METEOROLOGICAL AND STACK HEIGHT ANALYSIS FOR THE SAFE ATMOSPHERIC DISPERSION OF RADIOACTIVE WASTES

By

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Submitted In partial fulfilment of the requirements
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DECLARATION

This thesis is an original work carried out by the author under the supervision of Dr. S. B. Elegba and Dr. K. G. Boboli

To the best of my knowledge, no part thereof has been submitted elsewhere for the award of a degree, or diploma, and the work of others is acknowledged and referenced.

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CERTIFICATION

This thesis entitled "METEOROLOGICAL AND STACK HEIGHT ANALYSIS FOR THE SAFE ATMOSPHERIC DISPERSION RADIOACTIVE WASTES" by Mallam Haruna Bala GARBA, meets the regulations governing the award of the degree of Master of Science, Nuclear Physics of Ahmadu Bello University, and is approved for its contribution to knowledge and literary presentation.

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ABSTRACT

Ahmardu Bello University (A.B.U.),Zaria, Nigeria is planning to purchase and install a small nuclear research reactor within the Zaria environs. It is a well known fact that the operation of any nuclear facility generates some airborne wastes in addition to other classes of waste. This work was carried out to analyse the meteorological condition! inherent to the Zaria environment, with special referenc i to atmospheric dispersion of any airborne effluents the research reactor miqht release. To this end, meteorological data collected ov r thirty-two years at the Institute of Agricultural Research, A.B.U. Zaria was analysed. Result from the meteorological analysis was utilized to obtain the expected dispersion and distribution of airborne effluents from the reactor at the proposed site. Graphical presentation of ground level air concentration of emitted effluents from exhaust stacks of various heights is given.

Results of meteorological analysis for the selected site was utilized in conjuntion with the discharges from a reactor of similar make and rating with the Ahmadu Bello University reactor. An optimum stack height of not- less than thirty meters was obtained. This height will ensure adequate dilution of airborne effluents, with no downwind location being exposed to concentration level above the internationally accepted- maximum **permissible level.** For **stack height thirty** meters, airborne **effluent concentration downwind will always be below ten fermi-Curies per cubic centimeter. This holds for all the monthly cases analysed and also for the downwind locations where maximum concentrations occur.**

DEDICATION

This work is dedicated especially to my late parents, all their siblings and those who struggle for the cause of Allah. May Allah in His Mercy repose them and grant them peace in the hereafter.

TABLE OF CONTENTS

Chapter		Page
	Title Page	i
	Declaration	ii
	Certification	iii
	Acknowledgements	iv
	Abstract	vi
	Dedication	vii
	Table of Contents	viii
	List of Tables	x
	List of Figures	xii
	List of Appendices... ...	xiii
	Abbreviations,Definitions and Symbols	xiv
1.	INTRODUCTION	1
2.	THE ATMOSPHERIC DIFFUSION PROBLEM	5
2.1	Medium and Sources of Diffusion	7
2.2	The Continuous Point Source in a Real Atmosphere	10
3.	SOME FACTORS AFFECTING ATMOSPHERIC DIFFUSION DIFFUSION OF RADIOACTIVE WASTES	12
3.1	Reactor Factors	12
3.1.1	Stack height and orifice diameter	17
3.2	Meteorological Factors ...	20
3.2.1	Atmospheric factors ...	20
	Stability categories ...	22
	Wind direction and speed ...	26

Chapter		page
4.	THE SELECTED SITE FOR THE PROPOSED RESEARCH REACTOR OF AHMADU BELLO UNIVERSITY	30
4.1	Samaru-Zaria Location and Geography	30
4.2	Reactor Data	33
4.3	Meteorological Data... ...	35
4.3.1	Atmospheric data	35
4.3.2	Terrestrial factors... ...	47
4.3.3	Settling speed Vg	49
4.3.4	Rainfall washout coefficient ...	50
4.4	Numerical Solution	50
5.	DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS	53
5.1	Discussions	53
5.2	Conclusions and Recommendations.	58
REFRENCES	... ...	60
APPENDICES	... ...	66-99

LIST OF TABLES

TABLE NO.	CAPTION	PAGES
1.1	Maximum permissible concentrations for some important radionuclides in air for (168 hour/ week) occupational exposure ...	4
3.1	Grouping of radionuclides that may contribute significantly to the releases from nuclear power plants	14
3.2	Key to stability categories ...	22
4.2	Mean monthly temperature recorded at two levels, 30 and 122 cm above ground level, based on I.A.R. Meteorological Office records for the period 1954 - 1985. ...	36
4.3	Mean daily solar radiation, $\bar{H}(MJ/M^2/day)$, presented on a monthly basis for the period 1977 to 1985	39
4.4	Rainfall monthly means and standard deviation based on I.A.R.Meterological Office records for the period 1954 - 1985 ...	40
4.5	Monthly mean wind speed with standard deviations for data obtained from the I.A.R. Meteorological Office for the period 1957-1985	41
4.6	Chi-squared tests for main wind directions	46
4.7	Summary of plant cover height data ...	48
4.8	Values of constants used in calculations of dispersion coefficients	51-52

TABLE NO.	CAPTION	PAGES
B.1	Fission product release source summary- best total core release fraction ...	79
C	Airborne effluents release figures for the Texas A & M University reactor for the period 1983 to 1985...	83-88

LIST OF FIGURES

Figure No.	Caption	Pages
3.1	Stack effluent behaviour... ...	25
4.1	Proposed reactor site and its environs	32
4.2	Rough estimates of the vertical temperature profiles expected for the different months of the year at the proposed site.	37
4.3	Windroses for the twelve months of the year	42-45
5.1	A.B.U. Masterplan (extract), showing the reactor site	54
B.1	A typical Triga Fuel element... ...	76
B.2	Vertical section of a Triga Mark II Reactor showing reactor platform, Core and Pool	76
D.1	Relative air concentration at ground level as a function of downwind distance. ...	89-91
D.2	Relative air concentration at ground level as function of height.	92-93
D.3	Plume depletion fration as a function of downwind distance....	94-96
D.4	Mean concentration of stack effluent at ground level as a function of downwind distance	97-99

LIST OF APPENDICES

Appendix		pages
A.I	SOLVING THE INSTANTENEOUS POINT SOURCE PROBLEM	66
A. II	THE FRACTION OF EFFLUENT PASSING DOWNWIND LOCATIONS	74
B	RELEASE OF RADIOACTIVITY FROM THE CORE TO THE ATMOSPHERE	75
B.I	RELEASE FROM CORE TO CONTAINMENT BUILDING	
	Loss Of Coolant Accident	75
	Gap release	77
	Melt down release	80
	Vaporisation release	80
	Oxidation release	81
	Nuclear Excursions	81
B.II	RELEASE FROM CONTAINMENT TO OUTSIDE ATMOSPHERE	82
C	AIRBORNE RELEASES FROM THE TEXAS A & M UNIVERSITY REATOR	83-88
D	GRAPHICAL PRESENTATIONS OF RESULTS OBTAINED	89-99

h	=	mean plant cover height
h_b	=	increase in source height due to buoyancy
h_s	=	Physical stack height
h_v	=	Increase in source height due to effluent exit velocity.
Δh	=	sum of increases due to effluent buoyancy and exit velocity.
K, K_x, K_y, K_z.	=	diffusion constants of the K-theory.
Q	=	quantity of diffusing material(also used as emission rate at which diffusing passes a point) Q $m^3/_s$
q	=	heat flux
T	=	temperature
$T_{\frac{1}{2}}$	=	half life of a radioactive isotope
$\bar{u}$	=	mean wind speed
v_e	=	effluent exit velocity at stack orifice.
v_g	=	deposition velocity(of effluent material)
w	=	deposition rate per unit area

$\bar{\chi}$ or $\chi(x,y,z)$ = Mean concentration of effluent material in air at the specified location.

z_o = roughness length

$\sigma_y(x), \sigma_z(x)$ = the crosswind and vertical dispersion

CHAPTER ONE INTRODUCTION

The proposed nuclear research reactor is being studied vis-avis the site approved for its installation in terms of the formers effluents and the latters ambient meterological conditions. The operation of any nuclear facility generates radioactive wastes in the three states of matter, namely; solid, liquid and gas. This work is carried out to analyse the handling of gaseous wastes, of low level activity. This is necessary to enable the operators of the facility comply with the International Commission on Radiological Protection (ICRP) guideline that, "The authority in charge of any establishment or operation which might cause environmental contamination should limit the exposure of members of the public so as to comply with the relevant national or local requirements and the commissions recommendations by controlling the release of radioactive materials into the environment" (IAEA, 1977).

This work is therefore very relevant at the stage we are. It is hoped it will pave way for the acceptability and smooth take off of nuclear technology in the country. Disposing of radioactivity to the environment is sometimes inevitable but where this must be done, the level of radioactive contamination should always be below the internationally accepted maximum permissible level* for the radionuclides discharged. For the case of radioactive wastes contained in the gaseous state, certain steps are taken to control the level of contamination of the environment. These include storage for sometime to enable decay, filteration and dispersing

*see table 1.1 at the end of this chapter.

the remaining low level activity through the atmosphere (IAEA, 1966).

To disperse low level radioactive wastes through the atmosphere, meteorological analysis of the proposed site is necessary. Also necessary is the determination of the stack height range that would give adequate dispersion.

Dispersing waste material via a high exhaust stack enables the materials to be adequately diluted before it reaches the ground level. Its distribution on the ground will be principally along the downwind side of the stack with respect to wind direction. Generally speaking, the air concentration of the exhaust waste at ground level will be negligible near the stack base and increasing concentration will be met with increasing downwind distance until a point of maximum concentration is reached. After this point, concentration of the exhaust waste material will again gradually die out. The horizontal distance at which maximum concentration occurs is determined by wind speed, stability category of the atmosphere, nature of the terrain and some other factors. Thus the level of activity at the point of maximum concentration is of great importance in terms of radiation protection and stack height estimate.

In this work an attempt is made in studying the meteorological conditions obtained at the proposed site and applying them to study the ground level distribution of stack exhaust waste gas for various stack heights. From the analysis of the results obtained, some suitable stack heights are proposed to minimize environmental contamination, especially for settlement areas. Having enumerated some objectives of the work, its summary is given below.

A brief review and a derivation of the theory to be used in this work is given in chapter two. This derivation takes care of two types of sources as well as two types of media. These are the instantenuous and the continuous sources. While media discussed are ideal and real media. As regards to geometry of source, it could be point, linear or planar. The medium through which the effluent is dispersed if at rest is referred to as ideal , while if in motion is referred to as real. Most of these are adequately discussed in chapter two. Chapter three gives an analysis on factors affecting atmospheric dispersion of radioactive wastes. Factors thoroughly discussed are those involving the reactor which is the generating source of the radioactive wastes and meteorological factors which take care of the dispersion medium. Location and geography of the proposed site are discussed in the beginning of chapter four. The chapter continues with analysis of available data on the issues raised in chapter three. At the end of the chapter, a brief discussion of results for the selected site is given. Chapter five gives some discussion, conclusion and recommendations that can be made on the basis of the data available and the results obtained. At the tail end of the write up, are appendices that highlight certain essential issues that are avoided in the main text, for the sake of clear presentation.

Appendix A is the mathematical derivation of the instantenuous point source problem, for the K-theory. Appendix B highlights modes through which some radioactive materials move from the reactor core to the atmosphere. Graphical representation of the results obtained are given in appendix C.

Below is a listing of some of the most significant radionuclides and their maximum permissible concentrations (MPC) in air.

Nuclide	Nuclide	MPC in air (uCi/cc)
	$^{3}H(\beta^-)$	2×10^{-4}
	$^{41}Ar(\beta^-,\gamma)$	4×10^{-8}
	$^{87}Kr(\beta,\gamma)$	2×10^{-8}
	$^{85}Sr(\epsilon,\gamma)$	4×10^{-9}
	$^{90}Sr(\beta^-)$	7×10^{-10}
	^{125}I	8×10^{-11}
	$^{131}I(\beta^-,\gamma,e^-)$	1×10^{-10}
	$^{135}Xe(\beta^-,\gamma)$	1×10^{-7}
	$^{135}Cs(\beta^-)$	4×10^{-9}
	$^{137}Cs(\beta^-,\gamma,e^-)$	5×10^{-9}

Table 1.1- Maximum permissible concentrations of some important radionuclides in air (for 168 hour week) occupational exposure
(Extracts from Henry,1969; Brodsky)

CHAPTER TWO: THE ATMOSPHERIC DIFFUSION PROBLEM

A number of models have been developed for solving the atmospheric diffusion problem. Among these are the statistical model, the mixing length model, the similarity theory and the K-theory, see for example Sutton (1977), Vogt(1974). In this work the K-theory will be utilized in analysing the atmospheric diffusion problem at the sellected site for the proposed Ahmadu Bello University, research reactor. This choice is based on the simplicity and direct applicability of the theory to the problem at hand. The starting point of the K-theory is the conduction of heat in a material (Sutton, 1977). The working equation of the theory, for isotropic material, is

$$\frac{dE}{dt} = K \nabla^2 E$$

$$= K\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}\right) E \qquad (2.1)$$

For anisotropic material the equation is

$$\frac{dE}{dt} = \left(K_x \frac{\partial^2}{\partial x^2} + K_y \frac{\partial^2}{\partial y^2} + K_z \frac{\partial^2}{\partial z^2}\right) E \qquad (2.2)$$

The derivation of this relation can be found in relevant textbooks (for example Micrometeorology by Sutton, 1977).

E is used in general as entity of interest that diffuses in the medium. For the case of atmospheric problem, which is the diffusion of one gas

into another, E would be replaced by χ. where χ is denoting concentration of the diffusing gas. To attempt a successfull solution of the above equation initial and boundary conditions must be imposed in conformity with the problem.

The simplest case to be considered is the so called instanteneous point source in an ideal medium. In it, a quantity, q, of diffusing material is considered to be released at a point in a stationary diffusion medium. Logically, high concentration occurs at the point of release at that instance. Diffusion thus occurs and the concentration of the diffusing material becomes so much dilute that it tends to zero, at all points in space, after a prolonged duration. Therefore, the problem is stated (Sutton, 1977; Pasquill, 1974) as

$$\frac{d\chi}{dt} = K\nabla^2\chi$$

Subject to the boundary conditions

$$\chi \longrightarrow 0 \quad \text{as} \quad t \to 0, r > 0 \qquad (2.3)$$

$$\chi \longrightarrow 0 \quad \text{as} \quad t \longrightarrow \infty \qquad (2.4)$$

and the continuity condition.

$$Q = \int \chi d\vec{r} = 4\pi \int_0^\infty \chi r^2 dr.$$

The solution to this problem, derived in appendix A, for a source located at the origin that releases the diffusing material at the instance t=0 is,

$$\chi(x,y,z,t) = \frac{Q}{(4\pi t)^{3/2} K_x^{1/2} k_y^{1/2} k_z^{1/2}} \exp\left(-\frac{x^2}{4K_x t} - \frac{y^2}{4K_y t} - \frac{z^2}{4K_z t}\right) \quad (2.6)$$

This solution conforms to the initial and boundary conditions and was used to represent the diffusion of smoke formed by an explosion, see Sutton (1977). For a source outside the origin the solution is modified by replacing the point x,y,z and time t by $x-x'$, $y-y'$, $z-z'$ and $t-t'$ in the right hand side of above equations. The primed coordinates refer to the point and instance of release.

