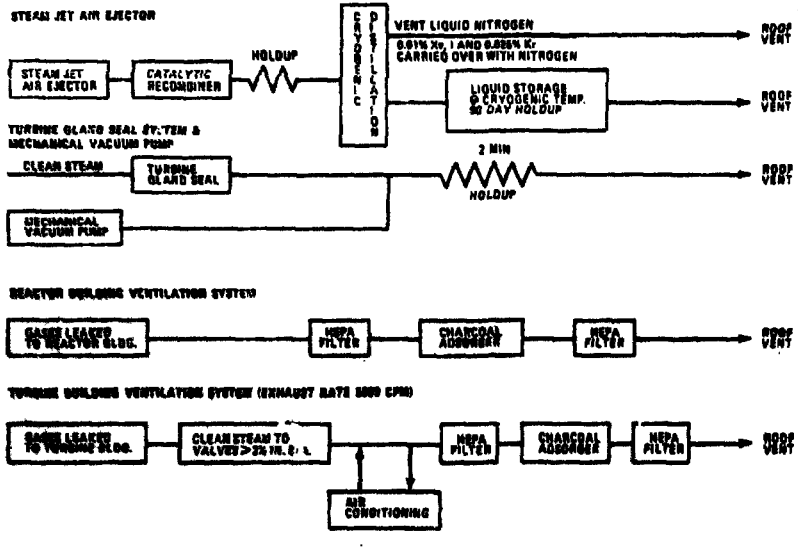


FIGURE 3.9 RADWASTE TREATMENT SYSTEM FOR BWR GAS CASE NO. 7

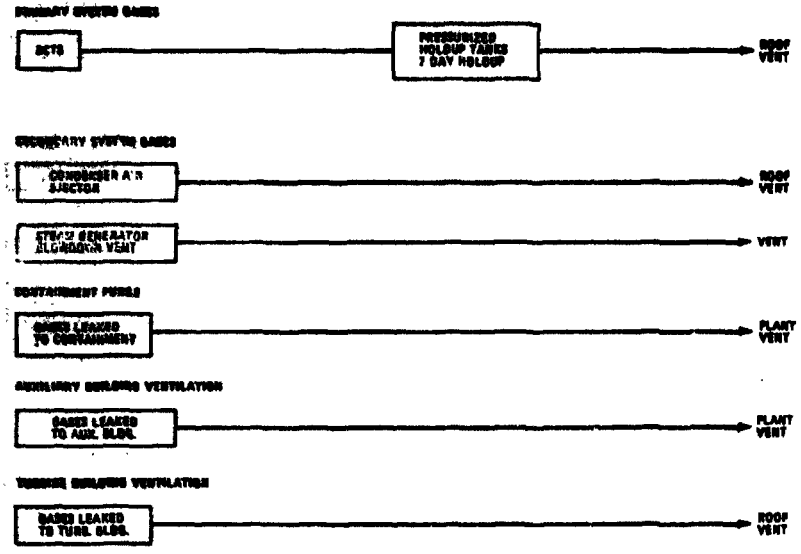


FIGURE 3.10 RADWASTE TREATMENT SYSTEMS FOR PWR GAS CASE NO. 1

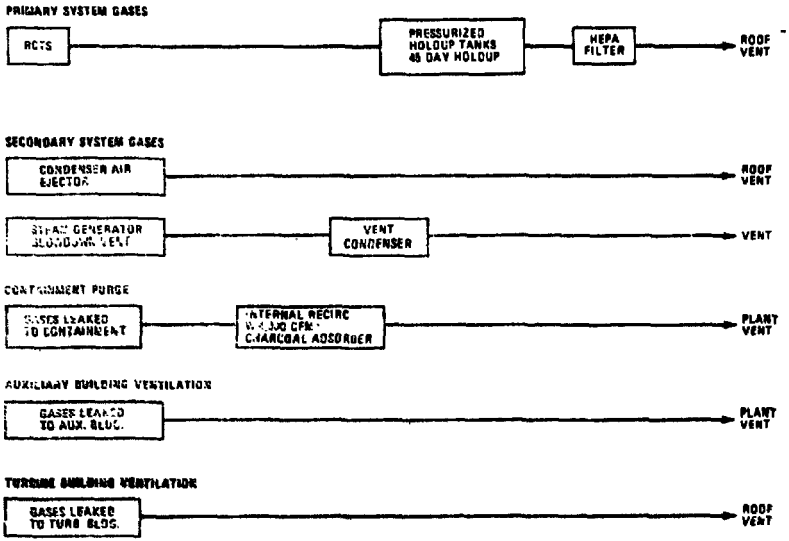


FIGURE 3.11 RADWASTE TREATMENT SYSTEMS FOR PWR GAS CASE NO. 2

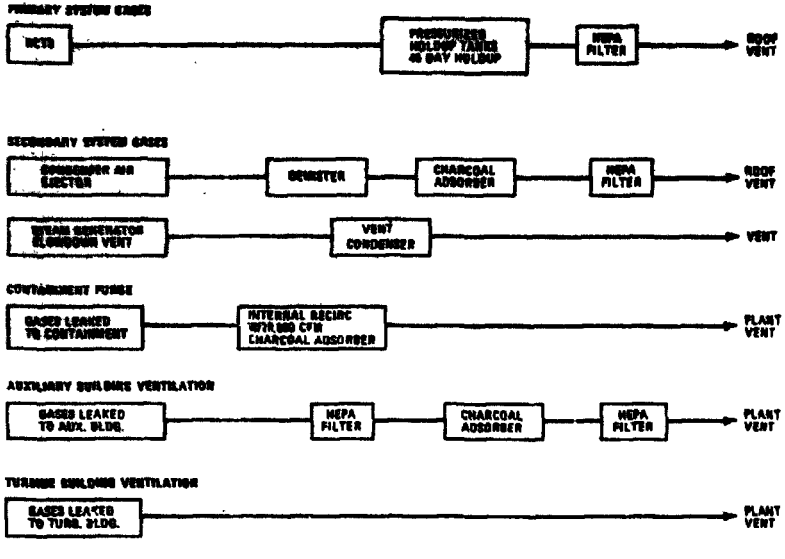


FIGURE 3.12 RADWASTE TREATMENT SYSTEMS FOR PWR GAS CASE NO. 3

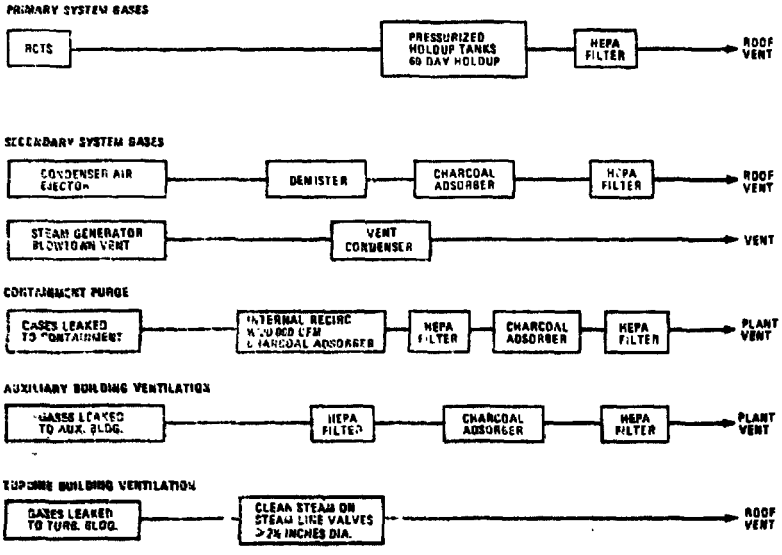


FIGURE 3.13 RADWASTE TREATMENT SYSTEMS FOR PWR GAS CASE NO. 4

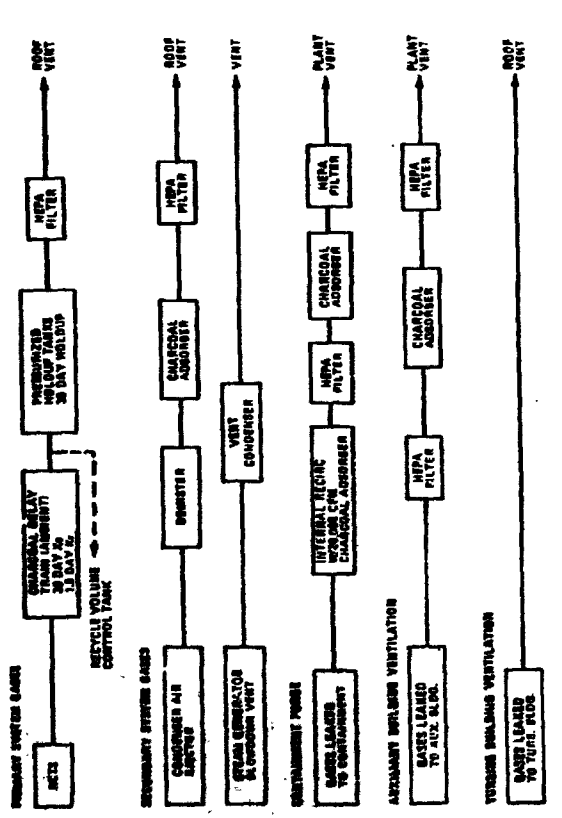


FIGURE 3.14 RADWASTE TREATMENT SYSTEMS FOR PWR GAS CASE NO. 8

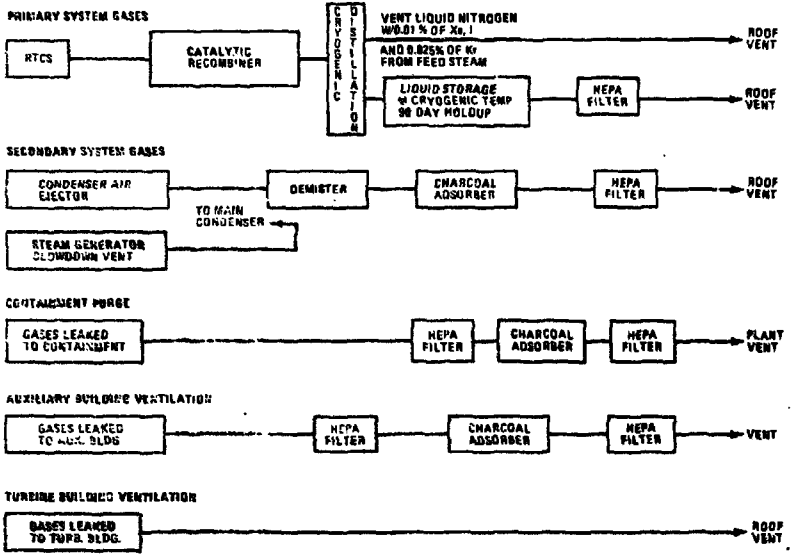


FIGURE 3. 15 RADWASTE TREATMENT SYSTEMS FOR PWR GAS CASE NO. 8

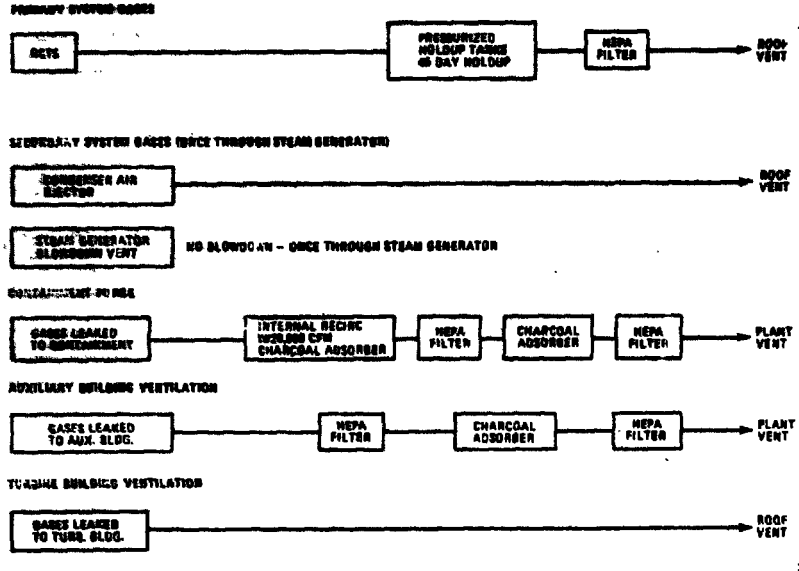


FIGURE 3.16 RADWASTE TREATMENT SYSTEMS FOR PWR GAS CASE NO. 7

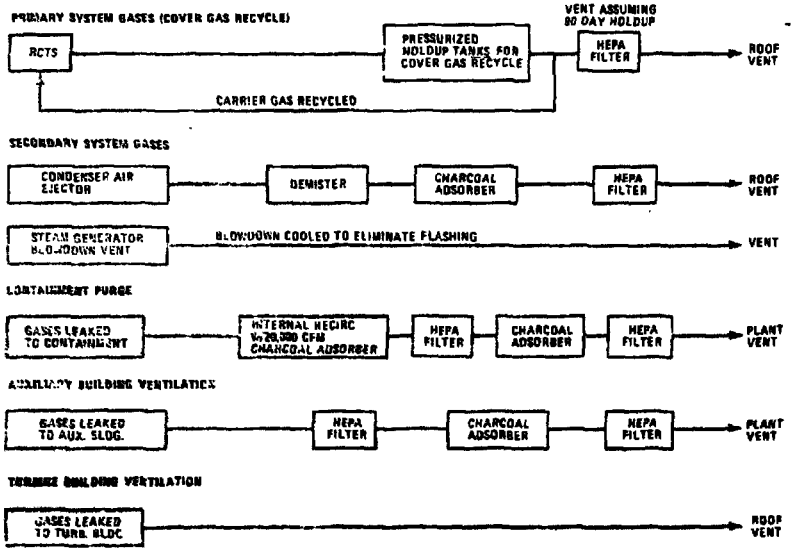


FIGURE 3.17 RADWASTE TREATMENT SYSTEMS FOR PWR GAS CASE NO. 8

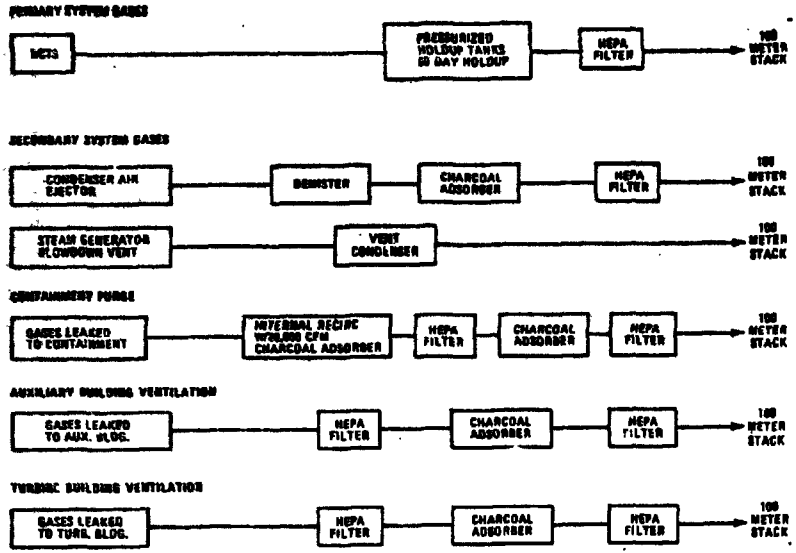


FIGURE 3.18 RADWASTE TREATMENT SYSTEMS FOR PWR GAS CASE NO. 8

4. ENVIRONMENTAL TRANSPORT MODEL

4.1. Introduction

Radioactivity materials such as aerosols, vapours or gases released in gaseous effluents from a nuclear power plant become dispersed in the surrounding air through variations in wind direction and turbulence of the atmosphere. The average concentration of radioactive material in air will depend upon the amount of release and the joint distribution of wind speed, wind direction and atmospheric stability for the site. Geographical features including hills, valleys and large bodies of water greatly influence the dispersion patterns around a site by affecting wind directions and stability conditions. Surface roughness, including vegetation cover, also affects the degree of mixing [7].

Airborne aerosols and vapours in the atmosphere are eventually reduced by deposition or by the scavenging action of precipitation. Noble gases are absorbed to some extent by precipitation but most simply continue to mix with the atmosphere. In all cases the amount of radioactive material released will decrease by radioactive decay.

In practical application there is frequently a distinction between local and regional dispersion. However, there is no generally recognized definition of the local and the regional range. Since the range concerned is dependent on the properties of the source and on the specific environmental conditions, any final determination of the range limits would be problematical. Therefore, the distinction between local and regional dispersion should be established according to the practical applications. Typical examples of local dispersion problems are environmental impact studies of single sources and assessments of the critical population group. More far-reaching environmental studies in connection with planning for area use on which the superimposed effects of a large number of sources are to be taken into consideration, or analysis of the population doses, are characteristic problems of regional dispersion.

The local range would in general correspond to a short time period after release before appreciable mixing or diffusion has occurred; the physical limits of the cloud will be quite sharply

defined. The cloud will have a limited size and steep concentration gradients. Consequently the effect of the release at near downwind locations may be quite critically affected by minor topographical features (i.e. buildings, hills and trees) by minor fluctuations in meteorological variables (i.e. wind direction, stability category, wind speed, etc.) and by release parameters (i.e. finite size of a source and rate of release). In the local range, the requirements for the application of the dispersion equations are generally fulfilled, and the diffusion is known with sufficient accuracy [7,8]. As regards the regional dispersion as a cloud moves farther from the point of release, continual diffusion will cause the concentration gradients to decrease. At greater distances the cloud will be relatively insensitive to local irregularities, but will be affected by major topographical features, gross changes in the meteorological conditions, limitation of vertical dispersion, and losses of pollutants due to disposition to make use of the dispersion concept up to areas of some hundred km extension. The decreasing reliability of the dispersion calculations for large/regional distances is caused by shortcomings of the model rather than by the decreasing accuracy of the diffusion parameters [7]. An essential fact is that the requirement of homogeneous dispersion conditions is not fulfilled in large regions since, on the one hand, systematic variations in wind direction due to Coriolis forces have to be considered, and on the other hand the meteorological conditions are subject to change during transport times of several hours. Frequent shifts of wind direction and changes in stability and wind speed may cause the plume to move to unforeseen areas.

The air transport model, presented in this report, simulates the spreading of released radionuclides into the environment via atmosphere mechanisms, and uses a one-dimensional version of the normal equation to estimate vertical diffusion of the radionuclides based on meteorological variables assessed on a yearly average basis [8,9,10,11]. Lateral distribution on an annual average basis is assigned individually to each of 12 compass-point sectors. Depletion of the airborne radionuclides by wet and dry precipitation processes is considered. During the transit of radionuclides, depletion by radioactive decay is taken into

account. The scheme of this model is shown in figure 4-1.

The air transport model, presented in this report, is designed to calculate the atmospheric radionuclide concentration at a particular point to distances up to about 1000 km from the nuclear power plant.

The general expression for calculation of the atmospheric radionuclide concentration is the following [12,13]:

$$C_i = Q_i \times R_i \times \left(\sum_{S=1}^{6} 0.01 \cdot f_s \cdot M_s \cdot F_{i,s} \right) \qquad (4\text{-}1)$$

where

C_i = the atmospheric concentration of i radionuclides at the location of interest; pCi/m^3

Q_i = release rate for nuclide i; pCi/s

f_s = the frequency of the occurrence of particular stability condisions A,B,C,D,E, and F; percent

M_s = meteorological dispersion factor for the location of interest for particular stability condition "s" $[pCi/m^3]/[pCi/s]$

$F_{i,s}$ = the correction factor for depletion due to dry and wet deposition for radionuclide "i" at the location of interest for particular stability condition "s"

R_i = the correction factor for depletion due to decay for radionuclide "i" at the location of interest.

When both sides of the equation are divided by Q_i, we obtain:

$$T_i = \frac{C_i}{Q_i} = \left(\sum_{s=1}^{6} 0.01 \; f_s \cdot M_s \cdot F_{i,s} \right) \cdot R_i \qquad (4\text{-}2)$$

where