2.1 Media and Diffusion sources

Basically two types of medium of atmospheric diffusion can be considered; these are, the ideal (medium at rest) and the real (medium in motion) media. Sub-classes of each may be isotropic and anisotropic. Sources on the other hand can be point, linear or planar; in addition each could be instanteneous or continuous. The solution derived above is for instantenous point source. The solution derived can be related to these other situations, as is done for some few below.

The solution for the instanteneous point source in an ideal anisotrophic medium in cartessian

$$\chi(x,y,z,t) = \frac{Q}{[4\pi(t-t')]^{3/2} K_x^{1/2} K_y^{1/2} K_z^{1/2}} \exp\left[-\frac{(x-x')^2}{4K_x(t-t')} + \right.$$

$$\left. - \frac{(y-y')^2}{4K_y(t-t')} - \frac{(z-z')^2}{4K_z(t-t')}\right] \qquad (2.7)$$

Now consider a moving medium. Let the primed coordinates represent the moving frame, moving with mean velocity, $\bar{u}$, along the x-axis for example. Then for a puff released at the point (0,0,H) and time $t' = 0$ of the moving frame, the concentration of diffusing material in the non-moving frame at any point by virtue of the x- direction motion is given by

$$\chi(x,y,z,t) = \frac{Q}{[4\pi t]^{3/2} K_x^{1/2} K_y^{1/2} K_z^{1/2}} \exp\left[\frac{-(x-\bar{u}t)^2}{4K_x t} - \frac{y^2}{4K_y t} + \right.$$

$$\left. - \frac{(z-H)^2}{4K_z t}\right] \qquad (2.8)$$

Diffusion along the x-axis will be suppressed due to motion along that axis. The explicit statement of this is given by Lewis (1977) for $K_x \rightarrow 0$ as

$$\lim_{K_x t \to 0} \frac{\exp\left[\frac{-(x-\bar{u}t)^2}{4K_x t}\right]}{(4\pi K_x t)^{\frac{1}{2}}} = \delta(x-\bar{u}t) = \frac{1}{\bar{u}}\delta\left(\frac{x}{\bar{u}} - t\right) \quad ---(2.9)$$

By the properties of the delta function

$$\delta\left(\frac{x}{\bar{u}} - t\right) = \begin{cases} 1, \text{ for } \left(\frac{x}{\bar{u}} - t\right) = 0 \\ 0, \text{ for } \left(\frac{x}{\bar{u}} - t\right) \neq 0 \end{cases}$$

Therefore,

$$\chi(x,y,z,t) = \frac{Q}{(4\pi t)\, K_y^{\frac{1}{2}} K_z^{\frac{1}{2}}\, \bar{u}} \exp\left(-\frac{y^2}{4K_y t} - \frac{(z-H)^2}{4K_z t}\right)\delta\left(\frac{x}{\bar{u}} - t\right)$$

Substituting $t = \frac{x}{\bar{u}}$, into the right hand side of the above equation gives

$$\chi(x,y,z,t) = \frac{Q}{4\pi \frac{x}{\bar{u}} K_y^{\frac{1}{2}} K_z^{\frac{1}{2}}\, \bar{u}} \exp\left(-\frac{y^2}{4K_y \frac{x}{\bar{u}}} - \frac{(z-H)^2}{4(K_z \frac{x}{\bar{u}})}\right)\delta\left(\frac{x}{\bar{u}} - t\right)$$

$$= \frac{Q}{2\pi \bar{u}\, \sigma_y \sigma_z} \exp\left[-\frac{y^2}{2\sigma_y^2} - \frac{(z-H)^2}{2\sigma_z^2}\right]\delta\left(\frac{x}{\bar{u}} - t\right) \text{---(2.10)}$$

where, $\sigma_y^2 = \frac{2K_y x}{\bar{u}}$

and $\sigma_z^2 = \frac{2K_z x}{\bar{u}}$

(Lewis, 1977; Sutton, 1977; Vogt, 1974) are called dispersion coefficients.

For the instanteneous point source the spatial and time coordinates (x,y,z,t) define the point and time at which the plume concentration is determined. For the instanteneous source, plume concentration is only significant at the point the plume is. The possible reflection of plume at ground/air interface is taken care of by introducing a ground reflection factor. This is obtained by considering an image source located at (-H) below the stack base. This is explicitly expressed as

$$\chi(x,y,z,t) = \frac{Q}{2\pi\bar{u}\,\sigma_y\sigma_z}\left(\exp-\frac{y^2}{2\sigma_y^2}\right)\left\{\exp\left(-\frac{(z-H)^2}{2\sigma_z^2}\right)+\right.$$

$$\left.+\exp\left(-\frac{(z+H)^2}{2\sigma_z^2}\right)\right\}\delta\left(\frac{x}{\bar{u}}-t\right). \quad (2.11)$$

(Lewis, 1977; Pasquill, 1974; Vogt, 1974; Gyllander and Widemo, 1974).

2.2 The Continuous Point Source in a Real Atmosphere.

The continuous point source in a real medium may be considered as a rapid succession of instanteneous point source releases. If the succession of releases is rapid enough and the time elapsed since the beginning of the releases is also long, then plume material will be present at all down wind locations at all time.

In other words, a continuously emitting source may be assumed. Thus, this continuous source, emitting material at a rate $Q'(t)$ per second will generate an instantenuous mean concentration of plume at all locations and time given by

$$\bar{\chi}(x,y,z,t) = \int_{-\infty}^{t} \frac{Q'(t_o)}{2\pi\bar{u}\sigma_y\sigma_z} \exp\left(-\frac{y^2}{2\sigma_y^2}\right) \exp\left(-\frac{(z-H)^2}{2\sigma_z^2}\right) \times$$

$$\times \delta\left(\frac{x}{\bar{u}} - t\right) dt_o \quad -- (2.12)$$

(Lewis, 1977). A time independent release rate Q', thus, gives the following mean plume concentration at the ground level ($z = 0$)

$$\bar{\chi}(x,y,o) = \frac{Q'}{\pi\bar{u}\,\sigma_y\sigma_z} \exp\left[-\left(\frac{y^2}{2\sigma_y^2} + \frac{H^2}{2\sigma_z^2}\right)\right] \quad --- (2.13)$$

At the centre line (y=0) of the plume, the mean plume concentration is

$$\bar{\chi}(x,0,0) = \frac{Q'}{\pi\bar{u}\,\sigma_y\sigma_z} \exp\left(-\frac{h^2}{2\sigma_z}\right) \quad ---- (2.14)$$

These results will be used in the following chapters to determine the amount of dispersion and consequent level of radioactivity in the areas surrounding the nuclear reactor site.

CHAPTER THREE - SOME FACTORS AFFECTING ATMOSPHERIC DIFFUSION OF RADIOACTIVE WASTES

This chapter analyses some of the important factors in atmospheric dispersion of radioactive wastes. These have been classified into two namely reactor and meteorological factors.

The general equation giving spatial plume concentration distribution, that is

$$\chi(x,y,z) = \frac{Q'}{2\pi \bar{U} \sigma_y \sigma_z} \exp\left(\frac{-y^2}{2\sigma_y^2}\right)\left[\exp\frac{-(z-H)^2}{2\sigma_z^2} + \exp\frac{-(z+H)^2}{2\sigma_z^2}\right] \quad \text{----- (3.1)}$$

will be analysed in terms of the above mentioned factors.

3.1 Reactor Factors

In the equation (3.1), Q' is the rate of emission of radioactive waste materials from the orifice of the reactor stack at a height H above the ground. The unit of Q' could be in Curies of activity released per second or grams of radioactive materials released per second. The numerical strength of the emission rate in the above equation is dependent on the reactor capacity, integrity of the reactor core, efficiency of the filteration system and decay storage time.

Generally speaking the strength of emission rate increases with increase in power capacity of the facility. Research reactors designed with small power levels generally a few megawatts (Ewa, 1982) emit less radioactive wastes than power reactors of hundreds to thousands of megawatts (Kent et al, 1971). In terms of radioactivity emission to the environment, reprocessing plants tend to pose more problem than even power reactors as has been mentioned by Laser et al (1974).

Reactor core integrity refers to the state of reactor core and its surrounding envelope under both normal and accident conditions. A nuclear reactor operates on nuclear fuel which is fissionable material. Under bombardment from neutrons, atoms of the fissionable material absorb the neutrons and break up into daughter atoms. This is accompanied by the release of energy, radiations and free neutrons. For the successful harnessing of the energy and for the sake of safeguarding man and his environment against radiation damage, the nuclear fuel is placed in special claddings and the chamber in which nuclear reaction takes place is specially built. This special building is called core containment and serves as a fission products/radiations barrier.

The inventory of radionuclides from light water power reactors includes approximately 360 radionuclides (Hosemann et al,1974). Of these only a small fraction are important due to their radiological toxicity. Five main sources of activity have been given as fuel, bred fuel, fission product, activated structural materials and activated coolant (Hosemann et al,1974).The ability of radioactivity from any of the above sources to escape the primary system envelope (core containment) is determined mainly by volatility and chemical properties. Table 3.1(Lewis,1977) is a convenient classification of some radionuclides likely to escape under accident conditions.

Table 3.1 - Groupings of radionuclides that may contribute significantly to radioactive releases from nuclears power plants

Xe, Kr, Ar	Noble gases	I Inert
I, Br	Halogens	II Volatile
Cs, Rb	Alkali Metals	
Te, Se, Sb	Tellurium group	
Ba,Sr	Alkaline earths	III Nonvolatile
Ru, Rh, Pd, Mo, Tc	Noble metals	
Y, La, Ce, Pr, Nd, Pm, Sm, Eu, Np, Fu	Rare earths	
Zr, Nb	Refractory oxides	

Group I Consists of the noble gases Xenon, Krypton and Argon which are gaseous elements at room temperature.

Group II Members of this group are partly volatile at (power) reactor operating temperatures (300^{o}-$600^{o}C$). Members of this group will significantly be released in the case of fuel melting. On account of yield and half life this group is narrowed down to two members Iodine and Caesium.

Group III Elements of this group remain involatile even at fuel-melting temperature. Their significant release will only occur on event of fuel vaporization or chemical reaction (Oxidation); if this happens they would condense into aerosol particles.

On the chemical and radiological importance of the above elements the following can easily be inferred. The noble gases argon (Ar), Krypton (Kr) and Xenon(Xe) are chemically inert. However, because of their existence in the gaseous form, they can easily be inhaled during respiration. Iodine (I) and bromine (Br) belong to the group seven of the periodic table. To this group also belongs chlorine (Cl) which is a component part of common table salt (sodium chloride). It is possible for any of these, if injested or inhaled, to replace chlorine.

If such happens with radioactive isotope then radiological damage should be expected from incorporation to any organ. Moreover, the thyroid gland is very susceptable to iodine. Rubidium (Rb) and Caesium(Cs) are group one elements of the periodic table. This means they belong to the same group as sodium (Na) and potassium (K) which are essential elements of the human body. Ingesting radioactive rubidium or caesium may lead to their replacing these essential elements. This again will have important radiological consequences. Barium and strontium belong to the same group as calcium and magnesium. Calcium is the building component of the mammalian bone. Calcium can easily be replaced by strontium and the strontium once incorporated into the bone is difficult to remove (West and Kiefer,1982).

Of the remaining elements given in Table 3.1 mention may be made of antimony(Sb) selenium (Se) and tellurium. The first is group five element while the remaining two are in group six, of the periodic table. Oxygen an essential element for the survival of animals also belong to group six. Selenium and tellurium may but, with little probability replace oxygen.

Appendix B gives some highlight of accidents leading to the release of radioactivity from fuel and reactor core (inner containment) into outer containment. This is followed by a brief discussion of the likely route the

released radioactivity may take from the reactor outer containment up to its contact with the environment atmosphere.

These waste materials of low level activity emanating from the operation of nuclear facility can often be discharged into the environment after being stored for a certain length of time to enable short-lived radioisotopes, for example $^{138}Xe(T_{\frac{1}{2}}=14m)$, ^{138}Cs ($T_{\frac{1}{2}}$ = 32m), ^{87}Kr ($T_{\frac{1}{2}}$ = 76m) and so on, to decay. This reduces the level of activity significantly before its being discharged to the environment. To give a ten percent decay for any particular radionuclide the decay storage required is about seven times the half life of the radionuclide (IAEA, 1966). In addition to this the dischargeable materials are usually passed through filters which further reduce the level of activity of such wastes before the eventual discharging to the environment. Examples are iodine and particulate filters for gaseous discharges and demineralisers for aqueous discharges in water cooled reactors.

3.1.1 Stack height and orifice diameter

In addition the height of stack through which radioactive waste materials are emitted plays an important role in determining the extent of dilution and the horizontal downwind distance from stack base of occurence of maximum ground level concentration of such materials. The stack orifice diameter determines the increase in source height due to effluent exit velocity, v_e.

The source height, H, is made of three factor heights

$$H = h_s + h_b + h_v \qquad \text{------} \quad (3.2)$$

where H = effective stack height (source height)

h_s= physical stack height

h_b= increase in source height due to buoyancy

h_v= increase in source height due to effluent exit velocity

Related to the stack height is the buoyancy of the emitted materials, which depends on the density and temperature of the effluent relative to that of the ambient air. Methods of calculating increase due to buoyancy h_b, have been adequately treated by Bosanquent (1957), Best(1957) and Moses et al (1964).

It should be noted however, that the contribution, h_b, to source height due to buoyancy for the case of effluents from a small research reactor may be assumed to be fairly low. This is because of the small temperature difference between the emitted effluent and the ambient temperature, especially after a long decay storage time. This is very much unlike in the cases of blast furnace, smelting and other such works where effluent would be emitted at high temperatures, compared with the ambient temperature.

The effluent exit velocity also increases the source height. The effluent exit velocity is a function of the volume discharge rate and the stack orifice diameter. Reactor discharges are usually forced out in a bit to create a negative pressure in the containment. In addition to this, the increase h_v is also dependent on the ratio of the effluent exit velocity to the mean wind velocity. This is because the value of h_v is affected by result of the vectorial addition of the two velocities.

Again for a small research reactor, the gaseous effluents discharged through a stack of moderate diameter of about seventy five centimeters will be assumed to have small exit velocity, because of the small volume of matter discharged as compared to blast furnace, coke fire and so on.

On the basis of the fact that the increases h_b and h_v for a small research reactor may be considered to be small they may be neglected. If on the other their effects are considered significant enough to be taken into account, then their effects could be summed up as an increment Δh. This has been done by a number of people including Best (1957), Zuccaro Labellatre(1973)

$$\Delta h = h_b + h_v \qquad \text{----- (3.3)}$$

$$= 1.5 \frac{v_e}{u} d \left(1 + 1.8 \frac{\Delta T}{T} d\right) \qquad \text{----- (3.4)}$$

where v_e = effluent exit velocity

d = Stack orifice diameter

T = temperature of emitted effluent.

Equation (3.4) is known as Hollands' formula (**Moses et al, 1964**).

3.2 Meteorological Factors

Meteorological factors are divided into two main classes, atmospheric and terrestrial. Each class is given a brief discussion below.

3.2.1 Atmospheric Factors.

The lateral and vertical spreads of diffusing material are governed by the lateral and vertical diffusion coefficients respectively. There are no exact theoretical formulae that can be used in determining values of these dispersion coefficients. They are usually determined from experimental data. Atmospheric diffusion experiments are carried out both in the real atmosphere and controlled laboratory conditions (wind tunnel) with the aim of getting useful information on dispersion coefficients. Such experiments have been carried out in the real atmosphere according to Pasquill (1972) by Budden at Porton; Davies at Cardington; Cramer, Record and Vaughan at the Round Hill Field Station of Massachusetts, Institute of Technology; Barad in the Project Praise Grass of Nebraska plains at O'Neil and so on (see Pasquill,1972) and by Vanderbought et al (1983) at Beerse, Belgium. Wind tunnel experiments carried out include those of Seigneur et al (1983) and others mentioned in section 5.5 of Slade (1968).

In this work the diffusion coefficients used are the same as those used by Hosker (1974) and are defined below in Equations 3.5 - 3.7 (valid for real atmosphere).

The form of the vertical dispersion coefficient is

$$\sigma_z(x) = f(z_o;x)g(x) \qquad \text{--------} \quad (3.5)$$

where the main factor g(x) is given by

$$g(x) = \frac{a_1 x^{b_1}}{1+a_2 x^{b_2}} \qquad \text{--------} \quad (3.6)$$

and f, the Smiths roughness correction factor is given by

$$f(z_o;x) = \begin{cases} \ln c_1 \, x^{d_1} \left[1 + (c_2 \, x^{d_2})^{-1} \right], & z_o > 10\text{cm} \\ \ln c_1 \, x^{d_1} \left[1 + c_2 \, x^{d_2} \right]^{-1}, & z_o < 10\text{cm} \end{cases} \quad (3.7)$$

Values of the constants a_1, b_1, a_2, b_2 of equation (3.5) are stability dependent and are taken from a table of the paper by Hosker (1974). The set of contants c_1, d_1, c_2, d_2 are roughness length dependent. In the same paper above, are given values of this set of constants for six roughness lengths (1, 4, 10, 40, 100 and 400cm). By means of suitable graphs, values of the constants fitting roughness lengths of the selected site were obtained for this work.

In view of the fact that there is no known analytical expression for the dependence of the lateral dispersion coefficient on roughness length, we here again employ the form used by Hosker(1974). This is given by

$$\sigma_y(x) = \frac{C_3 x}{\sqrt{1+0.0001 x}} \qquad ----(3.8)$$

Stability categories

This is a classification of the surface layer of the atmosphere due to Pasquill (1961). In it he gave six categories of stability which are specified quantitatively in terms of wind speed, insolation and state of the sky. Table 3.2, is taken from this refrence.

Surface wind speed(at 10m) M/S	Insolation			Night	
	Strong	Moderate	Slight	Thinly overcast ≥ 4/8 low cloud	≤3/8 Cloud
< 2	A	A-B	B	-	-
2- 3	A-B	B	C	E	F
3- 5	B	B-C	C	D	E
5- 6	C	C-D	D	D	D
> 6	C	D	D	D	D

For A - B Take average figures for A and B, etc.

Table 3.2 Key to stability categories

Highlighting on this table Lewis (1977) and Slade (1968) defined the degree of cloudiness " as that fraction of the sky above the local apparent horizon which is covered by cloud". They also gave the following interpretations of the stability categories:

A - Extremely unstable conditions

B - Moderately unstable onditions

C - Slightly unstable conditions

D - Neutral conditions *

E - Slightly stable condition

F - Moderately stable condition

* Applicable to heavy overcast, day or night.

Furthermore, Culkowski(1963), for the sake of non-meteorologists refers to the three columns under daytime insolation that is strong, moderate, and slight as clear, partly cloudy and cloudy respectively.

The stability or mixing characteristics of the atmosphere are closely correlated to the relationship between the vertical temperature gradient and the adiabatic lapse rate. The adiabatic lapse rate is a unique atmospheric lapse rate in which an element of air displaced from one layer to another attains the same temperature as the surrounding (Slade, 1968). Its numerical value is about $1^{o}C/100m$.

The effects of the various possible atmospheric lapse rates as compared to the adiabatic lapse rate on the behaviour of plume from an exhaust stack are given in figure 3.1, with the following explanations.

Figure 3.1.a shows a superadiabatic lapse rate. Under such a condition a parcel of air rising will expand adiabatically but not cool as fast as to reach the temperature of the surrounding. As a result it will be at a hotter temperature (less dense) than the surrounding air and hence continue to rise. If on the other hand, the parcel of air was to sink under superadiabatic condition it will undergo adiabatic compression with a resultant temperature increase. This increase will however not be sufficient to cause the air to attain the ambient temperature. Thus the sinking air will be cooler(denser) than the air in the surrounding and will therefore continue to sink. In short, one can say that Vertical motions of a parcel of air under superadiabatic conditions will be accelerated. Therefore, a superadiabatic atmosphere is an unstable atmosphere and causes the looping of stack effluent. Figures 3.1.a and b show increasing stability of the atmosphere. With increase in stability a parcel of air tending to move upwards will on adiabatic expansion become cooler (denser) than the surrounding air and be forced back to its former level. Similarly, if air parcel was to attempt sinking, on undergoing adiabatic compression, it will

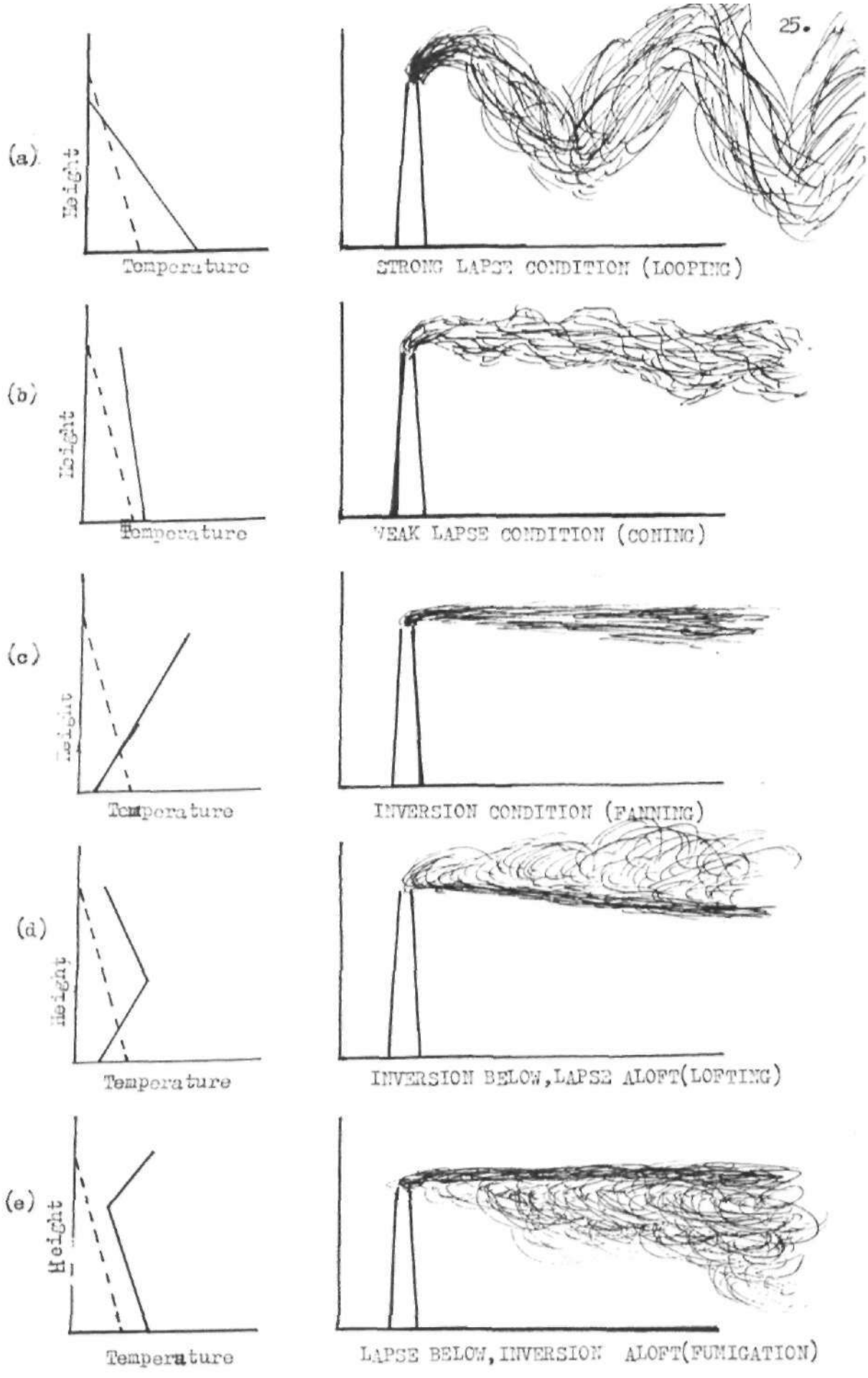


Figure 3.1 Schematic representation of stack-gas behaviour under various conditions of vertical stability. Actual temperature (solid line) and dry adiabatic lapse rate (dashed line)

aquire a lesser temperature than its surroundings and therefore will be forced back to its former level. Increasing stability therefore opposes vertical mixing of effluent materials. Specifically figures 3.1. b and c represent subadiabatic and inversion conditions respectively. Under an inversion condition the atmospheric lapse rate is positive. Two peculiar cases of lapse rates are represented by figures 3.1 (d) and (e). These are peculiar in the sense that the atmospheric lapse rate is not monotonically varying. The stack plume behaviour under these conditions are referred to as lofting or fumigation depending on whether inversion is above or below.

It is notewortly to mention here, that atmospheric lapse rate and stability categories undergo daily variations as may be caused by absorption of solar radiation by the earths' surface, cloud cover and wind speed.

Wind speed and wind direction :

Wind is a general term referring to the horizontal or near parallel to the earth's surface movement of air. Other movements of air out of this definition are referred to as air current (Albert, 1950). On the atmospheric scale, air motion is induced by differential heating of the earth's surface by the sun. As a result of intense heating of certain areas, the air there gets hot, expands and rises upwards. This results in loss of pressure from such areas. Naturally, air from adjacent areas being

at relatively higher pressure will flow to the areas of low pressure. This movement of air if fairly horizontal is referred to as wind. Meteorological observations and summaries give two important information about wind, these are direction and speed.

Wind direction is conventionally taken as the direction the wind blows from. The side of a body facing the direction the wind is from is known as the windwind side, while that opposite it is known as the leeward side. Wind direction is observed with the help of wind vane.

Wind direction data over a period of time is best presented for dispersion studies with the help of windrose. Windrose (cardinal directions) pictorical representation of wind direction data with lines of lengths proportional to frequencies of wind blowing along the cardinal directions converging to a centre (Slade, 1968). Prevailing Wind directions have the longest lines on the wind rose diagram. Prevailing winds are those winds that tend to blow more from one direction than any other direction (Gabler, 1975).

The rate at which air passes a refrence point is referred to as wind. This is a highly fluctuating quantity especially near the earth's surface. Wind speed is

affected by obstacles in the direction of flow. Wind speed also increases with elevation especially for the first few hundreds of meters of rise in elevation. Variations in wind speed also occur with the hour of day and season of the year. On this, Albert (1950) states that higher wind speed tends to occur during the day than at night, with maximum speed occuring between twelve mid-day and four in the afternoon. Minimum speeds on the other hand occur around daybreak or sunrise when all regions have attained nearly the same uniform temperature. This fact has been demonstrated by Olegba et al, (1982) for Zaria and other locations in Nigeria and Nwa (1981) for Zaria.

Terrestial factors also influence atmospheric dispersion coefficient. These include erected structures and plant cover. The concern due to these factors arises from the fact that each of them introduces an obstruction to the flow of air parallel to the earth's surface. With the flow restricted, elements of turbulence due to different aerodynamic roughness elements (obstructing materials) the concept of roughness becomes important. Derivation of roughness length is outside the scope of this work. It suffices to mention that it is derived from the vertical structure $(\frac{d\bar{u}}{dz})_o$ of mean wind velocity $\bar{u}$. More information on this may be obtained from Slade (1968). The roughness length, z_o, is however dependent on the mean height, h, of the aerodynamic roughness elements, which in the context of this work are mainly plant cover.

In his book, Campbell (1977) stated that for dense vegetation, such as agricultural crops:

$$z_o = 0.13h, \qquad \text{----- (3.9)}$$

This relation is dependent on shape, height h and spacing of the roughness element. Maize and rice are specifically treated by Uchijima(1976); while cotton is treated by Stanhill (1976). For maize and rice the roughness length, z_o, is given by:

$$z_o = 0.062\ h^{1.08} \qquad \text{----- (3.10)}$$

while for cotton it is

$$\log z_o = 1.476 \log h - 2.022 \qquad \text{----- (3.11)}$$

If the vegetation is dense tall trees, Oke (1978) gives

$$\log z_o = \log h - 0.98 \qquad (3.12)$$

For certain buildings which he refers to idealized building configuration, Oke gives,

$$z_o = 0.5h\ (A^*/A^1) \qquad \text{------- (3.13)}$$

where A^1 is assumed lots areas (m^2)

A^* is assumed sihoultte area (m^2).

Issues raised in this chapter contribute to determination of stack height. They will be used to determine a minimum stack height required to give adequate dilution of radioactive gaseous effluents before they reach ground level. Concentration of the effluents at ground level will be set well below the maximum permissible levels. This will also ensure that deposition will not increase the level of activity in the areas beyond acceptable limits.