$T_i = \frac{C_i}{Q_i}$ - Pathway model conversion factor relating the quantity of radionuclide "i" released to its concentration in the air at the location of interest, $[pCi/m^3]/[pCi/s]$.

4.2. Meterorological Dispersion Factor

The derivation of the fundamental diffusion equation is based on the statistical theory of turbulent diffusion by Taylor [8], which has the advantage of mathematical simplicity, flexibility, and easy applicability.

The concentration, χ, of gas or aerosols at x,y,z from a stationary case of continuous emission from elevated sources at the level H, and on the assumption that [8,11]:

- the plume spread has a Gaussian distribution in both the horizontal and vertical plans with standard deviation of plume concentration distributions on the horizontal and vertical of σ_y and σ_z, respectively, m
- the mean wind spread affecting the plume is u, m/s
- the uniform emission of radionuclides is Q/pCi/s
- the total reflection of the plume takes place at the earth's surface (i.e. there is no deposition or reaction at the surface)

is given by the following equation:

$$\chi(x,y,z) = \frac{Q}{2\pi\sigma_y\sigma_z u} \exp\left[-\frac{1}{2}\frac{y^2}{\sigma_y^2}\right] \cdot \left\{\exp\left[-\frac{1}{2}\frac{(z-H)^2}{\sigma_z^2}\right] + \exp\left[-\frac{1}{2}\frac{(z+H)^2}{\sigma_z^2}\right]\right\}. \qquad (4\text{-}3)$$

This equation is valid where diffusion in the direction of travel can be neglected, that is there is no diffusion in the x direction. This may be assumed if the release is continuous, or if the duration of release to or greater than the travel time (x/u) from the source to the location of interest. It should also be noticed that the assumption of a wind velocity being constant throughout the layer of dispersion is not consistent with experience [7].

Furthermore, a height dependence of the standard deviation must be expected. Nevertheless, measurements in plumes have proved the fact that the horizontal concentration distributions in gen-

eral have a nearly Gaussian distribution, while the vertical concentration profile is apparently at least not much in contradiction to the Gaussian distribution [7,8,11]. Consequently the problem of evaluating the diffusion lies in an adequate determination of the standard deviation.

If the reactor is located on the ground level (z = 0), then

$$\chi(x,y) = \frac{Q}{\pi\sigma_y\sigma_z u} \exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right] \exp\left[-\frac{1}{2}\left(\frac{H}{\sigma_z}\right)^2\right] . \qquad (4\text{-}4)$$

The ground-level crosswind-integrated concentration is often of interest. For a continuous elevated source this concentration is obtained by integrating (4-4) with respect to y from (-∞ to +∞) which yields (4-5)

$$\chi_{cwI} = \left(\frac{2}{\pi}\right)^{0.5} \frac{Q}{\sigma_z u} \exp\left[-\frac{1}{2}\left(\frac{H^2}{\sigma_z^2}\right)\right] . \qquad (4\text{-}5)$$

For a source that emits at a constant rate from hour to hour and day to day estimates seasonal or annual average concentrations can be made for any distance in any direction if stability wind "rose" data are available for the period under consideration. A wind rose gives the frequency of occurrence for each wind direction (usually from 12 to 16 points) and wind speed class (usually from 4 to 9 classes of wind speed).

If the wind directions are taken to n points and it is assumed that the wind direction within each sector is distributed randomly over a period of a month, season or year, it can further be assumed that the effluent is uniformly distributed in the horizontal direction within the sector [2,3,8]. The appropriate equation for average concentration is then received through multiplication of equation (4-5) by the frequency of wind directions in a given sector and divided by the width of that sector at the distance of interest, which gives

$$\bar{\chi}_{LTAS} = \left(\frac{2}{\pi}\right)^{0.5} \frac{0.01 \cdot f \cdot Q}{\sigma_{zs}\bar{u}(2\pi x/n)} \exp\left(-\frac{1}{2}\frac{H^2}{\sigma_{zs}^2}\right) . \qquad (4\text{-}6)$$

Dividing both sides by Q, this equation gives:

$$M_s = \frac{\bar{\chi}_{LTAS}}{Q} = \left(\frac{2}{\pi}\right)^{0.5} \frac{0.01\ f}{\sigma_{zs}\bar{u}\left(\frac{2\pi x}{n}\right)} \exp\left(-\frac{1}{2}\frac{H^2}{\sigma_{zs}^2}\right) . \qquad (4\text{-}7)$$

Equation (4-7) is the basic equation used in these calculations.

In the equation cited above the following nomenclature is used:

$\bar{X}_{LTAS}$ = the average air concentration in a particular sector of the compass during stability condition s. If the compass rose is divided into n sectors, each sector is characterized by the sector angle θ and frequency value f. If n = 12, the sector angle is 30°. The average air concentration is usually expressed as picocurie per cubic meter; pCi/m^3.

Q = the release rate of effluent into the atmosphere ...., pCi/s.

$M_s = \frac{\bar{X}_{LTAS}}{Q}$ - average meteorological dispersion factor in a particular sector of the compass during stability condition s, $[pCi/m^3]/[pCi/s]$.

σ_{zs} = the statistical diffusion parameter representing the standard deviation of vertical distribution of pollutant material in the airborne effluent plume during stability condition s ....., m

The accurate description of σ_z is given in point 4.2.1.

$\bar{u}$ = the mean wind speed for each wind direction sector, m/s.

f = the frequency of the occurrence of wind direction for the compass sector being considered, %.

n = number of compass rose sectors considered, in this report n = 12.

H = stack height or emission point above the surface, m.

x = distance downwind of source, m.

4.2.1. Diffusion-Parameter - σ_z

σ_z is the statistical diffusion parameter representing the standard deviation of vertical distribution of pollutant material

in the airborne effluent plume - the diffusion parameter. This is usually assumed to be a Gaussian distribution for relatively short distances [2,3,8], but for long travel distances a stable layer existing above an unstable layer will have the effect of restricting the vertical diffusion. The dispersion calculation can be modified for this situation by considering the height of the base of the stable layer L (mixing layer). At a height 2.15 σ_z above the plume centerline the concentration is one-tenth the plume centerline concentration at the same distance.

When one-tenth the plume centerline concentration extends to the stable layer, a height L, it is reasonable to assume that the distribution starts being affected by the "lid". The following method is suggested to take this situation [2,3,14,15] into account. Allow σ_z to increase with distance to a value of $\frac{L}{2.15}$ or 0.47 L. At this distance x_L, the plume is assumed to have a Gaussian distribution in the vertical direction. Assume that by the time the plume travels twice this far $2x_L$, it has become uniformly distributed between the surface of the earth and the height L.