CHAPTER FOUR THE SELECTED SITE FOR THE PROPOSED RESEARCH REACTOR OF AHMADU BELLO UNIVERSITY.

The Ahmadu Bello University, Zaria is one of two Universities in the country that the Federal Government has regarded as centres of excellence in Nuclear Sciences, and is therefore sponsoring research and training there, for the development of nuclear technology. To this end, the University is proposing to purchase and install a small nuclear research reactor. In his M.Sc. Thesis, Ewa (1982) after a detailed analysis of research reactors around the world, proposed a Triga Mark II reactor for the University. A site has since been chosen for the installation of the reactor, when purchased. The Zaria site case is studied in this chapter with respect to environmental and meteorological factors as obtained at the selected site.

4.1. Samaru-Zaria Location and Geography

The proposed Ahmadu Bello University research reactor is to be sited at Samaru, Zaria. This is located in Northern Nigeria ($11^{o}11'N$, $7^{o}\ 38'E$) at an altitude of 686m above sea level. Like most parts of Nigeria, this area has two distinct seasons, namely, the rainy and dry seasons. The rainy season commences around the month of April and lasts till sometime around October or so. The dry season on the other hand is from November to March and possibly early April. Prevailing wind directions during the rainy

and dry seasons are the South-West monsoons and the North-East tradewinds. One characterastic of the dry season period is the occurrence of harmattan haze. During such periods, harmattan dust covers the lower layers of the atmosphere reducing mainly visibility. As a result of less earth's surface heating low temperatures are usually experienced, especially at night during intense harmattan period.

The main occupation of the people in the locality is farming. Most of the farming is done during the rainy season. Principal crops grown are guinea corn (Sorghum,spp), Maize (Zea mays), millet (Pennisetum typhoides),yams (Dioscorea,spp) and some cotton (Gossypium,spp). Others are ground nuts(Arachis Hypogaea),beans (Vigna,spp), onions (Allium cepa), vegetables and so on. During the dry season, irrigation farming is carried out along most river sides. Main dry season crops are vegetables and sugar cane(Saccharum, spp). Cattle and sheep grazing is carried out around the settlement locations while goats are found within the settlement areas. Quite a number of civil servants are also living within the Zaria environs. They are centred mainly around the academic and other institutions that are situated within the locality.

Some of the settlement locations within the immediate vicinity of the selected reactor site are shown on Figure 4.1.

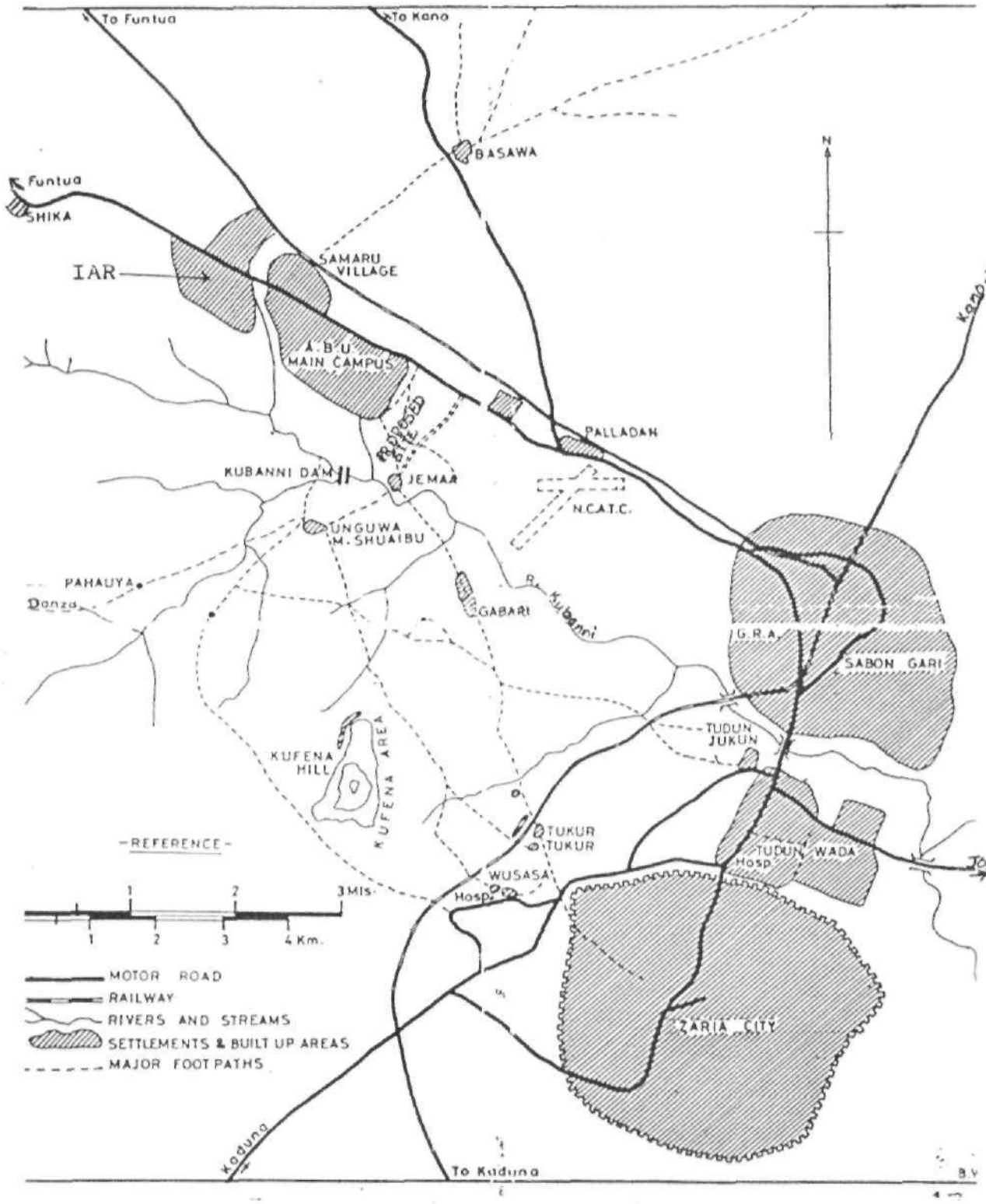


Figure 4.1: The proposed reactor site and its environs

4.2 Reactor Data

Being a research reactor of small power rating (1-3MW) the amount of fuel burn up of the proposed reactor will be small. Hence very little radioactive wastes will be generated. Gaseous radioactive wastes emission to the atmosphere will very much depend on the operation time length, power level, efficiency of filteration units and radioactivity from radioactive materials handling laboratories incorporated into the reactor facility design. These are technical data which are not yet available for the case of the proposed Ahmadu Bello University research reactor.

As an index as to how much radioactive gaseous effluents from a research reactor can vary with some of the above listed factors, mention is made of two operational Triga reactors in the United States of America. One is the unique University of Arizona (Tucson, United State of America) Triga reactor that operates at low coolant temperature of about six degrees centigrade for about three to four hours a week at one hundred kilowatts power level. Virtually no gaseous effluents are emitted from this reactor apart from minute quantities of argon fourty one(Ar-41) (Nelson, 1986). The other is the Texas Engineering Experiment Station, the Texas A & M University. This too is a Triga (open pool type) reactor. It is operated for the twenty four hours of the day and the three hundred and sixty five days of the year. The reactor has an air handling system of 5,000cubic feet per minute ($2.36m^3/s$). The main airborne radioactive discharges monitored for this reactor are Ar-41 and gross particulates.

Appendix C gives annual summaries for particulate and gaseous (Ar-41) effluent releases for the Texas A&M reactor for three consecutive years, 1983 to 1985 (Krohn, 1986).

No definite discharge figures are yet available for the case of the proposed Ahmadu Bello University research reactor. For this reason, the quantities Q_o and $Q(x)$ would be used for general discussion and these will later be replaced by discharge figures from the Texas A&M reactor. Q_o and $Q(x)$ are the rates of effluents passing the stack orifice (o) and location, x, respectively

Determination of stack height is one of the objectives of this work. Therefore, various values of it will be used to determine the effluent concentration of the various radioactive (effluent) gases. Stack height will be increased until the resultant effluent concentration falls well below the set maximum permissible limits. One of the highest stacks around Zaria that of the Zaria Industries Limited can be used as a starting or reference point for the reactor stack height calculation. The increase in source height given by Holland's equation,

$$\Delta h = 1.5\frac{v_e}{\bar{u}}d\left(1 + 1.8\frac{\Delta T}{T}d\right)$$

would be approximated (because $1.8\frac{\Delta T}{T}d \ll 1$) to

$$\Delta h = 1.5\frac{v_e}{\bar{u}}d.$$

This is a valid approximation because most of the effluent would be constituted of atmospheric air in addition to being emitted at virtually the same temperature as ambient air.

4.3 METEOROLOGICAL DATA

4.3.1 Atmospheric Data

Two meteorological stations are situated very close to the proposed site and are located on opposite sides with respect to the proposed site. These are the Institute of Agricultural Research (IAR) Ahmadu Bello University and the Nigerian Civil Aviation Training Centre (NCATC) Zaria meteorological stations(fig 4.1). Both are located within the one hundred and eighty kilometers distance from the site as proposed by Briggs (1973) for a reliable data collection for a proposed rural site. In fact, each meteorological station is located less than ten kilometers from the proposed site. The Institute of Agricultural Research Meteorological summary was the one readily available and extracts were made therefrom with respect to topics discussed in section 3.2 above. Analysis of the data is presented below.

Stability category has been noted earlier on to be a continuously changing phenomenon. Presented below are data on some of the factors upon which stability category depends.

Table 4.2 shows the summary of temperature readings at two altitutes as recorded at the Institute of Agricultural Research(I.A.R.) meteorological station. On the basis of the data a very rough estimate of the vertical temperature profile (atmospheric lapse) for morning period+ is presented in figure 4.2. Evening period* lapse rate presentation is not possible because data is available only for one altitute. Cloud cover

+ 9:00am

* 4:00pm

	30 cm AGL		122cm AGL	
Month	Mean Temp °C	Std.Dev. °C	Mean Temp °C	Std.Dev. °C
January	23.3	1.98	25.1	0.47
February	25.4	0.30	25.7	0.20
March	28.6	0.77	27.5	0.00
April	30.2	0.32	29.2	0.31
May	29.3	1.06	29.4	0.68
June	27.8	0.30	28.6	0.09
July	26.2	0.82	27.6	0.86
August	25.6	0.58	26.7	0.00
September	26.2	0.13	26.8	0.32
October	26.6	0.83	27.2	0.33
November	24.6	0.25	26.7	0.36
December	23.5	0.14	25.6	0.02

TABLE 4.2 Mean monthly temperature recorded at two levels, 30cm and 122 cm above ground level (A.G.L.), based on I.A.R. Meteorological Office records for the period 1954 - 1985.

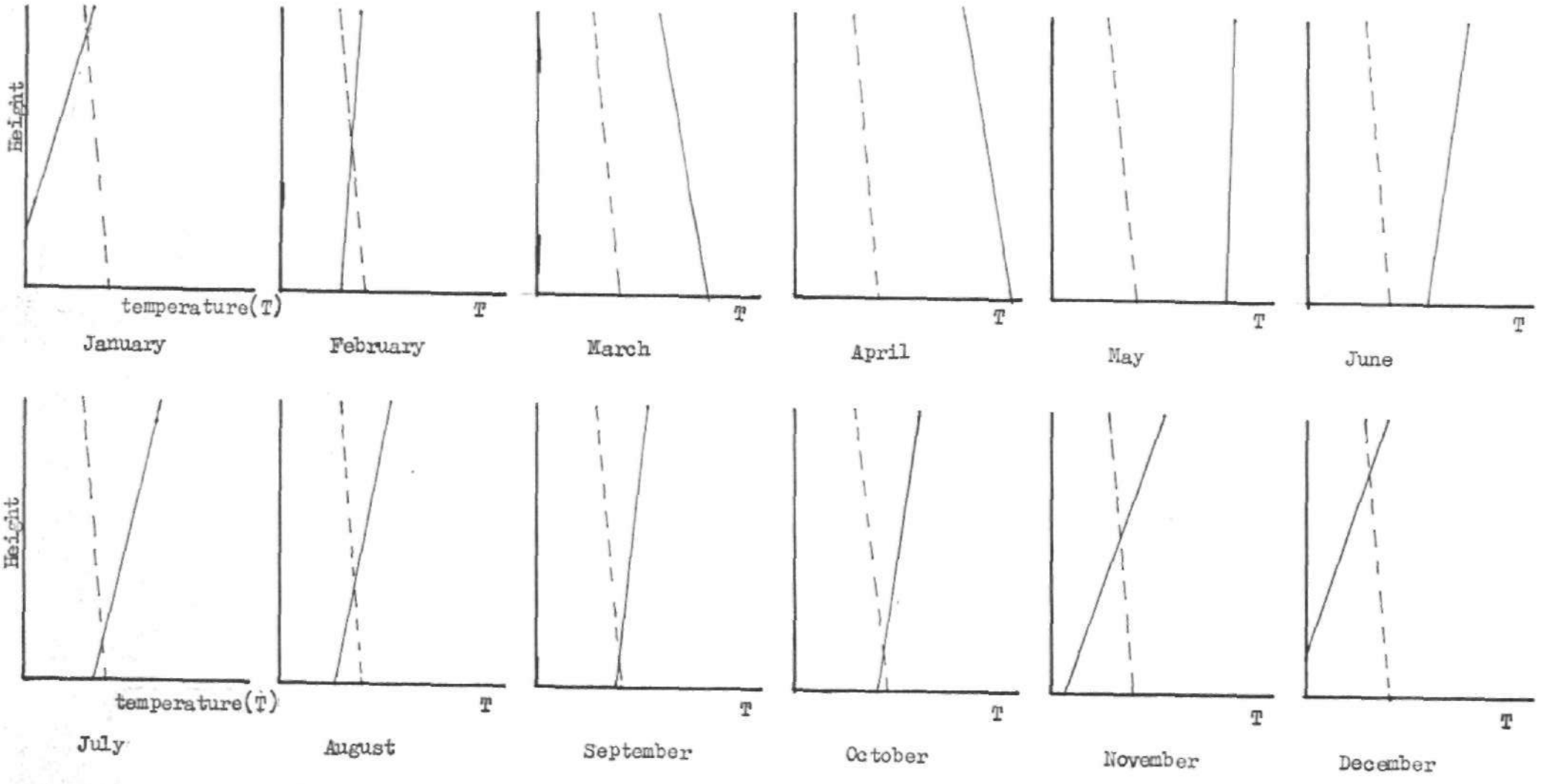


Figure 4.2 Rough estimates of the vertical temperature profiles (morning period) for the twelve months of the year for the proposed site. (Based on data from I.A.R. meteorological office for the period 1954-1985.) Actual temperature profile (solid line), dry adiabatic lapse rate (dashed line).

data is rather hard to summarise. On the basis of the data available one can say fair cloud cover is experienced over Zaria during the late May/ early June when the rainy season is commencing and during month of September when the rains are winding up for the year. Between these two periods, from mid June to the beginning of September, the cloud cover over Zaria is fairly heavy and rainfalls are frequent. October to mid-November is a period of clear sky. From the ending of November upto the late April, the sky is usually filled with harmattan dust. In compliment to this, tables 4.3 and 4.4 give summaries of solar insolation data as presented by Folayan and Ogunbiyi (1986) and the rainfall monthly means as obtained from the Institute of Agricultural Research meteorological station respectively.