Establishment of the vertical diffusion variable σ_z is accomplished by two methods for relatively short travel distances. σ_z was obtained by interpolation of the so-called "Pasquill" curves given in references [8,11], while for longer distances the methods developed at the National Reactor Testing Station (NRTS) are used [15] for three ranges of downwind distances.

- For distance $x < x_L$ - Gaussian Distribution

$\sigma_z(x)$ is evaluated using the following expression [16],

$$\log \sigma_z(x) = a_o + a_1 \log(x) + a_2[\log(x)]^2 \qquad (4\text{-}9)$$

where a_o, a_1, and a_2 are parameters associated with each stability classification. For each stability category, numerical values for a_o, a_1, and a_2 were obtained by fitting the graphs in reference [11] and listed below.

Stability conditions	a_o	a_1	a_2
A	2.611617	2.021631	0.548155
B	2.044469	1.057002	0.0303405
C	1.786247	0.0918815	-0.00397974
D	1.484478	9.733034	-0.0745961
E	1.329482	0.680872	-0.105925
F	1.137662	0.655019	-0.121964

- For distance $x_L \leq x \leq 2x_L$ - Medium Distribution between Gaussian Distribution and Uniform Distribution

$\sigma_z(x)$ for this range is evaluated using the following expression [15]:

$$\sigma_z = 0.465\ L + \frac{(x-x_L)}{x_L}\ (0.335\ L) \qquad (4\text{-}10)$$

where:

σ_z = diffusion parameter, m.

L = the mixing height which can be derived from the temperature gradient and which is dependent on the diffusion category, meters.

x_L = a downwind distance beyond which vertical mixing would be inhibited. This is also the downwind point where the vertical distribution of the pollutant loading may be considered to commence changing from Gaussian to uniform.

x = the downwind distance.

- For the distances $x > 2x_L$ - Uniform Distribution (where the vertical distribution of pollutant load concentration may be assumed to be uniform) [15].

$$\sigma_z = 0.8\ L \qquad (4\text{-}11)$$

4.3. Depletion of Cloud by Deposition and Radioactive Decay

As a release cloud travels downwind, material will be removed from it progressively by deposition of radionuclides on the ground and by radioactive decay.

The general correction factor for the depletion of the cloud may be estimated from the following equation:

$$G_i = F_i \cdot R_i \qquad (4\text{-}12)$$

where:

G_i = the general correction factor for depletion of cloud for radionuclide "i" at the location of interest.

F_i = the correction factor for depletion due to dry and wet deposition for radionuclide "i" at the location of interest.

R_i = the correction factor for depletion due to radioactive decay for radionuclide "i" at the location of interest.

4.3.1. Depletion of Cloud by Deposition

A number of processes other than natural atmospheric turbulent diffusion can be significant in the fate of radioactive material emitted into the atmosphere [8,18]. One of these processes is *deposition*. The mechanisms by which radioactive material will deposit on surfaces vary depending on whether the cloud passage is associated with precipitation. Dry deposition may result from gravitational settling or impaction on surfaces deflecting turbulent atmospheric flow. When precipitation occurs below the rain-forming level, the radioactive substances are washed out by falling raindrops.

Then the correction factor for depletion due to deposition of radionuclide "i" may be derived from the following equation:

$$F_i = \frac{N_{Di}\, f_D + N_{wi}\, f_w}{100} \qquad (4\text{-}13)$$

where

F_i = the correction factor for depletion due to deposition of radionuclide "i" at the location of interest.

N_{Di} = the correction factor for depletion due to dry deposition of radionuclide "i" at the location of interest.

f_D = effective period of time in which dry deposition process is active, %.

N_w = the correction factor for depletion due to wet deposition.

N_{wi} = deposition of radionuclide "i" at the location of interest.

f_w = effective period of time in which the wet deposition process is active, %.

4.3.1.1. Depletion of Cloud by Dry Deposition. With the exception of xenon, krypton and other noble gases, and the possible exception of iodine in true molecular form, the radioactive substances released from nuclear power plants would be in particulate form [6,19]. The physical process governing the deposition of aerosols and vapours is variously complicated and only partly understood at present, and it is impossible to give a precise prediction of the quantitative effects of deposition on the variation of radionuclide concentration with the distance that the cloud travels. With the exception of noble gases (krypton, xenon, etc.), the radioactive substances released from nuclear power plants would deposite on the ground to some extent as the cloud travels downwind. In the absence of rain, which would give rise to washout of a proportion of the radioactive substances, deposition would occur by [6,8,20]:

- sedimentation of the larger particles in the area closest to the reactor
- by processes of diffusion and impaction of the smaller particles
- by diffusion and chemical reaction of vapours at all distances.

The depletion of radioactive substances in the plume due to a dry deposition process during downwind travel is derived from the relationship given by I. Van der Hoven [8] as expressed in

the following expressions:

- For distances $x < x_L$ (where the vertical distribution of pollutant local concentration may be assumed to be Gaussian)

$$N_{DiI}(x,u,V_{di}) = \exp\left(-\left(\frac{2}{\pi}\right)^{\frac{1}{2}} \frac{V_{di}}{u} \int_0^x \frac{1}{\sigma_{zI}} \exp\left[-\frac{h^2}{2\sigma_{zI}^2}\right] dx\right) \quad (4\text{-}14)$$

where

$N_{DiI}(x,u,V_{di})$ = the correction factor for depletion due to dry deposition of radionuclide "i" for downwind distances less than x_L

V_{di} = the deposition velocity of radionuclide "i", m/s the description of V_{di} is given in point 4.3.1.1.

$\bar{u}$,h = as in equation (4-8).

σ_{zI} = is given by equation (4-9) (Gaussian Distribution).

- For distance $x_L \leq x \leq 2x_L$ (where the vertical distribution of pollutant load concentration may be assumed to be midway between Gaussian and uniform)

$$N_{DiII}(x,u,V_{di}) = N_{DiI}(x_L,u,V_{di}) \times$$
$$\times \exp\left\{-\left(\frac{2}{\pi}\right)^{\frac{1}{2}} \frac{V_{di}}{\bar{u}} \int_{x_L}^x \frac{1}{\sigma_{zII}} \exp\left[-\frac{h^2}{2\sigma_{zII}^2}\right] dx\right\} \quad (4\text{-}15)$$

where

$N_{DiII}(x,u,V_{di})$ = the correction factor for depletion due to dry deposition of radionuclide "i" for downwind distances between x_L and $2x_L$

$N_{DiI}(x_L,u,V_{di})$ = the correction factor for depletion due to dry deposition of radionuclide "i" for downwind distance x_L - expression (4-14)

V_{di},u,h = as in the expression (4-14)

σ_{zII} = is given by the equation (4-10) (Mediate Distribution).

- For distances $x > 2x_L$ (where the vertical distribution of pollutant load concentration may be assumed to be uniform)

$$N_{DiIII}(x,u,V_{di}) = N_{DiII}(2x_L,u,V_{di}) \times$$

$$\times \exp\left\{-(\tfrac{2}{\pi})^{\frac{1}{2}} \frac{V_{di}}{\bar{u}} \int_{2x_L}^{x} \frac{1}{\sigma_{zIII}} \exp\left[-\frac{h^2}{2\sigma_{zIII}^2}\right] dx\right\} \qquad (4\text{-}16)$$

where

$N_{DiIII}(x,u,V_{di})$ = the correction factor for depletion due to dry deposition of radionuclide "i" for downwind distances greater than $2x_L$

$N_{DiII}(2x_L,u,V_{di})$ = the correction factor for depletion due to dry deposition of radionuclide "i" for downwind distance $2x_L$ - expression (4-15)

V_{di}, u, h = as in the expression (4-14)

σ_{zIII} = is given by the equation (4-11) (Uniform Disribution).

4.3.1.1. Deposition Velocity. The deposition velocity of windborne materizl varies with the size, shape and density of the particle and with the chemical propoerties of the material of which the particle is composed [6]. However, even if the size and composition of the particles could be predicted in advance, this would not be sufficient to warrant more than a very approximate prediction of the deposition velocity since this has been found to vary with wind velocity and turbulence, and also with the nature of the surface upon which deposition occurs [6,19]. Iodine, which is specially considered in this report, presents exceptional difficulties when one attempts to assign a representative value to the deposition velocity. Some iodine would be released in molecular form, and a value of Vg = 2.5 cm/s has been found experimentally for this form [6,19]. Some iodine, initially in molecular form, would become attached to condensation nuclei, metal fumes and other submicron particles, and in this form the deposition velocity might be about 0.1 cm/s or even lower [19]. The presence of iodine in this form would probably account for the deposition velocities of 0.1-0.5 cm/s determined during the Windscale accident in 1957 [21]. Further information on deposition velocities

is available from a series of field tests of fission product releases carried out in the U.S.A. [22,23]. There were 9 experiments in which fuel was melted and effluent released near ground level. The overall result for iodine was V_g = 0.2 cm/s on gummed paper samples and 1.5 cm/s on a smaller number of grass samples. The measured deposition velocities for inversion and lapse conditions were not significantly different from each other. These data and experiments showed that the deposition velocity of iodine varies between about 0.1 cm/s and 3 cm/s depending on meteorological conditions, and whether the surface is grass, snow, or carbon, and on the physical and chemical form of the iodine, with most values falling between 0.2 and 2 cm/s. In this report it is assumed that the deposition velocity for the noble gases is 0 and for iodine 0.5 cm/s.

4.3.1.2. Depletion of Cloud by Wet Deposition. Depletion of a fraction of the material from the cloud may occur due to washout of particles or soluble vapours from any vertical section of the plume by rain or snow falling through it.

The depletion of the plume downwind by a washout process is accounted for by assuming that this process may be represented by an exponential term of the form [8]

$$N_{Wi} = \exp(-\Lambda_i \frac{x}{\bar{u}}) \qquad (4\text{-}17)$$

where:

N_{Wi} = the correction factor for depletion due to wet deposition of radionuclide "i" at the location of interest

$x, \bar{u}$ = as in equation (4-8)

Λ_i = the washout coefficient of radionuclide "i", s^{-1}; the description of Λ is given in point 4.3.1.2.1.

4.3.1.2.1. Washout coefficient. The fraction which is washed out in unit time is called the wash-out coefficient, Λ. The value of Λ depends on the particle size, the precipitation intensity and the size of drops. The difficulty in making a suitable choice of value from the experimental or theoretical information available is at least as great as in the case of V_d for dry deposition [6,8].

Predicted values of the washout coefficient Λ for iodine gas range from 10^{-5} to 10^{-4} s^{-1} in rainfall rates of 0.1 to 3 mm/h [6]. The three measurements for iodine gas gave values ranging from 3×10^{-6} to 2×10^{-7} s^{-1}, i.e. one or two orders of magnitude lower. This large difference is attributed to differences in their respective reaction rates with water [24]. During snowfall, washout coefficients were lower than in rain, for inorganic iodine it was about 5×10^{-8} s^{-1} in powder snow of 0.2 mm/h of rate [18].

Englemann [24] presents a survey of experimental results for washout coefficient measured at Harwell, Washington and . The values of Λ vary between 3×10^{-5} s^{-1} at a rainfall rate of 0.1 mm/h to 10^{-3} s^{-1} at 100 mm/h.

These data and experiments showed that the washout coefficient of iodine varies between 10^{-7} to 10^{-3}/s with most values falling between 10^{-5} and 10^{-4}/s; the highest values occurring when the effluent gas has a high water content and atmospheric conditions are conducive to condensation.

Englemann [18,24] discusses scavenging by snow and water scavenging of gases. He concludes that for particles of about 1 mm or less in diameter, i.e. those of interest in reactor releases, it is generally agreed that washout by rain is insignificant. In this report it is assumed that the washout coefficient for the noble gases is always 0 and for iodine 2×10^{-4} s^{-1}.

4.3.2. Depletion of Cloud by Radioactive Decay

When the source material is radioactive, correction factors must be included to account for the depletion by radioactive decay en route to the reactor. The depletion of concentrations for radioactive decay of the radionuclides is determined by the expression:

$$R_i = \exp\left(-\frac{0.693}{T_{\frac{1}{2}\,i}} \frac{x}{u}\right) , \qquad (4\text{-}18)$$

where:

R_i = the correction factor for depletion due to radioactive decay for radionuclide "i" at the location of interest

x,u = as in equation (4-8)

$T_{\frac{1}{2}\,i}$ = the radioactive half-life of radionuclide "i", s.