Wind speed data reduced to monthly means, for the twelve months of the year, is presented in table 4.5. Monthly wind direction data were reduced to a form from which the windroses of figure 4.3 were drawn. Chi-squared tests applied to the main wind directions gave the results shown in table 4.6.

	1977	1978	1979	1980	1981	1982	1983	1984	1985
January	22.51	25.37	24.16	25.12	21.70	20.79	20.37	22.39	24.03
February	25.37	27.16	27.09	24.97	26.72	23.89	28.23	26.58	24.02
March	24.29	26.60	25.08	27.00	27.39	26.45	29.31	28.51	24.97
April	26.55	24.53	25.88	24.79	29.14	25.61	30.49	25.61	24.53
May	25.92	28.36	26.18	23.21	24.83	25.66	28.51	25.39	19.27
June	23.27	19.28	23.75	22.16	21.17	25.38	22.94	24.16	21.31
July	18.87	16.13	20.90	19.94	20.50	20.35	19.54	20.50	18.98
August	16.70	19.30	19.55	19.55	20.38	20.08	16.96	23.20	20.75
September	21.57	21.31	21.97	22.67	22.27	20.36	21.57	22.37	21.31
October	24.15	21.04	25.77	22.53	22.94	23.48	25.63	22.25	24.56
November	24.56	23.73	24.82	24.02	22.40	24.02	26.18	25.39	25.64
December	21.57	22.38	23.89	21.15	23.20	25.64	23.74	20.48	19.67

TABLE 4.3 – Mean daily solar radiation, $\bar{H}$(MJ/m^2/day), presented on a monthly basis for Zaria for the period 1977 to 1985 (extracted from Folayan and Ogunbiyi, 1986).

Month	Mean Total Rainfall mm	Standard deviation mm
January	-	-
February	0.6	0.6
March	28.5	4.4
April	57.6	57.6
May	103.8	36.9
June	152.5	10.3
July	223.0	90.1
August	261.8	5.5
September	212.5	49.2
October	66.3	17.5
November	9.0	9.0
December	-	-

TABLE 4.4 - Rainfall monthly means and standard deviations based on I.A.R. Meteorological Office records for the period 1954 - 1985.

Month	Mean wind speed m/s	Standard deviation m/s
January	1.68	0.28
February	1.77	0.31
March	1.70	0.45
April	1.96	0.23
May	2.18	0.76
June	2.07	0.68
July	1.85	0.18
August	1.58	0.01
September	1.15	0.12
October	1.02	0.11
November	1.22	0.24
December	1.48	0.19

TABLE 4.5 - Monthly mean wind speed with standard deviation for data obtained from the I.A.R. Meteorological Office for the period 1957 - 1985.

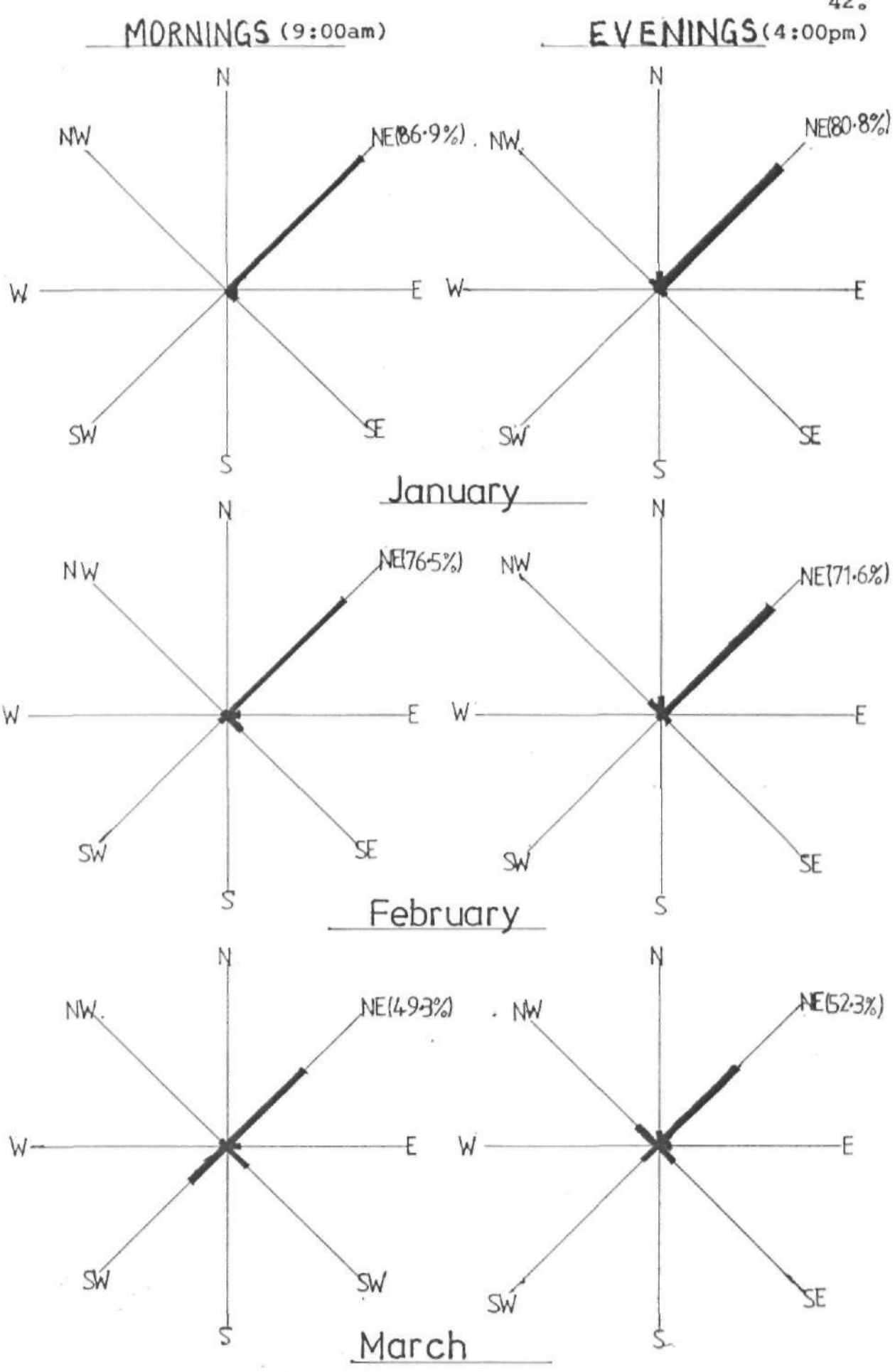


Fig. 4.3.a – Windroses for the months of January, February and March.
(figures in brackets give percentage of wind in prevailing direction).

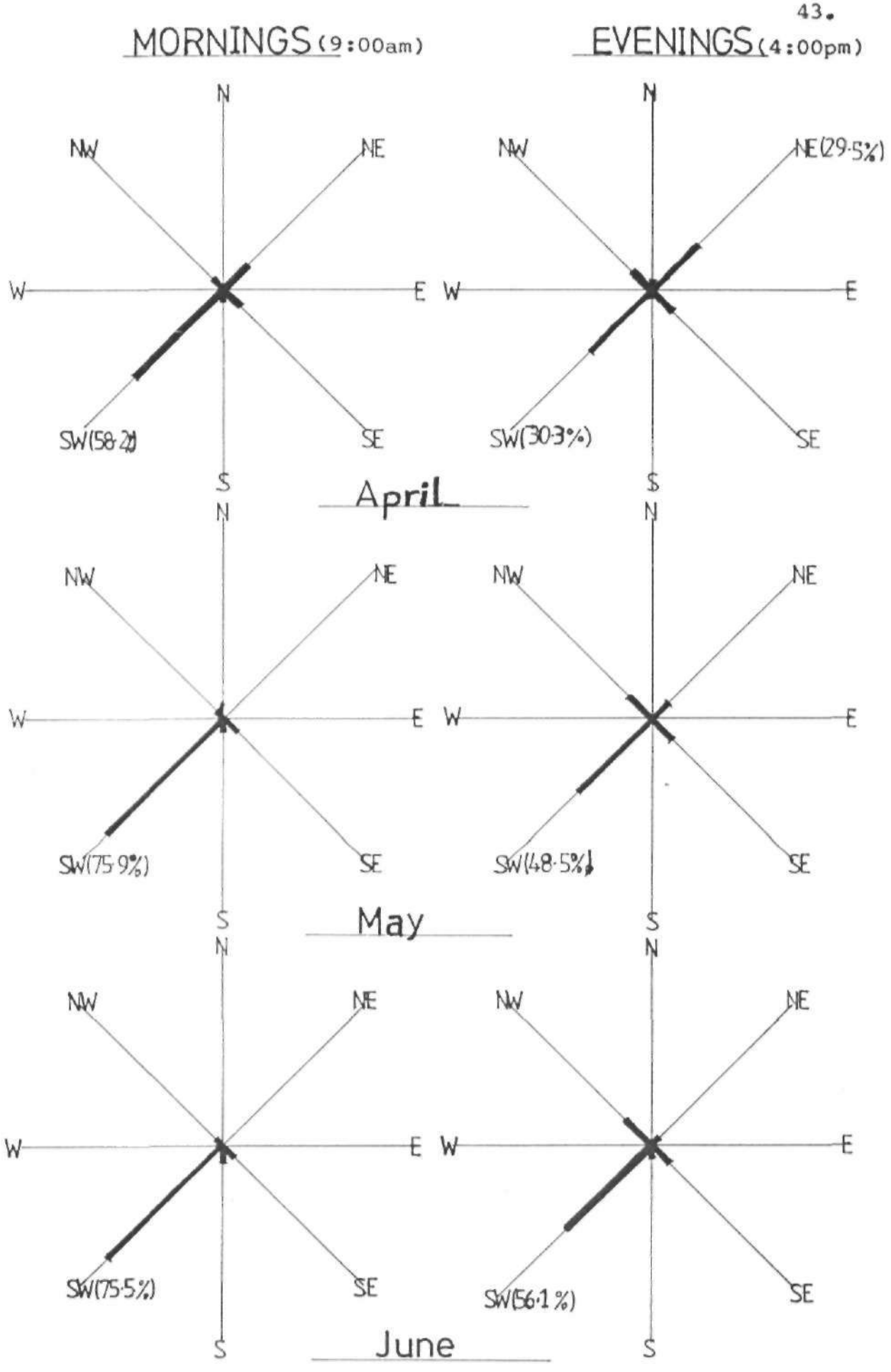


Fig.4.3.b - Windroses for the months of April, May, and June. (Figures in brackets give percentage of wind in prevailing direction).

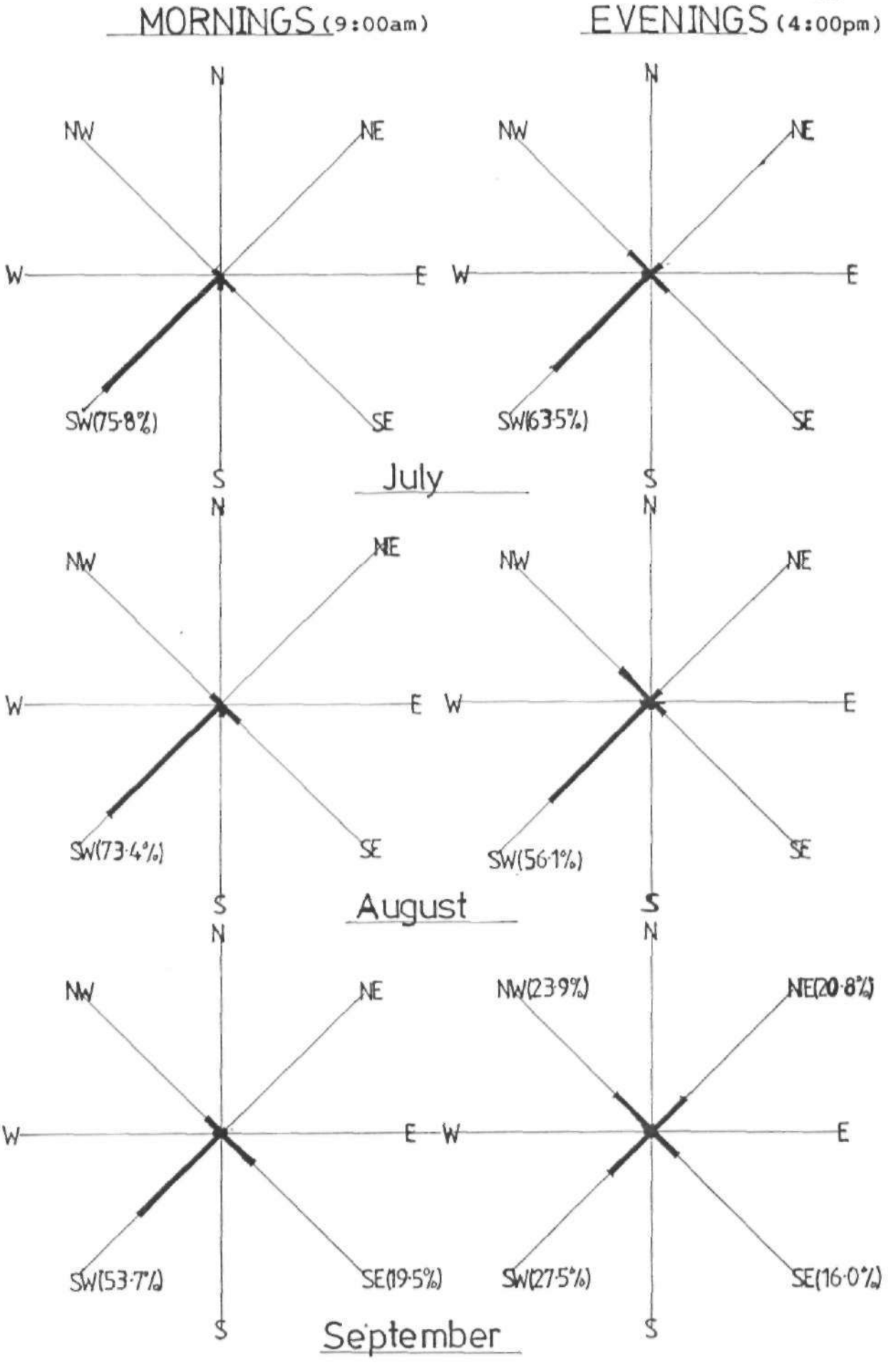


Fig.4.3.c - Windroses for the months of July, August and September.
(Figures in brackets give percentage of wind in prevailing direction).

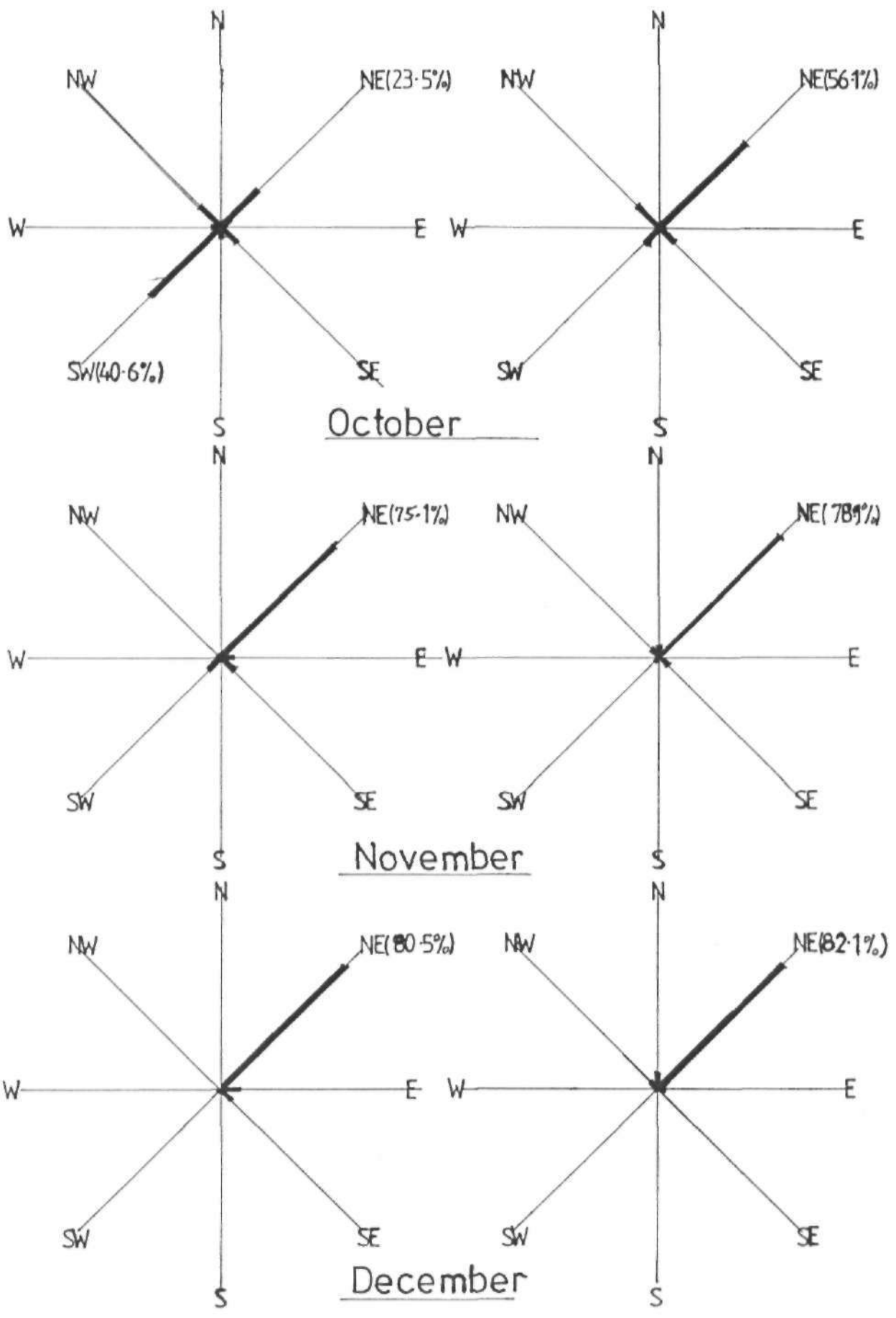


Fig.4.3.d – Windroses for the months of October, November and December.
(Figures in brackets give percentage of wind in prevailing direction).

Month	Main wind direction	Expected number of days for main wind direction.	*Chi-squared
January	NE	27	12.89
February	NE	22	31.23
March	NE	15	52.27 +
April	SW	18	39.78
May	SW	24	17.96
June	SW	23	12.96
July	SW	24	17.50
August	SW	23	19.20
September	SW	16	15.44
October	SW	13	56.46 +
November	NE	24	48.48 +
December	NE	25	20.28

TABLE 4.6 - Chi-squared test results for the main wind directions.

*Critical value for chi-squared test with 27 degress of freedom at 5% significant level is 43.113.

+Chi-squared value greater than critical value.

4.3.2. Terrestrial factors

The selected site is a gently rolling terrain almost along the north east-sourthwest direction. With the aid of a theodolite, measuring tape, telescope and a leveling staff the selected site was surveyed. Data was also collected for the plant cover height within the selected site and its adjacent locations for both the rainy and dry seasons.

The average slope of the gently rolling terrain was found to be about thirteen in one thousand. The northeastern part is on the higher elevation than the southwestern part . Near the Kubanni river bank and the dam the slope is slightly higher. From the plant cover height roughness lengths were calculated. Assumptions made here are that grass and crops belong to the same class as rice and maize. It is also assumed that these contributed a non-varying height within each month during the growing season (late May to early September). Negligible contribution from trees is assumed, due to the rather low tree number density. On the northwestern side however, where the built up area of the Main Campus of Ahmadu Bello University is, plant cover is mainly trees. Average tree height of this area is about ten meters. Table 4.7 gives a summary of the plant cover data, including some data collected by Chobe (1986).

Month	Mean plant height h(cm)	Roughness length z_o(cm)
January	10	0.7
February	10	0.7
March	10	0.7
April	10	0.7
May	15	1.2
June	33	2.7
July	84	7.4
August	153	14.2
September	230	22.0
October	150	13.9
November	60	5.2
December	30	2.4
Main Campus side	1000	107.7

TABLE 4.7 - Summary of plant cover height data.

4.3.3 Settling speed Vg

This is a coefficient that is used in multiplying the air concentration of the effluent to obtain deposition rate. Even though it has the units of velocity, it does not refer to actual gravitational settling velocity. Its units are derived from dividing the quantity of material deposited per unit area by the volumetric concentration in the air just above the area (Culkowski, 1963). Settling speed may actually be orders of magnitude higher than would be expected from purely gravitational settling. This is because apart from gravitational settling other factors like absorption, impaction, diffusion and possibly chemical and electrostatic effects all contribute to settling velocity (Gifford and Pack, 1962). Values of settling speed Vg quoted in the literature for gaseous and perticulate radioactive effluents fall in the range $3x10^{-3}$ $-3x10^{-2}$ m/s for iodine, 0.1-0.2 m/s for caesium and strontium on vegetation (Cowser et al, 1971). These values are of the orders of those used in simulating the Chernobyl, April 1986, nuclear reactor accident (ApSimon and Wilson, 1986 ; ApSimon et al, 1986). One other factor that is likely to increase the settling speed in the Zaria location is the persistent harmattan dust cover for the greater part of the dry season. Naturally, absorption and coalition of some of the effluent material and harmattan dust will increase the settling speed of the composite material.

4.3.4 Rainfall washout coefficient.

Of all the data presented in this chapter the data on rainfall has the greatest dispersion. In addition to this no data has been obtained on the average rainfall duration and intensity. Cowser et, al (1971), have indicated some values derived for both vapours and particles. These are that at rainfall intensities of a few millimeters per hour values are of the order of 10^{-4} per second. For particules of a few microns diameter this coefficient is in the range 10^{-4} to $3x\ 10^{-4}$ per second. Values in the same range have been reported for lycopodium spores(Culkowski, 1963).

4.4 Numerical Solution.

Computer programs were written, on the Iya Abubakar Computer (Cyber 72) of Ahmadu Bello University, to evaluate the dispersion coefficients $\sigma y(x)$ and $\sigma_z(x)$ as functions of downwind distance, x. These were utilized in evaluating the relative concentration of stack effluent material per unit area, $\bar{\chi}/Q(x)$, at ground level along the centre line of the prevailing wind axis. The value, Q(x), representing the rate at which effluent material passes location x, is utilized rather than the emission rate at stack orifice, Q_o, to account for reduction in material due to depositional losses. The ground depositional rate per unit area, w(x,y) is itself given by,

$$W(x,y) \equiv v_g \bar{\chi}\ (x,y,o). \qquad (4.1)$$

For the relationship between Q(x) and Q_o, see the derivation

in appendix A.II. Graphical representation of some of the results obtained for some stack heights is presented in the figures of appendix D. Figure D.1 gives variations relative air concentration per unit area $\bar{\chi}/Q(x)$, at ground level, with horizontal distance x. Figure D.2 is a special variation of some of the results in D.1. It shows the expected effluent relative air concentration per unit area, at some of the important locations as function of physical stack height. Figure D.3 gives the plume depletion, $Q(x)/Q_o$, as a function of downwind distance. A 'NAG' library subroutine, 'D01AHF' was utilized in evaluating the integral envolved in $Q(x)/Q_o$. This subroutine was also utilized in evaluating $\bar{\chi}$, the mean concen- of effluent at ground level, along the axis, figure D4. For the results for which D.4 was drawn, the airborne effluent discharges of Texas A&M Triga reactor were utilized.

Constants used in the computer calculations are from Hosker (1974). Summary of these is given in table 4.8.

Stability Category	a_1	b_1	a_2	b_2	c_3
A	0.112	1.06	5.38×10^{-4}	0.815	0.22
B	0.130	0.950	6.52×10^{-4}	0.750	0.16
C	0.112	0.920	9.05×10^{-4}	0.718	0.11
D	0.098	0.889	1.35×10^{-3}	0.688	0.08
E	0.0609	0.895	1.96×10^{-3}	0.684	0.06
F	0.0638	0.783	1.36×10^{-3}	0.672	0.04

TABLE 4.8a- Values of constants a_1, b_1, a_2, b_2 used in calculating $g(x)$ for the vertical dispersion coefficient $\sigma_z(x)$ and c_3 used in calculating the lateral dispersion coefficient $\sigma_y(x)$ for the various stability categories (x is in meters).

Month	Mean wind speed (m/s)	Main wind direction	Roughness length (cm)	c_1	d_1	$\ln(c_2)$	d_2
January	1.68	NE	0.7(≃1)	1.56	0.048	-7.378	0.45
February	1.77	NE	0.7(≃1)	1.56	0.048	-7.378	0.45
March	1.70	NE	0.7(≃1)	1.56	0.048	-7.378	0.45
April	1.96	SW	0.7(≃1)	1.56	0.048	-7.378	0.45
May	2.18	SW	1.2	1.60	0.048	-7.2	0.45
June	2.07	SW	2.7	1.75	0.038	-7.3	0.40
July	1.85	SW	7.4	1.45	0.010	-6.75	0.13
August	1.58	SW	14.2	3.15	-0.018	1.8	-0.02
September	1.15	SW	22.0	3.90	-0.037	3.4	-0.10
October	1.02	SW	13.9	3.15	-0.018	1.8	-0.02
November	1.22	NE	5.0	2.12	0.020	-7.1	0.10
December	1.48	NE	2.4	3.15	0.038	-7.3	0.32
Main Campus Side	1.15	SE	107.7	7.6	-0.098	8.5	-0.61

TABLE - 4.8b Values of constants c_1, d_1, c_2, d_2, used in calculating roughness correction factors $F(z_o;x)$ used in conjunction with $q(x)$ to evaluate vertical dispersion coefficient. (extracts from previous data presented and from graphs of c_1, c_2, d_1, d_2 vs z_o).

CHAPTER FIVE DISCUSSION, CONCLUSION AND RECOMMENDATIONS

5.1 DISCUSSION

The selected site for the research reactor of Ahmadu Bello University and the Zaria surrounding environs have been presented in figure 4.1. Extracts from the Ahmadu Bello University masterplan, figure 5.1, shows the detailed boundary of the site. The site extends to about seven hundred metres along the Northeast -Southwest direction and is about five hundred metres in the Northwest-Southeast direction. Some important locations close to the site are the Area A (one of the staff residential areas) of the Main Campus, the Federal Ministry of Works and Housing quarters (along the Sokoto road) the residential quarters under construction opposite it, the Nigerian Civil Aviation Training Centre (Staff quarters) Jema'a village/ abbatoir, the Kubanni river/dam, Unguwar Mallam Shuaibu and farming/grazing lands around these locations. All these are shown either in figure 4.1 or 5.1. From the windrose diagrams of figure 4.3, two prevailing wind directions can easily be identified. These are the Northeast and Southwest directions. These figures in conjuction with the rainfall data confirms that the Southwest winds bring moisture-laden air for rainfalls. The Northeasterly wind on the other hand, is dry and harmattan dust laden.