A Scheme of Air Transport Model

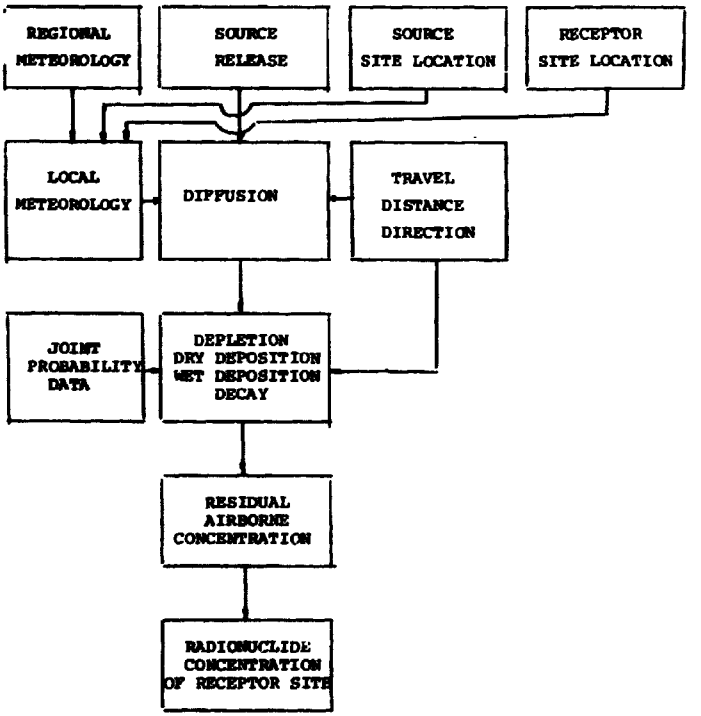


Figure 4-1

5. DOSE MODELS

In the event of the release of radioactive materials to the atmosphere the radiation dose received by people and animals can be considered in two phases [8]; the initial or acute phase while the airborne material is passing the receptor and the recovery phase following the passage of the cloud.

The radiation dose in the initial phase will include the external radiation from the cloud passage, some contribution from the materials deposited on the ground, body or other surfaces, and the radiation from any material inhaled during the cloud passage.

The dose received in the latent phase will consist of external radiation from material deposited on the ground or other surfaces and internal radiation from ingestion of foodstuffs or liquids that have become contaminated by the passage of the cloud. Possibly an additional internal dose could be received during this phase by inhalation of resuspended dust in the contaminated area.

This report takes into account only the initial phase of recovery radiation dose, i.e.

- the dose from submersion in air
- the dose from inhalation of air during the passage of the cloud.

5.1. Individual Dose

The fundamental equation for calculation of the individual radiation dose from submersion in air and inhalation air is given by the following equation:

$$D_{i,k,j,n} = Q_i \cdot T_i \cdot F_{i,k,j,n} \qquad (5\text{-}1)$$

where:

$D_{i,k,j,n}$ = the individual dose rate to organ j individuals in the group n from nuclide i, via pathway k, at the location of interest mrem/year

Q_i = release rate for nuclide i, pCi/s; the description of Q_i is given in point 3 of this report.

T_i = pathway model conversion factor relating quantity of radionuclide i released to its concentration in the air at the location of interest, $pCi/m^3/pCi/s$; the description of T_i is given in point 4 by equation (4-2) of this report.

$F_{i,k,j,n}$ = Dosimetry conversion factor (Dose Factor) relating concentration of radionuclide i in the air to resultant dose to n group of people on organ j via pathway k, mrem/y per pCi/m^3.

The dose factor is a number which can be used to calculate the radiation dose to a person (or organ) from external exposure to a given concentration of radionuclides in environmental air (Submersion Dose Factor) and from the inhalation of radionuclides (Inhalation Dose Factor).

5.1.1. Submersion Dose Factor

The Submersion Dose Factor (mrem/y per pCi/m^3) was calculated by multiplying the Hourly Submersion Dose Factor (mrem/h per pCi/m^3) by the occupancy factor (h/y) [2,3].

The occupancy factor

Since the principal contributions to the external air submersion dose are from noble gases, the assumption was made that the air concentration of radionuclides was essentially the same indoors as out of doors. Thus no shielding and occupancy factor are applied. Therefore 8784 hr/yr (24 hr/day × 30.5 days/month × 12 months/year) is used for calculation of the submersion dose factor.

The Hourly Submersion Dose Factor

In this report the hourly Submersion Dose Factor from external exposure to air was derived on the assumption that the amount of contaminated air was large enough to be considered as an infinite volume relative to the range of the radiation emitted [2,3,14]. Under this assumption the energy emitted per gram of air is equivalent to the energy absorbed per gram of air. The dose factor merely converts MeV per disintegration per gram to rem and corrects for the differences in energy absorption between

air and tissue.

It is important to notice that the concept of a semi-infinite cloud is not valid unless the dimensions of the actual cloud exceed approximately 3-5 mean free paths of the radiation in air. The mean free path of gamma rays is of the order of 100 meters, and the dimensions of the cloud are the same order of magnitude at distances which vary from 1 to 100 kilometers depending upon weather conditions [6]. At points nearer to the source of release, the dimensions of the cloud would be much smaller than the mean free path of gamma rays. Consequently the dimensions of the cloud and distribution of activity within have to be taken into account if a proper estimate is to be made of the γ dose from the cloud.

The mean range of beta rays in air is roughly 1 to 10 meters for beta energies of 0.5 to 2 MeV [6]. Since the dimensions of the cloud will be greater than this at any appreciable distance from the point of the release, and a human body would serve as a nearly perfect absorber, the semi-infinite cloud formula can be used with good accuracy to calculate the beta dose. The dose from submersion in air is an external dose to either the skin only or both the skin and total body, depending upon the penetrating power of the radionuclide emitted by the airborne radionuclides. Only beta and gamma radiation, which would penetrate 7 mg/cm^2 of tissue, were considered in calculating the skin dose. A gamma radiation dose at 5 cm depth in tissue was used for calculating the external dose to the total body (and for internal organs).

The 2π geometry was used for a person standing on the ground surrounded by a very large semi-infinite hemisphere of contaminated gas for both beta and gamma radiation. The geometry follows from the half-infinite volume for gamma radiation. For the beta radiation with shorter ranges in air the physical arrangement approaches the infinite volume (4π), but since the beta radiation is of limited penetrating power, it will irradiate the skin from one side only, not two sides as with the penetrating gamma radiation.

The equation for calculating the hourly Submersion Dose Factor is given below [2,3].

$$(H.S.D.F.)_i = 8.87 \cdot 10^{-7} \left(\bar{E}_{\beta_i} + \bar{E}_{\gamma_i}\right) \qquad (5\text{-}2)$$

where:

$(H.S.D.F.)_i$ = the Hourly Submersion Dose Factor for nuclide (i) in units mrem/hr per pCi/m^3 based on a half-infinite cloud geometry and corrected for the fractional penetration of beta and gamma radiations to the appropriate tissue depth (7×10^{-3} cm for skin and 5 cm for total body)

$E_{\beta i}$ = the effective beta energy per disintegration of radionuclide (i) in unit MeV, at the appropriate depth in tissue.

$E_{\gamma i}$ = the effective gamma energy per disintegration of radionuclide (i) in unit MeV, at the appropriate depth in tissue.

8.87×10^{-7} = the constant which takes into consideration the density of air as well as the conversion from MeV to rem.

In application of this equation, the Hourly Submersion Dose Factor is independent of body size. This follows from an assumption that the presence of the person does not significantly perturbate the radiation field.

The value of the Submersion Dose Factor is presented in Table 5-1 (for fifteen isotopes of noble gases and iodines and for two organs: total body and skin) [2,3].

5.1.2. Inhalation Dose Factor

The inhalation Dose Factor (mrem/y per pCi/m^3) was calculated by multiplying the person's breathing rate (m^3/hr), an occupancy factor (hrs/year), and the Intake Dose Factor (mrem/pCi intake).

Inhalation rates

The ICRP [25] has defined the inhalation rate of Standard Man as 20 m^3/day. This rate was adopted for the adult. Data on inhalation rate versus age are limited [2,3]. Values selected for this report were those derived by Rohner and Kaye [2,3] from oxygen consumption, oxygen concentration in ambient air (20.9%), and oxygen content of exhaled air. The data of Rohner and Kaye for male and female children were averaged to yield rates of

14 m^3/day for the teenager (14 yrs old) and 7.3 m^3/day for the child (4 yrs old).

The occupancy factor

The occupancy factor was assumed to be 24 hr/day × 30.5 days/month × 12 months/year (8784 hrs/yr), assuming that the person spends the major portion of this time in the place where he resides.

The intake dose factor

Inhaling radioactive materials can result in a radiation dose to (1) lungs and upper respiratory tract from isotopes deposited in the passages, (2) gastrointestinal tract (GI tract) from isotopes originally deposited in the respiratory tract and later removed by ciliary action and swallowed, (3) other organs in which the isotopes may be deposited after they are absorbed into the bloodstream from either the lung or GI tract.

The radiation dose rate to each organ will depend upon the physical and chemical characteristics of the radionuclides in the cloud and the distribution and retention of these materials in the body. Although in many instances it is difficult to predict the biological fate of the source material released from a facility, radioiodine in most forms will be quickly absorbed from the lungs into the blood stream and translocated to the thyroid. The noble gases do not enter into the body metabolism but may be dissolved to some extent in body fluids or fat.

The mathematical relationship that governs the accumulation of a radionuclide in an organ during a period of exposure is not known exactly. The ICRP [25] and NCRP [26] have assumed that for each isotope there is one or more critical organ having a characteristic rate of accumulation and excretion. The radionuclides are assumed to accumulate in the critical organ at a rate determined by the amount present in air, the rate of inhalation, the rate of metabolic transfer to the critical organ, and the rate at which the body eliminates the radionuclides. It is assumed that elimination is exponential, a constant fraction of the organ burden being eliminated in unit time. Use of the exponential model permits the concept of the "biological half-life" T_b, a factor which can be used conveniently, in conjunction with the radioactive half-life T_r. The overall rate at which the radio-

activity owing to a radionuclide diminishes in the critical organ can be expressed as the effective half-life T, which is expressed by the following expression,

$$T = \frac{T_r \, T_b}{T_r + T_b} \quad . \tag{5-3}$$

The exponential model is undoubtedly an oversimplification but it is used because of its convenience as well as its conservatism. The intake Dose Factor can be calculated from the equations given by the ICRP [25].

$$(I.D.F.) = \frac{0.074 \in T \, fa}{m} \left(1 - e^{\frac{-0.693t}{T}}\right) \tag{5-4}$$

where:

(I.D.F.) = intake dose factor/mrem/pCi intake).

$\in$ = effective absorbed energy of the specific nuclide in the specific organ under consideration, MeV

fa = the fraction of the inhaled material that reached the organ under consideration.

T = the effective half-life of the nuclide in the organ under consideration/days.

t = length of time over which the dose is calculated, days. For present application t was 1 year.

m = mass of the organ, gram.

Values of the parameters required for these equations were taken from the ICRP [25] for the adult. Values of the parameters for children and teenagers for calculation of the radiation dose to the thyroid from radioiodine were taken from the literature [2] and are presented in table 5-2.

Effective decay energies were derived for children's organs by utilizing the model of the ICRP, whereby the nuclide is considered to be concentrated in the center of a spherical organ of effective radius (x) [25]. The values of x were determined from organ weights, using the assumptions that (x) was proportional

to the cube root of the organ weight, and the proportionality factor was the same as that for the corresponding adult organ. Decay schemes chosen were those of Lederer et al. [27]. Average beta energies were estimated from the graphs of $\bar{E}/E_0$ given by Stack and Way [28]. Organ weights for thyroid and total body were derived from the literature [2] listed in Table 5-3.

The calculated value of the Inhalation Dose Factor is presented in Table 5-4 (for five isotopes of iodines, three groups of people: child, teenager and adult, and two organs: thyroid and total body). The Inhalation Dose Factor represents the dose in the first year after intake.

5.2. Population Doses

The Population Dose (Dp) in man-rem/year to organ (j) of the individuals in the group n from nuclide i, via pathway k, is determined by multiplying the average individual dose to the same organ j of the same group of people n from the same nuclide i, via the same pathway k, by the number of the population group n located within the sector in question [29,30] and summing over all subgroups of people in this sector. Mathematically this can be expressed:

$$D(P)_{i,k,j} = \sum_{n=1}^{w} D_{i,k,j,n} \cdot N_n \cdot 10^{-3}$$

where

$D(P)_{i,k,j}$ = Population Dose from release of radionuclide i via pathway k to j organ within a given sector, man-rem/year

$D_{i,k,j,n}$ = The average individual dose within a given sector from radionuclide i via pathway k to organ j of group n of the population, mrem/year

N_n = the number of people in n group of the exposed population within a given sector.

Submersion population doses and inhalation population doses were calculated from the above expressions.

Table 5-1

Submersion Dose Factors
(mrem/y per pCi/m^3)[a)]

Radionuclide	Skin	Total body[b)]
Ar-39[c)]	1.05×10^{-3}	2.9×10^{-6}
Ar-41	1.40×10^{-2}	9.65×10^{-3}
Kr-85m	2.78×10^{-3}	1.13×10^{-3}
Kr-85[c)]	1.30×10^{-3}	1.91×10^{-5}
Kr-87	2.34×10^{-2}	1.13×10^{-2}
Kr-88	1.74×10^{-2}	1.3×10^{-2}
I-129	3.46×10^{-5}	9.5×10^{-6}
I-131	4.25×10^{-3}	2.7×10^{-3}
I-132	2.34×10^{-2}	1.74×10^{-2}
I-133	7.65×10^{-3}	3.8×10^{-3}
I-135	1.74×10^{-2}	1.3×10^{-2}
Xe 131m	4.15×10^{-4}	2.42×10^{-5}
Xe 133m	5.2×10^{-4}	2.3×10^{-4}
Xe 133	6.0×10^{-4}	2.16×10^{-4}
Xe 135	4.3×10^{-3}	1.85×10^{-3}

a) Applicable for all groups of people

b) Total body factors also apply to internal organs

c) Including bremsstrahlung.