With respect to the site and northeasterly winds blowing therefore, the Kubanni river/dam and Unguwar Mallam Shuaibu lie along the leeward side. Any airborne effluent from the reactor at the site will thus be blown over these areas. This will happen mainly for the months of November, December, January, February and parts of March and October. (see windroses of figure 4.3). The Kubanni river/dam is located at about one

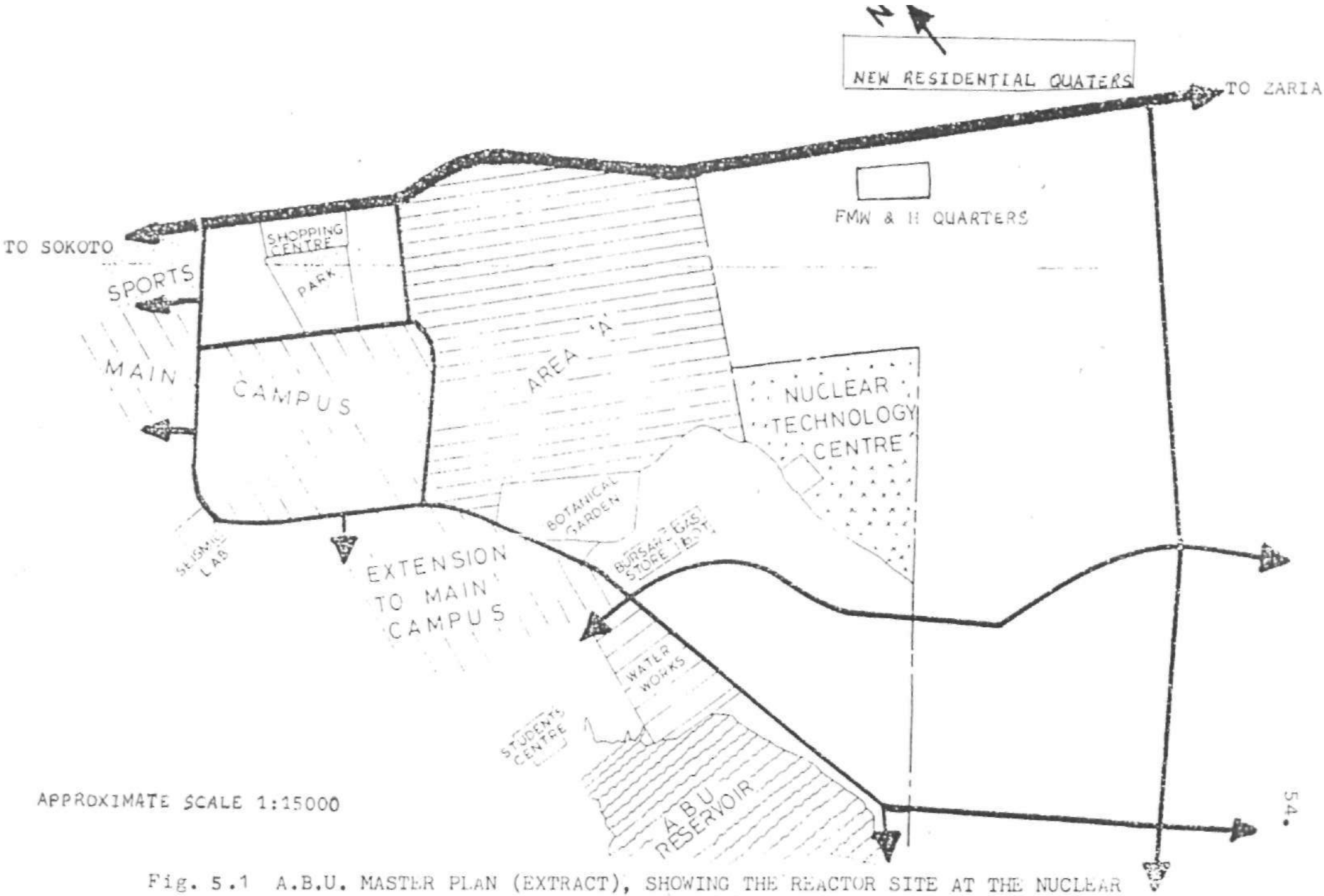


Fig. 5.1 A.B.U. MASTER PLAN (EXTRACT), SHOWING THE REACTOR SITE AT THE NUCLEAR TECHNOLOGY CENTRE.

thousand metres away; while Unguwar Mallam Shuaibu is located at well over two thousand metres. Relative air concentration per unit area at these two locations may be read off from the diagrams of November and February in figure D.1. These however, tends to be misleading at first glance, a more straightforward information is obtained from figure D.2 (for the same months). Figure D.3 gives the plume depletion fraction $\chi(x)/\chi_o$ This gives information on deposition of effluents with downwind distance. Figure D.4 for these months gives the expected ground level concentrations of effluent waste material for stack of various heights. The Texas A & M University, Texas, U.S.A., one megawatt Triga reactor discharge data was utilized in evaluating the downwind concentration of effluent of this figure. The months of February and November were specifically selected for treating the dry season effluent downwind concentration distribution because they represent the highest differences that occur in both windspeed and roughness length for that period (see table 4.8b). It should be recalled that windspeed and roughness length are important factors in determining stack effluent distribution pattern.

For wind from the southwest of the site, airborne effluent materials will be carried over the Federal Ministry of Works and Housing quarters, the houses under construction opposite it, parts of the Sokoto road in between these two and may be some small portion of aviation staff quarters and areas beyond. The approximate distance to the first three from the centre of the site is over one thousand metres. The months during which wind is predominantly southwest are May, June, July, August and parts of September and April (see windroses of

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figure 4.3). Again on the basis of windspeed and roughness length, table 4.8b, the months of May, July and September were chosen from the southwest wind direction period for analysis. Results for these months are given in figures D.1 to D.4.

The Area A staff quarters of the Main Campus presents a perculiar case of itself. It is one of the closest locations to the site and has dense tree plant cover, of average height over ten metres throughout the year. Airborne waste material will be blown over this area for southeast winds. Southeast wind greatest probable period is September, and this has only about twenty percent occurance probability out of the September period for the thirty two years data analysed (see windroses of figure 4.3). Results for the Main Campus side for the month of September are also shown within figures D.1 to D.4.

By virtue of the windroses of figure 4.3, discussion on deposition and effluent concentration at ground level is limited to the above. Results of chi-squared tests applied to the main wind directions. Table 4.7 strongly suggests that any effluents will be mainly dispersed along the directions discussed, that is southwest and northeast. The only periods exceptions may be applied are October, November, March and possibly April where chi-squared tests have failed. It is not suprising however, that the tests have failed for these months, because it is during them that main wind direction and seasonal changes occur, see figure 4.3 and table 4.4. Considering data on windspeed, daytime insolation and the tropical location of the site, the stability categories most likely to occur at the site are A, B and may be C. The cases of stability categories A to D were however, utilized in evaluating the results presented in appendix D, which are discussed below.

Figure D.1, from a recast of equation 2.14, gives relative concentration, $\chi/Q(x)$, of effluents at ground level as a function downwind distance for various stack heights. The numerical value of maximum $\chi/Q(x)$ decreases with increase in stack height. The downwind location of maximum $\chi/Q(x)$ on the other hand increases with increase in stack height. Very low stack height produces large $\chi/Q(x)$ near stack base for all stability categories. Represented in figure D.2 are versions of the diagrams of figure D.1. In these diagrams, relative air concentration of effluent, $\chi/Q(x)$, at ground level is plotted as a function of physical stack height, h_s, for some selected downwind locations, x. The downwind locations selected correspond to approximate boundaries of exclusion and restricted areas, settlement and farming/grazing locatins. Effects of increased stack heights for each of these locations can be observed from the aforementioned graphs. Figure D.3 gives plume depletion fraction. This fraction represents the crosswind integral of effluent materials remaining in the air, Q(x), divided by the quantity Q_o emitted at the stack orifice. Subtracting plume depletion fraction, at any location, from unity gives the amount of ground deposition that has taken place between the stack base and that location. From the diagrams in this figure, it can be observed that both deposition quatity and rate reduce with increase in stack height. The final figure, that is, D.4 combines the information of figures D.1 and D.3. In evaluating the results used in plotting the graphs of D.4, the highests values of airborne effluents discharges from the Texas A & M one megawatt reactor were utilized. The graphs show the values of mean concentration of effluents, $\bar{\chi}$, in air at ground level as a function of downwind distance for various stack heights. The very useful information derived from figure D.4 is the basis of fixing the minimum stack height required to give a maximum concentration of effluents (Ar-41) in units of

fermiCuries per cubic centimetres (10^{-18} Ci/cm^3) at all downwind locations for any of the stability categories A to D.

The minimum stack height required to achieve the value of concentration given above is thirty metres, see figure D.4 (in particular for May and September). To arrive at the figure of picoCuries percubic centimetres, the usual criterion of limiting the exposure of members of the public to less than ten percent the maximum permissible limit for the radiation worker was applied to the data of table 1.1. In addition a further reduction factor was applied, to take care of possibilty of expansion and higher releases due to malfunctioning of the reactor and/or the airborne effluent processing units. The resultant minimum dilution factor of effluents concentration (concentration at stack orifice divided by maximum concentration downwind) achieved for the thirty metres stack height is over a thousand. This dilution factor is much smaller than that achieved at the exclusion area of the Texas A & M reactor (footnotes tables C.1,C.3,C.5). It is worthwhile to mention here that should the discharge figures of the Ahmadu Bello University research reactor be much different from those utilized in stack height analysis, the concentration figures of figure D.4 may be utilized by appropiately multiplying, to check whether or not a different stack height is required to achieve the above set limits. Similarly, should any major accidental release of airborne effluents occur, the resulting concentration of efluents may be determined by appropriate multiplication of the concentration of in figure D.4.

5.2 CONCLUSIONS AND RECOMMENDATIONS

The objectives of this work, meteorological and stack height analysis, have been presented above. The available meteorological data have been adequqtely analysed. Results show that the site

for the installation of the Ahmadu Bello University research reactor has reliable meteorological features for the safe atmospheric dispersion of low level airborne radioactive wasres. Among these are fair windspeeds, well defined wind directions, seasonal variations and other atmospheric dispersive capabilities for adequate dilution of airborne effluents. One other adevantage of the site is the low population density along the main wind directions. The results of the meteorological analysis when applied to the stack analysis, gave the figures of appendix D. The minimum stack height required to give a resultant concentration of less than ten fermi-Curies per cubic centimeter is thirty meters above ground level. This height gives a minimum dilution factor of over a thousand. Under normal conditions, the reactor can be operated all the year round at this site. In the event of any accidental releases, areas requiring immediate health emergency measures or evacuation, if the need arises are those located downwind of the site. These include some peripherial parts of Area A, the farming/grazing land around the Kubanni river/dam, Unguwar Mallam Shuaibu, Jemaa and far away Pahauya and Danza villages for the period October to April. If the period is May to September on the other hand, then emergency measures should centre around the Federal Ministry of Works and Housing Quarters, the new residential quarters under construction opposite it and some small portion of the Aviation Staff Quarters (Site II). With the reactor at the selected site, the bulk of A.B.U. Main Campus, Samaru village, Basawa, Palladan, Sabon-Gari, Tudun Wada, Zaria city, Wusasa, Tukur-Tukur and Gabari are safe all year round.

To limit the number of members of the public that can get exposed to radiation and to limit the scope of of any emergency operation that may need to be taken, settlement expansion in areas located downwind of the site should be strongly discouraged. Com-

mencement of background surveys and analysis of airborne radioactivity at the Zaria site and all over the Federation is recommended. Classification of results of such surveys into levels of activity and possible radionuclides will facilitate determining the additional manmade radioactivity the environment can tolerate. In addition, it will also help in determining whether the regional mining of uranium ore in the neighouring Niger Republic and the global use of nuclear energy for power production, weapon testings and catastropes of Chernobyl type are producing noticeable effects in Nigeria. It is believed that these are basic prerequisites that will help in determining locations in Nigeria where nuclear power plants can be sited.

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APPENDIX A

A.1 SOLVING THE INSTANTENEOUS POINT SOURCE PROBLEM.

As has been discussed in chapter two of this work, the instanteneous diffussion problem to be solved is

$$\frac{d\chi}{dt} = K\nabla^2\chi$$

$$= \frac{K}{r^2}\frac{\delta}{\delta r}\left(r^2 \frac{\delta\chi}{\delta r}\right) \qquad (a.1)$$

subject to the boundary conditions

$$\chi \longrightarrow 0 \quad \text{as} \quad t \longrightarrow o, \quad r > 0 \qquad (a.2)$$

$$\chi \longrightarrow 0 \quad \text{as} \quad t \longrightarrow \infty \qquad (a.3)$$

and the continuity condition

$$\int \chi d\vec{r} = 4\pi \int \chi r^2 dr = Q \qquad (a.4)$$

By the first statement of boundary condition (a.2) is meant that the diffusing material is confined to the release point at the instance of release. In other no diffusing material would be found far off the release point. At the instance of release therefore the spatial concentration of the diffusing material may be represented a delta function. The second statement of the boundary condition implies that after a substantial time interval has elapsed the spacial concentration of the diffusing material will tend to zero, due to the dilution effect of the diffusion. The continuity condition on the other hand is a necessary condition requiring the conservation of diffusing material. The spacial integral

of concentration of diffusing material over all space must be **equal to the quantity of material released.**

To solve this problem, Kompaneyets (1978) made the following transformation to a dimensionless quatity.

$$\xi = \frac{r^2}{Kt} \qquad (a.5)$$

implying the dimension $[K] = [l^2/t]$

This is because the initial volume containing the diffusing material is infinitesimal and as such characteristic quantites with dimensions of length are not involved. For the quantity of diffusing material to be independent of time he goes on with the transformation to the continuity condition.

$$= 4\pi\int_0^\infty \chi r^2 dr = 4\pi\int_0^\infty f\left(\frac{r^2}{Kt}\right)\frac{r^2}{(Kt)^{3/2}}\,dr$$

$$= 4\pi\int_0^\infty f(\xi)\,\xi^{1/2}\,d\xi \qquad (a.6)$$

where $\chi = (Kt)^{-3/2} f\left(\frac{r^2}{Kt}\right)$

$$= (Kt)^{-3/2} f(\xi) \qquad (a.7)$$

Justification for the above statement stems from the fact that the quantity of diffusing material is time independent and the following analysis.

$$r^2 = Kt\,\eta$$

$$2r\,dr = Kt\,d\eta$$

$$\therefore\quad r^2 dr = (Kt)^{3/2}\,\frac{\eta^{1/2}}{2}\,d\eta$$

Since the quantity is time independent then function χ must involve a coefficient of $(Kt)^{-3/2}$ to neutralize that in r^2dr. Hence, the relation

$$\chi = (Kt)^{-3/2} f(\eta)$$

Substituting this to the left had side of equation (a . 1)

$$\frac{d\chi}{dt} = \frac{d}{dt}(kt)^{-3/2} f(\eta)$$

$$= \frac{-3}{2t(Kt)^{3/2}} f + \frac{1}{(kt)^{3/2}} \frac{\delta\eta}{\delta t}$$

but $\eta = \dfrac{r^2}{Kt}$.

$$\delta\eta = -\frac{r^2}{Kt^2}\,t \qquad \Rightarrow \quad \frac{\delta\eta}{\delta t} = -\frac{\eta}{t}$$

$$\therefore\quad \frac{d\chi}{dt} = -\frac{3}{2}\,\frac{f(\eta)}{t(Kt)^{3/2}} - \frac{\eta}{t(Kt)^{3/2}}\,\frac{\delta f}{\delta\eta}$$

$$= -\frac{1}{t(Kt)^{3/2}}\left(\frac{3f}{2} + \eta\frac{\delta f}{\delta\eta}\right) \qquad (a.8)$$

Substituting equation (a.7) into the right hand side of equation (a.1) and working the derivatives.

$$\frac{\delta}{\delta r}\chi = \frac{1}{(Kt)^{\frac{1}{2}}} \frac{\delta}{\delta r}\left(\frac{\delta f}{\delta \zeta}\right)$$