Table 5-2

Values of Parameters Required for Calculation of Radiation Dose to the Thyroid from Inhalation of Radioiodine

Parameter		4 years	14 years	Adult
fa		0.2	0.2	0.23
m (gram)		5	15	20
Tb (days)		13	30	138
T_R (days)		The same for all groups of people I 129 - 5.86×10^9 I 131 - 8.05 I 132 - 9.58×10^{-2} I 133 - 0.875 I 135 - 0.279		
T (days)	I 129	13	30	138
	I 131	4.97	6.35	7.61
	I 132	9.58×10^{-2}	9.58×10^{-2}	9.58×10^{-2}
	I 133	0.820	0.850	0.869
	I 135	0.273	0.276	0.278

Table 5-3

Organ Mass and Effective Radius
for Children and Teenagers

	Children (4 yr)		Teenagers (14 yr)	
Organ	Mass (gram)	Radius (cm)	Mass (gram)	Radius (cm)
Total body	16400	20	49000	27
Thyroid	5	2	15	2.7

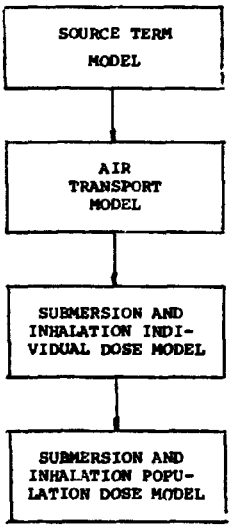
Table 5-4

Inhalation Dose Factor
(mrem/y per pCi/m^3)

Radio-nuclide	Child		Teen		Adult	
	T. body	Thyroid	T. body	Thyroid	T. body	Thyroid
I 129	5.58×10^{-3}	4.86	4.23×10^{-3}	3.6	3.26×10^{-2}	3.4×10^{1}
I 131	1.65×10^{-2}	8.2	1.22×10^{-2}	5.75	1.83×10^{-2}	1.04×10^{1}
I 132	1.52×10^{-3}	0.48	1.13×10^{-3}	0.33	1.2×10^{-3}	0.427
I 133	5.0×10^{-3}	2.98	3.48×10^{-3}	1.97	3.85×10^{-3}	2.57
I 135	3.06×10^{-3}	1.08	2.28×10^{-3}	0.74	2.47×10^{-3}	0.98

6. APPLICATION - EXAMPLE

The model of calculation submersion populatio doses and inhalation population doses presented in this report is used to calculate these doses for people located within 200-1000 km's distance from a hypothetical nuclear power plant sited near the geographical centre of Denmark during normal operation [35]. The scheme of this model is the following:



6.1. Source Term Model - Q_i

In this example two cases are considered.

- Unit release rates of 15 isotopes of noble gases and iodines.
- Actual release rates for two types of Light Water Reactor Plants (LWR): the Boiling Water Reactor (BWR) and the Pressurized Water Reactor (PWR).

6.1.1. Unit Release Rates - Q_1 = 1 pCi/s

In this example unit release rates (1 pCi/s) are considered of 15 isotopes of noble gases and iodines which are listed below.

Radionuclide	Half Life
Ar-39	270 y
Ar-41	1.83 h
Kr-85m	4.4 h
Kr-85	10.76 y
Kr-87	76 m
Kr-88	2.8 h
I-129	1.6×10^7 y
I-131	8.05 d
I-132	2.3 h
I-133	21 h
I-135	6.7 h
Xe-131m	12 d
Xe-133m	2.3 d
Xe-133	5.27 d
Xe-135	9.2 h

6.1.2. Actual Release Rates for PWR and BWR

The estimation of release rates of radioactive substances (ten isotopes of noble gases and iodines) in gaseous effluents for a 1000 MWe reactor, type BWR (for 7 BWR Gaseous Radwaste Treatment Cases) or PWR (for 9 PWR Gaseous Radwaste Treatment Cases), perhaps located in the middle of Denmark, is presented below. An accurate description of these values is given in point 3 of this report [4,5].

Release Rates for PWR pCi/s

Isotope	I	II	III	IV	V	VI	VII	VIII	IX
Kr 85m	3.13(5)	3.13(5)	3.13(5)	3.13(5)	2.61(5)	3.13(5)	3.13(5)	2.61(5)	3.13(5)
Kr 85	2.53(7)	2.53(7)	2.53(7)	2.53(7)	2.53(7)	2.53(7)	2.53(7)	2.51(7)	2.53(7)
Kr 87	1.83(5)	2.09(5)	2.09(5)	2.09(5)	1.57(5)	2.09(5)	2.09(5)	1.57(5)	2.09(5)
Kr 88	5.74(5)	5.74(5)	5.74(5)	5.74(5)	4.70(5)	5.74(5)	5.74(5)	4.70(5)	5.74(5)
Xe 131m	1.17(7)	1.64(6)	1.67(6)	9.4 (5)	1.83(6)	5.22(5)	1.67(6)	3.13(5)	9.4 (5)
Xe 133m	4.44(6)	7.05(5)	7.05(5)	7.05(5)	1.57(5)	7.05(5)	7.05(5)	1.57(5)	7.05(5)
Xe 133	1.12(9)	7.05(7)	7.05(7)	6.26(7)	1.31(7)	6.26(7)	7.05(7)	1.02(7)	6.26(7)
Xe 135	9.92(5)	9.92(5)	9.92(5)	9.92(5)	6.26(5)	9.92(5)	9.92(5)	6.26(5)	9.92(5)
I 131	3.13(4)	8.61(3)	1.41(3)	7.83(2)	1.31(3)	2.09(3)	1.46(2)	1.15(3)	7.31(2)
I 133	1.54(4)	9.96(3)	9.92(2)	5.74(2)	9.14(2)	9.14(2)	1.7 (2)	8.09(2)	5.74(2)

Release Rates for BWR pCi/s

Isotope	I	II	III	IV	V	VI	VII
Kr 85m	3.65(9)	3.65(9)	2.11(8)	2.11(8)	2.11(8)	1.91(6)	9.66(5)
Kr 85	2.01(7)	2.01(7)	2.01(7)	2.01(7)	2.01(7)	2.01(7)	1.96(7)
Kr 87	8.87(9)	8.87(9)	1.51(6)	7.31(6)	1.77(6)	2.61(5)	2.48(6)
Kr 88	1.12(10)	1.12(10)	1.28(8)	1.28(8)	1.28(8)	2.87(5)	3.13(6)
Xe 131m	1.75(7)	1.75(7)	8.09(6)	8.09(6)	8.09(6)	2.22(6)	7.83(4)
Xe 133m	2.43(8)	2.43(8)	4.44(6)	4.44(6)	4.44(6)	2.61(4)	2.61(4)
Xe 133	6.79(9)	6.79(9)	1.31(9)	1.31(9)	1.31(9)	1.31(8)	6.00(7)
Xe 135	1.91(10)	1.91(10)	1.10(7)	1.10(7)	1.15(7)	9.66(6)	1.15(7)
I 131	3.92(5)	1.02(4)	7.05(3)	7.05(3)	8.87(3)	1.8 (3)	4.18(2)
I 133	2.24(6)	5.74(4)	3.92(4)	3.92(4)	4.96(4)	1.02(4)	1.33(3)

6.2. Air Transport Model - C_i

In this example is calculated the atmospheric radionuclide concentration from 200 km up to 1000 km (250 km, 350 km, 450 km, 550 km, 650 km, 750 km, 850 km, 950 km) downwind distances from a hypothetical nuclear power plant sited near the geographical centre of Denmark to each of 12 compass-point sectors for unit release rates of 15 radionuclides and actual release rates (BWR and PWR).

The expressions for calculating the atmospheric radionuclide concentration are given in section 4 (4-1, 4-7, 4-13, 4-14, 4-15, 4-16, 4-17, and 4-18). The values of the parameters used in the calculations are the following:

fs = the frequency of the occurrence of particular stability conditions A, B, C, D, E, and F. In this example is used the values of fs which are obtained by measurements along the Risø tower in the period from February 1st, 1958, to December 31st, 1967: 1.177%; 1.741%; 3.361%; 60.257%; 27.108%; 6.526% correspondingly for the A, B, C, D, E, and F categories.

L = the mixing height. This calculation uses the values of L attributed to Klug [7,17] for West Germany which are given below for A - 1500 m; B - 1500 m; C - 1000 m; D - 500 m; E - 200 m; F - 196 m.

$\bar{u}$ = the mean wind speed for each wind direction sector; the values of $\bar{u}$ in this calculation were obtained by measurements along the Risø tower in the period from February 1st, 1958, to December 31st, 1967, and are presented below.

Wind direction sectors	0	1	2	3	4	5	6	7	8	9	10	11
$\bar{u}$; m/s	7.7	8.0	8.0	8.7	8.0	6.9	6.4	5.9	4.9	8.3	8.8	8.2

f = the frequency of the occurrence of wind direction for the compass sector being considered. The values

of f were also obtained by measurements at the Risø tower during the same period as $\bar{u}$ and fs and are listed below: for 0 - 7.4%; 1 - 10.8%; 2 - 14%; 3 - 12.9%; 4 - 7.7%; 5 - 6.0%; 6 - 6.2%; 7 - 5.1%; 8 - 4.1%; 9 - 7.4%; 10 - 9.4%; 11 - 9.1% [31].

n = number of compass sectors considered; in this case n = 12.

h = stack height or emission point above the surface; this calculation uses h = 0.

f_D = the effective period of time in which the dry deposition process is active; in this calculation it is assumed that f_D is equal to 56.5%.

fw = the effective period of time in which the wet deposition process is active; this example uses fw for Denmark that is equal to 43.5% (percentage of days with rain) [32].

V_{di} = the deposition velocity of radionuclide i; in this report it is assumed that noble gases and iodine have deposition velocities of 0 and 0.5 cm/s respectively [16].

Λ_i = the washout coefficient of radionuclide i; in this report it is assumed that the noble gases and iodine have washout coefficients of 0 and 2×10^{-4} sec^{-1} respectively [16].

6.3. Submersion and Inhalation Individual Dose Model

In this report the submersion and inhalation individual doses are calculated at the following distances: 250 km, 350 km, 450 km, 550 km, 650 km, 750 km, 850 km, and 950 km from a nuclear power plant to each of 12 compass point sectors for unit release rates of 15 radionuclides (isotopes, noble gases, and iodines) and actual release rates from a BWR or a PWR (9 cases for a PWR and 7 cases for a BWR).

6.3.1. Submersion Individual Dose Model

The Submersion Individual Dose was only calculated for one group of people because it is independent of body size. This fol-

lows from an assumption that the presence of the person does not significantly perturb the radiation field.

The Submersion Individual Dose Rate (S.I.D.) is given by the following equation:

$$(S.I.D.)_{i,j} = C_i \cdot F_{i,j}(sub)$$

where:

$(S.I.D.)_{i,j}$ = the submersion individual dose rate to organ j individuals from nuclide i at the location of interest, mrem/year.

C_i = the atmospheric concentration of radionuclide i at the location of interest, pCi/m^3 (expression (4-1)).

$F_{i,j}(sub)$ = the submersion dose factor relating concentration of radionuclide i in the air to resultant dose to organ j individuals, mrem/y per pCi/m^3. The value of the submersion dose factor used in our calculation is presented in table 5-1.

The calculation values of Submersion Individual Dose Rates, mrem/year for 15 isotopes of noble gases and iodines (unit release) and actual releases from a PWR (9 cases) and a BWR (7 cases) at distances 250 km, 350 km, 450 km, 550 km, 650 km, 750 km, 850 km, and 950 km from hypothetical nuclear power plants situated near the geographical centre of Denmark (Aarhus) to each of 12 compass-point sectors are presented in Appendix A (Unit Release), Appendix C (PWR Release), and Appendix D (BWR Release).

6.3.2. Inhalation Individual Dose Model

The Inhalation Individual Dose Rate was calculated in this report for three groups of people: children (age 4 years), teenagers (age 14 years), and adults (age > 18 years) to two organs of the individual: thyroid and total body. The Inhalation Individual Dose Rate (I.I.D.) is given by the following equation:

$$(I.I.D.)_{i,j,n} = C_i \cdot F_{i,j,n}(inh)$$

where:

$(I.I.D.)_{i,j,n}$ = the inhalation individual dose rate to organ j individuals in the group n from nuclide i at the location of interest, mrem/year.

C_i = the atmospheric concentration of radionuclide i at the location of interest, pCi/m^3 (expression (4-1)).

$F_{i,j,n}(inh)$ = the inhalation dose factor relating to radionuclide i in the air to resultant dose to n group of people on organ j, mrem/y per pCi/m^3. The value of inhalation dose factors for three groups of people to thyroid and total body are listed in table 5-4.

The calculation values of Inhalation Individual Dose Rates, mrem/year for 15 isotopes of noble gases and iodines (unit release) and actual release from a PWR (9 cases) and a BWR (7 cases) at distances 250 km, 350 km, 450 km, 550 km, 650 km, 750 km, 850 km, and 950 km from hypothetical nuclear power plants situated near the geographical centre of Denmark (Aarhus) to each of 12 compass-point sectors are presented in Appendix A (Unit Release), Appendix C (PWR Release), and Appendix D (BWR Release).

6.4. Submersion and Inhalation Population Dose Model

In this report are estimated the submersion population dose and inhalation individual dose at the following range of distances: 200-300 km, 300-400 km, 400-500 km, 500-600 km, 600-700 km, 700-800 km, 800-900 km, 900-1000 km from a nuclear power plant to each of 12 compass-point sectors (totalling 96 sector segments) for unit release rates of 15 radionuclides (isotopes, noble gases, and iodines) and actual release rates from a BWR or a PWR.

6.4.1. Submersion Population Dose - (S.P.D.)

The Submersion Population Doses (S.P.D.) within the m sector segment in question are given by the following equation:

$$(S.P.D.)_{i,j,m} = (S.I.D.)_{i,j,m} \cdot N_m \times 10^{-3}$$

where:

$(S.P.D.)_{i,j,m}$ = the Submersion population dose from a release of radionuclide i to organ j of people within m sector segment in question, man-rem/year.

$(S.I.D.)_{i,j,m}$ = the average submersion individual dose rate to organ j individuals from radionuclide i within sector segment m in question, mrem/year.

N_m = the number of people within m sector segment in question, man.

The Submersion Population Dose (S.P.D.) within a given sector (whole) is given by the following equation:

$$(S.P.D.)_{i,j,q} = \sum_{m=1}^{8} (S.P.D.)_{i,j,m}$$

where:

$(S.P.D.)_{i,j,q}$ = the submersion population dose from a release of radionuclide i to organ j of people for wind direction sector q (In the range of 200-1000 km), man-rem/year.

$(S.P.D.)_{i,j,m}$ = the submersion population dose from a release of radionuclide i to organ j of people within each m segments of wind-direction sectors q (8 segments for one direction wind sector), man-rem/year.

The Submersion Population Dose (S.P.D.) for one ring sector to all wind direction sectors is given by the following equation:

$$(S.P.D.)_{i,j,z} = \sum_{m=1}^{12} (S.P.D.)_{i,j,m}$$

where:

$(S.P.D.)_{i,j,z}$ = the submersion population dose from a release of radionuclide i to organ j of people within z ring sector for all wind direction sectors (12), man-rem/year.

$(S.P.D.)_{i,j,m}$ = the submersion population dose from a release of radionuclide i to organ j of people within each m segment of ring sectors q (12 segments for one ring sector), man-rem/year.

The Submersion Population Dose for all ring sectors is given by the following expression:

$$(S.P.D.)_{i,j} = \sum_{z=1}^{8} (S.P.D.)_{i,j,z}$$

where:

$(S.P.D.)_{i,j}$ = the submersion population dose from a release of radionuclide i to organ j of people within all ring sectors (8), man-rem/year.

$(S.P.D.)_{i,j,z}$ = the submersion population dose from released radionuclide i to organ j of people within each ring sector z (8 ring sectors), man-rem/year.

The calculated values of Submersion Population Dose Rates, man-rem/year, for 15 isotopes of noble gases and iodines (unit release) and actual releases from PWR (9 cases) and BWR (7 cases) for each of 96 (8 × 12) sector segments, each of 12 wind direction sectors, each of 8 ring sectors, and for all ring sec-

tors around a hypothetical nuclear power plant eventually situated near the geographical centre of Denmark (Aarhus) are presented in Appendix B (Unit Release), Appendix C (PWR Releases), and Appendix D (BWR Releases).

6.4.2. Inhalation Population Dose - (I.P.D.)

The Inhalation Population Doses (I.P.D.) within m sector segments in question are given by the following equation:

$$(I.P.D.)_{i,j,m} = \sum_{n=1}^{3} (I.P.D.)_{i,j,n,m} \cdot N_{n,m} \times 10^{-3}$$

where:

$(I.P.D.)_{i,j,m}$ = the inhalation population dose from a release of radionuclide i to organ j of people within m sector segment in question, man-rem/year.

$(I.P.D.)_{i,j,m,n}$ = the average inhalation individual dose rate to organ j of group n of people from a release of radionuclide i within m sector segment in question, mrem/year; the inhalation individual dose rate was calculated for three groups of people: child (age 4), teenager (age 14), and adult (age > 19).

$N_{n,m}$ = the number of n group of people within m sector segment in question, man; in this report is considered the following groups of people: children (age 0-9); teenagers (age 10-19), and adults (age > 19).

The Inhalation Population Doses for each wind direction sector, each ring sector and all ring sectors were calculated in the same way as the Submersion Population Doses.

The calculation values of Inhalation Population Dose Rates, man-rem/year, for 15 isotopes of noble gases and iodines (unit release), and actual release from PWR (9 cases) and BWR (7 cases) for each of 96 (8 × 12) sector segments, each of 12 wind direction

sectors, each of 8 ring sectors and for all ring sectors around hypothetical nuclear power plants located near the geographical centre of Denmark (Aarhus) are presented in Appendix B (Unit Release), Appendix C (PWR Release), and Appendix D (BWR Release).

6.4.3. The Population Distribution around Hypothetical Nuclear Power Plants Located Near the Geographical Centre of Denmark - Aarhus

The population was considered from 200 km to 1000 km around a hypothetical nuclear power plant situated near the geographical centre of Denmark. The area around the plant was divided into 96 (8 × 12) sector segments and the population within these sector segments was determined according to 1972 census figures [33] as reported by the United Nations. The population distribution by sector segment and for three groups of people: children (age 0-9), teenagers (age 10-19), and adults (age > 19) are shown below and in figure 6-1.

Direct Sector	Age	200-300 km	300-400 km	400-500 km
0	Total	39300	177000	282000
	0-9	6300	28300	45000
	10-19	6300	28300	45000
	≥ 19	26700	121300	172000
1	Total	144000	198000	423000
	0-9	23500	31600	67500
	10-19	23500	31600	67500
	≥ 19	47000	134800	288000
2	Total	236000	330000	211500
	0-9	38000	53000	33800
	10-19	38000	53000	33800
	≥ 19	160000	224000	143900
3	Total	144000	132000	21150
	0-9	23000	21000	3380
	10-19	23000	21000	3380
	≥ 19	98000	90000	14390
4	Total	338000	242000	2500000
	0-9	54000	38700	400000
	10-19	54000	38700	400000
	≥ 19	220000	164600	1700000
5	Total	825000	2890000	4180000
	0-9	132000	462000	665000
	10-19	132000	462000	665000
	≥ 19	561000	1966000	2850000
6	Total	3250000	4550000	5290000
	0-9	520000	730000	845000
	10-19	520000	730000	845000
	≥ 19	2210000	3090000	3600000
7	Total	650000	3030000	6750000
	0-9	104000	485000	1080000
	10-19	104000	485000	1080000
	≥ 19	442000	2060000	4590000
8	Total	0	0	0
	0-9	0	0	0
	10-19	0	0	0
	≥ 19	0	0	0
9	Total	0	0	0
	0-9	0	0	0
	10-19	0	0	0
	≥ 19	0	0	0
10	Total	0	0	0
	0-9	0	0	0
	10-19	0	0	0
	≥ 19	0	0	0
11	Total	78500	220000	141000
	0-9	12600	35000	22600
	10-19	12600	35000	22600
	≥ 19	53300	150000	95800

500-600 km	600-700 km	700-800 km	800-900 km	900-1000 km
346000	410000	540000	312000	198000
55400	65500	85000	50000	32000
55400	65500	85000	50000	32000
235200	279000	334000	212000	134000
516000	610000	355000	400000	623000
82500	97500	57000	64000	100000
82500	97500	57000	64000	100000
351000	415000	241000	272000	423000
1403959	76200	109000	498000	1507000
226000	12200	17500	79500	240000
226000	12200	17500	79500	240000
851959	51800	74000	339000	1027000
0	374000	1570000	2230000	1640000
0	60000	250000	356000	260000
0	60000	250000	356000	260000
0	254000	1070000	1518000	1120000
3050000	3600000	4720000	4700000	5250000
490000	575000	755000	750000	835000
490000	575000	755000	750000	835000
2070000	2450000	3210000	3200000	3500000
4000000	4140000	4340000	4700000	5960000
640000	660000	695000	750000	950000
640000	660000	695000	750000	950000
2720000	2820000	2950000	3200000	4060000
5840000	7640000	9850000	11000000	9920000
930000	1220000	1580000	1760000	1590000
930000	1220000	1580000	1760000	1590000
3980000	4200000	6690000	7480000	6740000
8280000	10210000	9850000	5110000	5720000
1300000	1630000	1580000	820000	915000
1300000	1630000	1580000	820000	915000
5680000	6950000	6690000	3470000	3890000
0	1110000	10200000	15600000	12100000
0	177000	1630000	2500000	1940000
0	177000	1630000	2500000	1940000
0	756000	6940000	10600000	8220000
0	0	7050000	6270000	1640000
0	0	1130000	1000000	260000
0	0	1130000	1000000	260000
0	0	4790000	4270000	1120000
0	0	510000	294000	410000
0	0	81500	47000	65500
0	0	81500	47000	65500
0	0	347000	200000	279000
259000	163000	0	0	0
41500	26000	0	0	0
41500	26000	0	0	0
176000	111000	0	0	0

Fig. 1

6.5. Sensitivity Studies: Effects of Parameter Variations

Parameter variations were made and analysed to better understand the mechanisms in the model of calculation. In a general study such as this it is virtually impossible to take into account all variations which might occur; however, sensitivity studies were performed to evaluate the effects of uncertainties in the parameters believed to be most significant in their effects on the radiation potentially received by the population. A series of calculations was made to estimate the effects of variations in meteorological conditions on individual doses. Changes were assumed in mixing layer depth, atmospheric stability, deposition velocity, washout coefficient, and frequency of precipitation.

6.5.1. Mixing Depth

In this report different versions of the depth of the mixing layer are:

a) at first are used the values of the depth of the mixing layer (L) attributed to Klug [7,17] for West Germany which are the following for A - 1500 m; B - 1500 m; C - 1000 m; D - 500 m; E - 200 m; F - 196 m (base case).

b) in the second case it is assumed that the value of L is 1.5 times higher than in the base case (with the exception of value L for stability category F, because the depth of the mixing layer for this category must be less than 196 m in this calculation model). This gives the following values: for A - 2250 m; B - 2250 m; C - 1500 m; D - 750 m; E - 300 m; F - 196 m.

c) in the third case it is assumed that the value of L is 1.5 times lower than in the base case. The values of L are the following: for A - 1000 m; B - 1000 m; C - 666 m; D - 333 m; E - 133 m; F - 130 m.

Because ^{85}Kr is unaffected by any depletion mechanism - other than diffusion - this radionuclide was chosen for this text.

The results of the calculations are presented in Appendix E.

6.5.2. Stability Class

In this report three different versions of stability class are considered:

a) in the first case (base case) are used the values of the frequency of the occurrence of a particular stability class (fs) which were obtained by measurements along the Risø tower. The values of fs are the following: for A - 1.177%; B - 1.741%; C - 3.341%; D - 60.257%; E - 27.10%; F - 6.52% [31].

b) in the second case it is assumed that the average daytime stability classification could be approximated by type C and the night-time classification by type D. Then the values of fs are the following: for A - 0%; B - 0%; C - 50%; D - 50%; E - 0%; F - 0%.

c) in the third case it is assumed that the average stability classification during the whole time is D; then the values of fs are the following: for A - 0%; B - 0%; C - 0%; D - 100%; E - 0%; F - 0%.

Because ^{85}Kr is unaffected by any depletion process - other than diffusion - this radionuclide was chosen for this test.

The results of the calculation are presented in Appendix E.

6.5.3. Deposition Velocity

In this report five values of deposition velocity are taken into account - Vg

- 0 cm/s
- 0.2 cm/s
- 0.5 cm/s (base case)
- 1 cm/s
- 2 cm/s

Iodine-131 was chosen for this test. The results of the calculation are presented in Appendix E.

6.5.4. Washout Coefficient

In this report five values of washout coefficient are considered -

- 0 sec^{-1}
- 10^{-5} sec^{-1}
- 5×10^{-5} sec^{-1} (base case)
- 2×10^{-4} sec^{-1}
- 10^{-3} sec^{-1}

Iodine-131 was chosen for this test. The results of the calculations are presented in Appendix E.

6.5.5. Rainfall Variations

In this report five values of the percent frequency of rainfall - fw - were considered

- 0%
- 25%
- 43.5% (base case)
- 75%
- 100%

Iodine-131 was chosen for this test. The results of the calculations are given in Appendix E.

7. SUMMARY

A model for estimation of the potential submersion and inhalation radiation doses to people located within a distance of 1000 km from a nuclear power plant during its normal operation is presented in this report. The model was used to calculate these doses for people living 200-1000 km from a hypothetical nuclear facility situated near the geographical centre of Denmark. For this situation two cases of sources are considered:

- unit release of 15 isotopes of noble gases and iodines (listed in 6.1.1) which constitute the major radiation hazards in gaseous effluents,
- effluent releases from two types of 1000 MWe Light Water Power Reactors: the Boiling Water Reactor (BWR) and the Pressurized Water Reactor (PWR).

This report considers 16 conceptual gaseous radwaste treatment systems covering the range of the state-of-the-art in treat-

ment technology for BWR and PWR systems: 7 cases for BWR and 9 cases for PWR. Case No. 1 in each category is intended to provide a basis for comparison to demonstrate the effectiveness of subsequent treatment systems. The succeeding cases are developed to evaluate modifications in radwaste systems to reduce radioactive emission.

Radionuclide releases from these facilities are estimated, transport through the region is modelled, and the resulting concentrations are used to calculate submersion and inhalation doses to 235 million inhabitants of the study area.

The results of the study based on selected radiation waste treatment systems for PWR and BWR reactors show that the radiation potentially received by the population from discharges of radionuclides from these reactors represents only a small fraction of the radiation received from natural background radiation. Table 7.1 presents a tabulation of the various sources of radioactivity to which man is usually or occasionally exposed [34].

The total average annual whole body dose to the population of the study area (mrem/capita) from natural and man-made sources (without doses from radioactive effluents from the nuclear industry) is about 136-351 mrem/capita. The average annual whole body dose to the population of the study area from nuclear effluents from PWR releases is about $2.0 \times 10^{-7} - 2.0 \times 10^{-5}$ mrem/capita and BWR releases $1 \times 10^{-6} - 7 \times 10^{-4}$ mrem/capita. The results of the study indicate that the radiation doses generally received by people in this region as the result of the operation of a hypotehtical nuclear power plant located in Denmark would be a very small addition to the unavoidable dose due to natural background radiation, medical treatment, fallout from nuclear weapons, and a variety of miscellaneous scurces of radiation.

In table 7.2 and table 7.3 are presented the average individual dose rates for the whole region of study (mrem/year per capati) for PWR releases and BWR releases respectively for 9 PWR Gaseous Treatment Systems and 7 BWR Gaseous Treatment Systems.

Average individual doses for particular wind directions for all rings and for particular rings for all wind direction sectors are listed in tables 7.4 and 7.5 respectively (for PWR case 7).

Parameter variations were made and analysed to better understand the mechanism in the model. Because of the large contributions from airborne radionuclides, uncertainties in meteorologi-

cal parameters can have relatively large effects on radiation potentially received by the population. A series of calculations was made to estimate the effects of variations in meteorological conditions on airborne radionuclide transport. Changes were assumed in mixing layer depth (Figure 7-1), atmospheric stability (Figure 7-2), frequency of precipitation (Figure 7-3), deposition velocities (Figure 7-4), and washout coefficients (Figure 7-5). Extreme variations of any one parameter could affect doses by a factor of ten or greater. However, variations of this type are expected to be short-lived and would not affect the season-average values used in the study.

Table 7.1

Average annual whole body dose to population of study region from various environmental sources, mrem

Source	Annual dose mrem
Naturally occurring background radiation [34]	100
Fallout [34]	5
Medical-dental sources of radiation [34]	30-200
Miscellaneous man-made sources of radiation (TV, Watch, dials, etc.) [34]	1
TOTAL	136-351
Potential radiation from 1000 MWe BWR Nuclear Power Facility effluents (Normal operation)	$1 \times 10^{-6} - 7 \times 10^{-4}$
Potential radiation from 1000 MWe PWR Nuclear Power Facility effluents (Normal operation)	$2 \times 10^{-7} - 2 \times 10^{-5}$

Table 7.2

Average individual doses for PWR release
(for all sectors and all rings)
mrem/year per capita

Case	Annual costs ($ thousands)	Av. individual submersion dose, mrem/y per capita		Av. individual inhalation dose, mrem/y per capita	
		Skin	Total body	Thyroid	Total body
1	68	5.02×10^{-5}	1.72×10^{-5}	2.77×10^{-6}	5.02×10^{-9}
2	90	5.79×10^{-6}	1.16×10^{-6}	7.70×10^{-7}	1.39×10^{-9}
3	244	5.79×10^{-6}	1.16×10^{-6}	1.29×10^{-7}	2.31×10^{-10}
4	442	5.45×10^{-6}	1.03×10^{-6}	7.15×10^{-8}	1.29×10^{-10}
5	289	3.34×10^{-6}	2.66×10^{-7}	1.20×10^{-7}	2.15×10^{-10}
6	245	5.40×10^{-6}	1.03×10^{-6}	1.84×10^{-7}	3.32×10^{-10}
7	264	5.79×10^{-6}	1.16×10^{-6}	1.41×10^{-8}	2.52×10^{-11}
8	400	3.14×10^{-6}	2.19×10^{-7}	1.05×10^{-7}	1.89×10^{-10}
9	731	5.45×10^{-6}	1.03×10^{-6}	6.72×10^{-8}	1.21×10^{-10}

Table 7.3

Average individual doses for BNR release
(for all sectors and all rings)
mrem/year per capita

Case	Annual costs ($ thousands)	Av. individual submersion dose, mrem/y per capita		Av. individual inhalation dose, mrem/y per capita	
		Skin	Total body	Thyroid	Total body
1	138	1.98×10^{-6}	7.11×10^{-7}	5.91×10^{-8}	1.01×10^{-10}
2	358	1.58×10^{-6}	7.11×10^{-7}	1.53×10^{-9}	2.62×10^{-12}
3	657	6.17×10^{-8}	2.24×10^{-8}	1.06×10^{-9}	1.80×10^{-12}
4	963	6.17×10^{-8}	2.24×10^{-8}	1.06×10^{-9}	1.80×10^{-12}
5	820	6.17×10^{-8}	2.25×10^{-8}	1.33×10^{-9}	2.27×10^{-12}
6	715	8.26×10^{-9}	2.28×10^{-9}	2.71×10^{-10}	4.64×10^{-13}
7	1130	5.32×10^{-9}	1.26×10^{-9}	5.06×10^{-11}	8.81×10^{-14}

Table 7.4

Average individuals doses for particular wind directions for all rings
(PWR case 7)
mrem/year per capita

Doses	0	1	2	3	4	5	6	7	8	9	10	11
Average individual submersion dose to total body, mrem/year per capita	1.34×10^{-6}	1.61×10^{-6}	2.49×10^{-6}	1.6×10^{-6}	1.17×10^{-6}	1.20×10^{-6}	1.33×10^{-6}	1.14×10^{-6}	7×10^{-7}	8.73×10^{-7}	9.92×10^{-7}	2.27×10^{-6}
Average individual inhalation dose to thyroid, m/year per capita	2.05×10^{-8}	3.06×10^{-8}	4.14×10^{-8}	2.16×10^{-8}	1.63×10^{-8}	1.67×10^{-8}	1.76×10^{-8}	1.24×10^{-8}	3.05×10^{-9}	9.6×10^{-9}	1.14×10^{-8}	4.7×10^{-8}

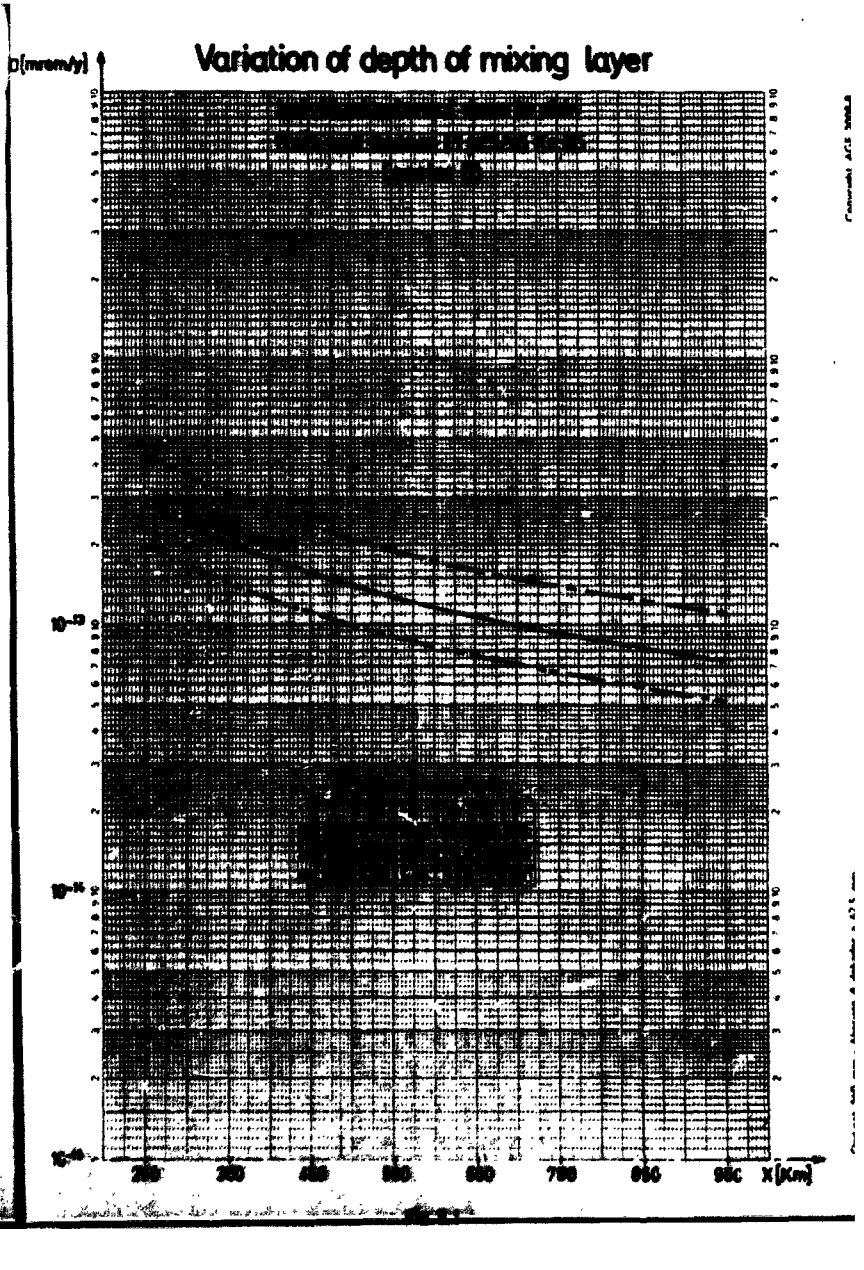

Variation of depth of mixing layer
D(mem/y)
X(Km)

Table 7.5

Average individual doses for particular rings
for all wind directions (PWR case 7)
mrem/year per capita

Ring	Average individual submersion dose to total body mrem/year per capita	Average individual dose to thyroid mrem/year per capita
200- 300 km	3.77×10^{-9}	9.18×10^{-11}
300- 400 km	2.40×10^{-9}	4.67×10^{-11}
400- 500 km	1.75×10^{-9}	2.76×10^{-11}
500- 600 km	1.45×10^{-9}	1.9×10^{-11}
600- 700 km	1.13×10^{-9}	1.18×10^{-11}
700- 800 km	9.47×10^{-9}	8.35×10^{-12}
800- 900 km	8.12×10^{-10}	5.87×10^{-12}
900-1000 km	7.36×10^{-10}	4.49×10^{-12}

Variation of frequency of rain
p[mm/h]
10⁻¹⁰
10⁻¹¹
10⁻¹²
X[Km]

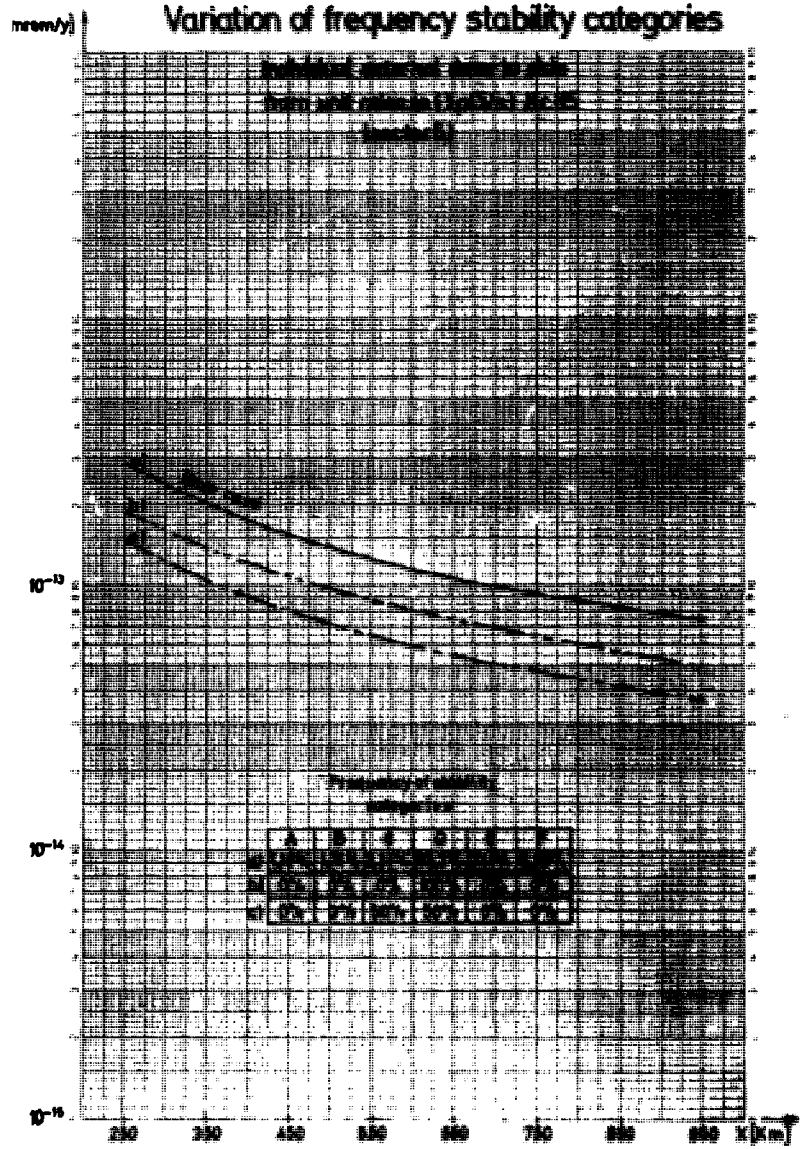
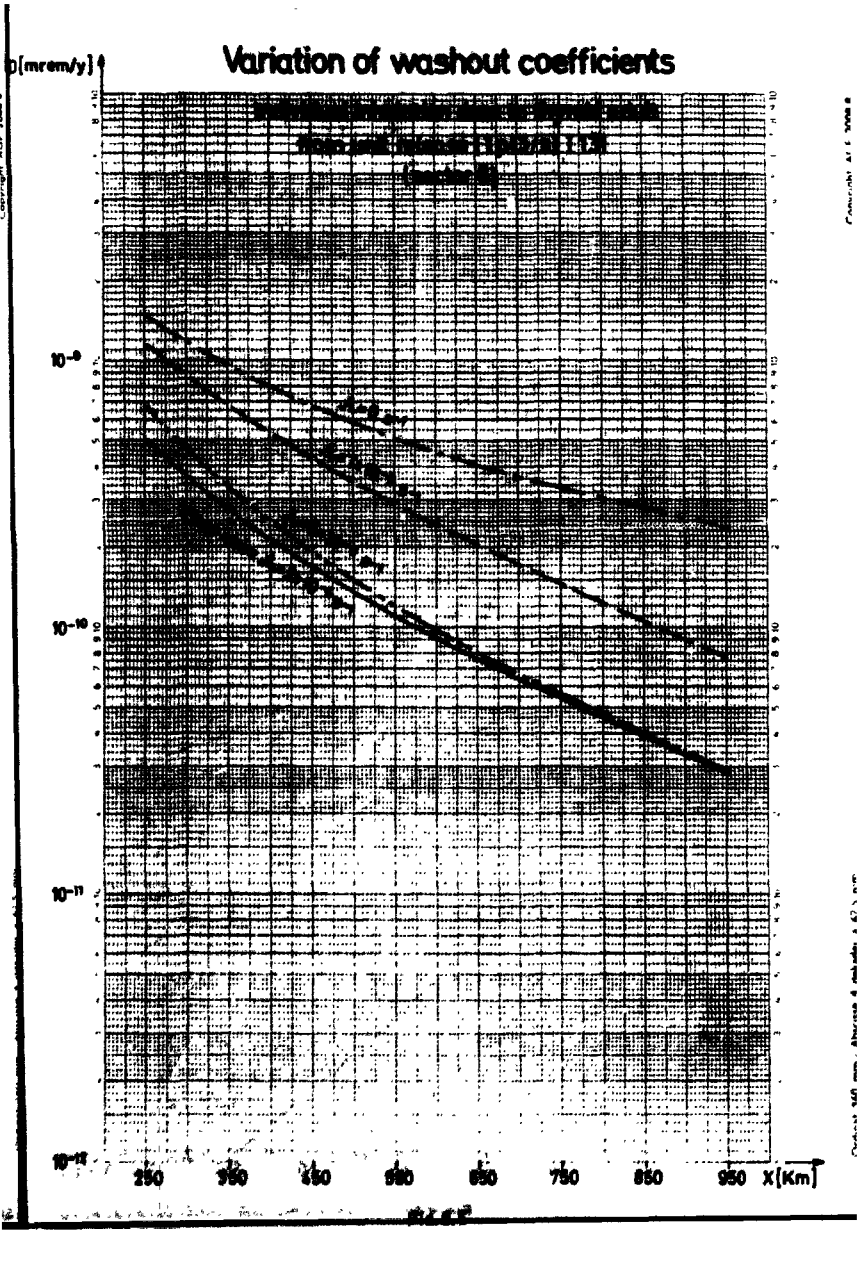

Variation of frequency stability categories
mrem/yl
10^{-13}
10^{-14}
10^{-15}
A
B
C
D
E
F

Fig 6.2


Variation of washout coefficients
D[mrem/y]
10⁻⁹
10⁻¹⁰
10⁻¹¹
10⁻¹²
250
350
450
550
650
750
850
950
X[Km]

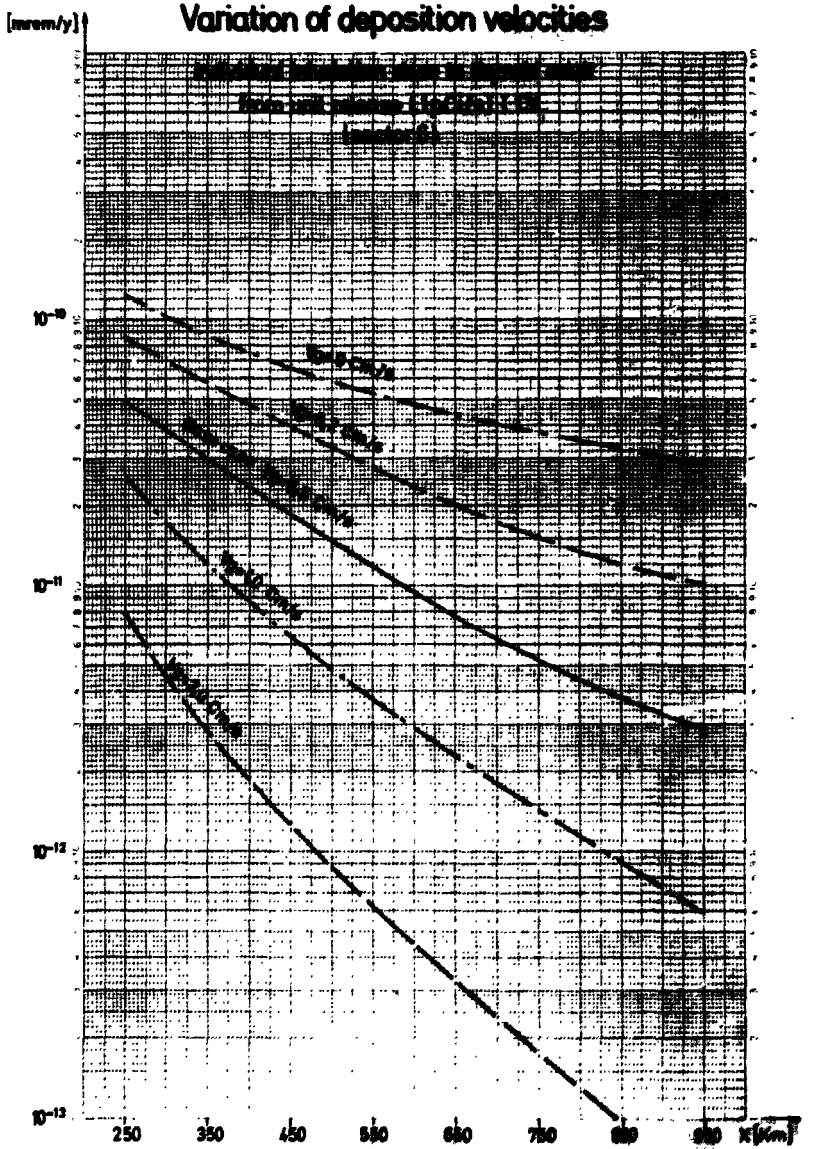

[mm/y]
Variation of deposition velocities
10^{-10}
10^{-11}
10^{-12}
10^{-13}
250
350
450
550
650
750
850
950
x [km]

Fig. 8.4.

ACKNOWLEDGEMENTS

I would like to express my sincere thanks to Mr. Ole Walmod-Larsen, Mr. Søren Thykier-Nielsen, and Mr. Per Hedemann Jensen for their helpful discussions and review of this manuscript. I am also grateful to Mr. Hedemann Jensen for writing the computer program used in these calculations.

REFERENCES

1) The Safety of Nuclear Power Reactors (Light Water-Cooled) and Related Facilities, WASH-1250 (July 1973).

2) The Potential Radiological Implications of Nuclear Facilities in the Upper Mississipi River Basin the the Year 2000, WASH-1209 (January 1973).

3) Hermes: A Digital Computer Code for Estimating Regional Radiological Effects from the Nuclear Power Industry, BNDL-TME 71-168 (December 1971).

4) Final Environmental Statement Concerning Proposal Rule Making Action: Numerical Guides and Limiting Conditions for Operation to Meet the Criterion "As Low as Practicable" for Radioactive Material in the Light-Water-Cooled Nuclear Power Reactor Effluents, RIS-AA-73-1252-F-1 (July 1973).

5) Draft Environmental Statement Concerning Proposed Rule Making Action: Numerical Guides for Design Objectives and Limiting Conditions for Operation to Meet the Criterion "As Low as Practicable" for Radioactive Material in Light-Water-Cooled Nuclear Power Reactor Effluents, U.S. Atomic Energy Commission (Januar 1973).

6) J.M. Beattie and Pamela M. Bryant, Assessment of Environmental Hazards from Reactor Fission Product Releases, AHSB(S)R 135 (May 1970).

7) K.J. Vogt, Dispersion of Airborne Radioactivity Released from Nuclear Installations, Population Exposure in Local and Regional Environment, Symposium on the Physical Behaviour of Radioactive Contaminants in the Atmosphere (IAEA, 12-16 November 1973, Vienna).

8) Meteorology and Atomic Energy, TID-24190 (July 1968).

9) F. Pasquil, The Estimation of Dispersion of Windborne Material, Meteorological Magazine 90, 1063, 33-49 (1961).

10) J.M. Eisenbund, Environmental Radioactivity, Academic Press (1973).

11) D.B. Turner, Workbook of Atmospheric Dispersion Estimates. Environmental Protection Agency (1970).

12) Environmental Analysis of the Uranium Fuel Cycle, EPA-520-9-73-3-D (October 1973).

13) Environmental Radiation Dose Commitment: An Application to the Nuclear Power Industry, U.S. Environmental Protection Agency (February 1974).

14) J.F. Fletcher et al., "Modelling the Regional Transport of Radionuclides in a Major United States River Basin", Symposium on the Environmental Behaviour of Radionuclide Released in the Nuclear Industry (IAEA, 14-18 May 1973, Aix-En-Provence).

15) C.R. Dickson, Meteorology for the Loss of Fluid Test Reactor - Progress Report, IDO-12059 (1967).

16) Reactor Safety Study, An Assessment of Accident Risks in U.S. Commercial Nuclear Power Plants, WASH-1400 (August 1974).

17) A. Bayer et al., Population Dose Considerations for the Release of Tritium, Noble Gases and ^{131}I in a Special Region, Symposium on the Population Dose Evaluation and Standards for Man and His Environment (IAEA, 20-24 May 1974, Portoroz).

18) R.J. Engelmann, Calculation of Precipitation Scavenging of Particulates and Gases from the Atmosphere, Nuclear Safety 7 (3), 354 (1966).

19) J.R. Beattie, An Assessment of Environmental Hazards from Fission Product Releases, AHSB(5)R 9 (May 1961).

20) R.H. Clarke, Physical Aspects of the Effects of Nuclear Reactors in Working and Public Environments, Berkley Nuclear Laboratories, Central Electricity Generating Board (January 1973).

21) M.G. Stewart and R.N. Crooks, Long-range Travel of the Radioactive Cloud from the Accident at Windscale, Nature Vol. 182, p. 627 (1958).

22) U.S. Air Force Report NARP-59-32I, Fission Product Yield Release (1959).

23) M.E. Fields, Deposition Velocities of Airborne Fission Products, Convair Report FZM 1985 (1960).

24) R.J. Engelmann, Wash-Out Coefficients for Selected Gases and Particulates, BNWL-SA-657 (1966).

25) Report on Committee II on Permissible Dose for Internal Radiation, ICRP Publications 2 (1959).

26) National Council on Radiation Protection and Measurements, Basic Radiation Protection Criteria, NCRP Report No. 39 (January 1971).

27) C.M. Lederer et al., Table of Isotopes, 6-th Ed., John Wiley and Sons, Inc., New York (1967).

28) L. Shook and K. May, Radiations from Radioactive Atoms in Frequent Use, U.S. Atomic Energy Commission, Washington, D.C. (1959).

29) J.F. Soldat et al., "Applications of a General Computational Model for Composite Environmental Radiation Doses, Symposium on the Environmental Behaviour Radionuclides Released in the Nuclear Industry (IAEA, 14-18 May 1973, Aix-En-Provence).

30) J.K. Soldat et al., Computational Model for Calculating Doses from Radionuclides in the Environment, Battle Pacific Northwest Laboratories (May 1973).

31) B.G. Jensen, Occurrences of Stability Classes Wind Speeds and Wind Directions as Observed at Risø, Risø-M-1666 (October 1973).

32) Danmarks Statistik, Statistisk Arbog, 1972.

33) Demographic Year Book 1972, United Nations.

34) Ionizing Radiations: Levels and Effects, A Report of the United Nations Scientific Committee on the Effects of Atomic Radiation to the General Assembly with Annexes (1972).

35) Per Hedemann Jensen, POPDOS, A Computer Model for Calculating Individual and Population Doses Within a Radius of 1000 km, Health Physics Department - Risø, March 1975.