From $\zeta = \frac{r^2}{Kt} \Rightarrow \delta\zeta = \frac{2r\delta r}{Kt}$

$$\therefore \frac{\delta \zeta}{\delta r} = \frac{2r}{Kt}$$

$$\therefore \frac{\delta \chi}{\delta r} = \frac{2r}{(Kt)^{\frac{3}{2}}} \frac{\delta f}{\delta \zeta}$$

and $$\frac{K}{r^2}\frac{\delta}{\delta r}\left(r^2 \frac{\delta \chi}{\delta r}\right) = \frac{K}{r^2}\frac{\delta}{\delta r}\left(r^2 \frac{2r}{(Kt)^{\frac{3}{2}}}\frac{\delta f}{\delta \zeta}\right)$$

$$= \frac{2K}{r^2(Kt)^{\frac{3}{2}}}\frac{\delta}{\delta r}\left(r^3 \frac{\delta f}{\delta}\right)$$

$$= \frac{2}{r^2(Kt)^{\frac{3}{2}}}\left\{\frac{\delta f}{\delta \zeta}\cdot 3r^2 + r^3 \frac{\delta}{\delta r}\frac{\delta f}{\delta \zeta}\right\}$$

$$= \frac{2}{r^2 t(Kt)^{\frac{3}{2}}}\left\{3r^2\frac{\delta f}{\delta \zeta} + r^3 \frac{\delta \zeta}{\delta r}\frac{\delta}{\delta \zeta}\frac{\delta f}{\delta \zeta}\right\}$$

$$= \frac{2}{r^2 t(Kt)^{\frac{3}{2}}}\left\{3r^2 \frac{\delta f}{\delta \zeta} + r^3\left(\frac{2r}{Kt}\right)\frac{\delta^2 f}{\delta \zeta^2}\right\}$$

$$= \frac{2}{r^2 t(Kt)^{\frac{3}{2}}}\left\{3r^2 \frac{\delta f}{\delta \zeta} \cdot 2r^2\left(\frac{r^2}{Kt}\right)\frac{\delta^2 f}{\delta \zeta^2}\right\}$$

$$= \frac{1}{t(Kt)^{\frac{3}{2}}}\left\{6\frac{\delta f}{\delta \zeta} + 4\zeta \frac{\delta^2 f}{\delta \zeta^2}\right\} \quad (a.9)$$

Equating equations (a .8) and (a .9)

$$-\frac{1}{t(Kt)^{3/2}}\left(\frac{3}{2}f + \zeta\frac{\delta f}{\delta\zeta}\right) = \frac{1}{t(Kt)^{3/2}}\left(6\frac{\delta f}{\delta\zeta} + 4\frac{\delta^2 f}{\delta\zeta^2}\right)$$

$$\text{or}\quad 4\zeta\ddot{f} + 6\dot{f} + \zeta\dot{f} + \frac{3}{2}f = 0 \qquad (a.10)$$

$$\text{where}\quad \dot{f} = \frac{\delta f}{\delta\zeta}\ ;\quad \ddot{f} = \frac{\delta^2 f}{\delta\zeta^2}$$

Equation (a.10) may be solved by the Frobenius method (Stephenson, 1973). This means we try a series solution of the problem.

$$\text{Let}\quad f = \sum_{n=0}^{\infty} a_n \zeta^{s+n}$$

where s and a_n are constants.

$$\dot{f} = \sum_{n=0}^{\infty}(n+s)a_n\zeta^{S+n-1}$$

$$\ddot{f} = \sum_{n=0}^{\infty}(n+s-1)(n+s)\,a_n\zeta^{s+n-2}$$

Therefore, equation (a.10) becomes

$$\sum_{n=0}^{\infty}4(n+s-1)(n+s)a_n\zeta^{n+s-1} + \sum_{n=0}^{\infty}6(n+s)a_n\zeta^{n+s-1} +$$

$$+\sum_{n=0}^{\infty}(n+s)a_n\zeta^{n+s} + \sum_{n=0}^{\infty}\frac{3}{2}a_n\zeta^{n+s} = 0 \qquad (a.12)$$

$$\sum_{n=0}^{\infty}(n+s)\left[4_n + 4_s - 4 + 6\right]a_n\zeta^{n+s-1} + \sum_{n=0}^{\infty}(n+s+\tfrac{3}{2})a_n\zeta^{n+s} = 0$$

$$\sum_{n=0}^{\infty}(n+s)(4n + 4s + 2)\,a_n\zeta^{n+s-1} + \sum_{n=1}^{\infty}(n+s+\tfrac{1}{2})a_{n-1}\zeta^{n+s-1} = 0$$

(a.13)

For n=o

$$s(4s + 2)\, a_o \left(\tfrac{3}{2}\right)^{s-1} = 0$$

$$a_o \neq 0 \Rightarrow \quad s = 0 \; ; \quad s = -\tfrac{1}{2}$$

Taking s =0, equation (a.13) becomes:

$$\sum_{n=o} n(4n+2)\, a_n \left(\tfrac{3}{2}\right)^{n-1} + \sum_{n=1} (n+\tfrac{1}{2})\, a_{n-1} \left(\tfrac{3}{2}\right)^{n-1} = 0$$

$$\sum_{n=1} n(4n+2) a_n \left(\tfrac{3}{2}\right)^{n-1} + \sum_{n=1} (n+\tfrac{1}{2}) a_{n-1} \left(\tfrac{3}{2}\right)^{n-1} = 0$$

$$\sum_{n=1} \left[n(4n+2)a_n + (n+\tfrac{1}{2})a_{n-1} \right] \left(\tfrac{3}{2}\right)^{n-1} = 0 \qquad \text{(a.14)}$$

$$\Rightarrow n(4n+2)a_n + (n+\tfrac{1}{2})a_{n-1} = 0$$

$$\text{or } 4n(n+\tfrac{1}{2})a_n + (n+\tfrac{1}{2})a_{n-1} = 0$$

$$\therefore a_n = -\frac{a_{n-1}}{4n} \; ; \quad a_o \neq 0 \text{ for } n \geq 1$$

This gives

$$a_1 = \frac{-a_o}{4.1}$$

$$a_2 = \frac{-a_1}{4.2} = \frac{a_o}{4^2.2!}$$

and generally $a_n = \dfrac{(-1)^n a_o}{4^n . n!}$ (a.15)

$$\therefore \quad f(\zeta) = \sum_{n=0}^{\infty} a_n \zeta^{s+n}$$

$$= \sum_{n=0}^{\infty} \frac{(-1)^n}{4^n \cdot n!} a_o \zeta^n \qquad (a.16)$$

or $$f(\zeta) = a_o \sum_{n=0} \left\{\frac{-\zeta}{4}\right\}^n \frac{1}{n!}$$

This can be expressed as:

$$f = a_o \exp(-\zeta/4) \qquad (a.17)$$

This function assures the constancy of the quantity, Q, diffusing material unlike in the case where $s = -\frac{1}{2}$ (Kompaneyets, 1978).

Using the equation (a.17) in the continuity condition, that is, (a.6), the value of the constant a_o may be obtained thus;

$$Q = \frac{4\pi}{2} a_o \int_0^{\infty} \zeta^{\frac{1}{2}} \exp(-\zeta/4) d\zeta$$

let $\eta = \zeta/4$

$$4d\eta = d\zeta \quad \text{and} \quad 2\eta^{\frac{1}{2}} = \zeta^{\frac{1}{2}}$$

$$\therefore \quad Q = \frac{4\pi}{2} a_o 4\times 2 \int_0^{\infty} \eta^{\frac{1}{2}} \exp(-\eta) d\eta$$

$$Q = 16\pi a_o \Gamma(3/2)$$

$$= 16 a_o \pi \frac{\pi^{1/2}}{2} = \underline{8a_o \pi^{3/2}}$$

$$\therefore a_o = \frac{Q}{8\pi^{3/2}} \qquad (a.17)$$

$$\therefore f(\zeta) = \frac{Q}{8\pi^{3/2}} \exp(-\zeta/4) \qquad (a.18)$$

Therefore, the spatial concentration equation, (a.7), on substituting equations (a.18) and (a.5) becomes:

$$\chi(r,t) = \frac{Q}{(4\pi Kt)^{3/2}} \exp(-r^2/4Kt) \qquad (a.19)$$

A.II THE FRACTION OF EFFLUENT PASSING DOWNWIND LOCATIONS.

Ideally the concentration of effluent material at ground passing any downwind point is given by

$$\bar{\chi}(x,y,o) = \frac{Q_o}{\pi\sigma_y\sigma_z\bar{u}} \exp\left[-\left(\frac{y^2}{2\sigma^2} + \frac{H^2}{2\sigma^2}\right)\right]. \quad (a.20)$$

Deposition of the effluent on surfaces at this level however causes a reduction to the initial source strength Q_o. Therefore Q_o may be replaced by $Q(x)$. If the deposition velocity is v_g, then the rate at which material is deposited per unit area, w, is given by

$$w(x,y) = v_g\bar{\chi}(x,y,o) \quad (a.21)$$

Therefore, the actual rate of passage of effluent over any point will be lower than for the ideal case. The depletion of the source per unit distance is given by

$$\frac{\delta Q}{\delta x} = -\int_{-\infty}^{\infty} w(x,y)dy$$

(see Hosker (1974), Slade (1977)).

From substituting $Q(x)$ for Q_o in equation (a.10), therefore,

$$\frac{\delta Q(x)}{\delta x} = -\sqrt{\frac{2}{\pi}}\ \frac{Q(x)}{\sigma_z}\ \frac{v_g}{\bar{u}} \exp\left(-\frac{H^2}{2\sigma_z}\right)$$

Rearranging, integrating and substituting the values of $Q(x)$ at the origin, that is Q_o, gives

$$\frac{Q(x)}{Q_o} = \exp\left[-\sqrt{\frac{2}{\pi}}\ \frac{v_g}{\bar{u}} \int_0^x \frac{dx}{\sigma_z \exp\left(\frac{H^2}{2\sigma_z^2}\right)}\right] \quad (a.22)$$

This relation is to be evaluated numerically.

APPENDIX B.

RELEASE OF RADIOACTIVITY FROM THE CORE TO THE ATMOSPHERE

B.I Release From Core To Containment Building

Loss of coolant accident

The fuel element of a reactor usually consists of uranium dioxide, mixed oxides of uranium and plutonium or uranium in Zirconium hydride for example $UZr\,H_{1.65}$, the standard Triga fuel (Ewa, 1982). The fuel is compressed into pellet form and put into metallic tubes called claddings. Figure B.1 shows the configuration of a typical Triga fuel element in Zircaloy cladding. In water-cooled power reactors the fuel elements in bundles and moderator usually water too are put in a specially constructed strong container called the reactor core containment vessel. This containment is provided with a number of ducts and closed loop tubings for the circulation of the coolant and running the generator. Most Triga research reactors have the reactor core surrounded by graphite reflectors and lead shield with the whole system contained at the base of a large water tank called a pool. The vertical section of the Triga Mark II reactor is shown in figure B.2 (see Ewa, 1982).

The nuclear reactor has its basis on nuclear reactions of the form.

neutron + fissionable atom ⟶ fission products + neutrons + energy

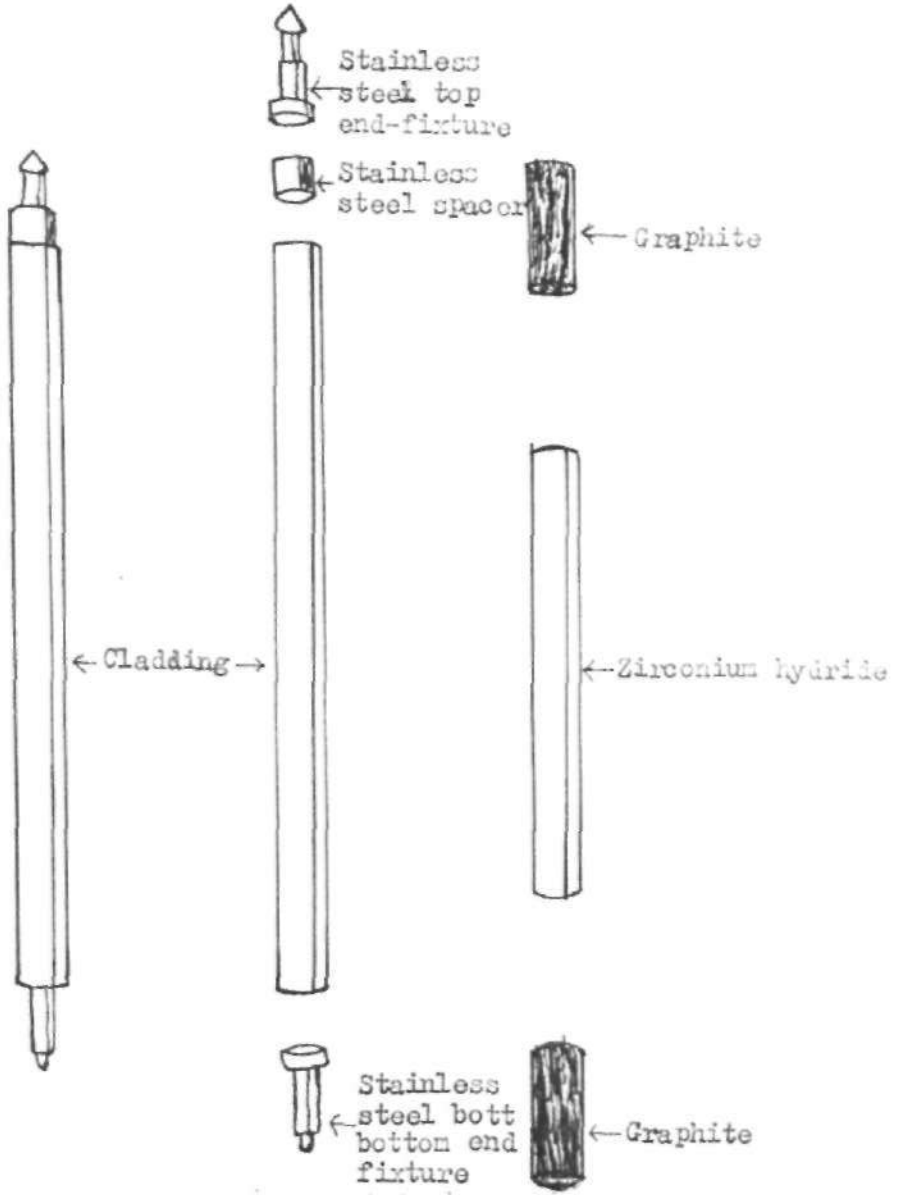


Figure B.1 A typical Triga fuel element

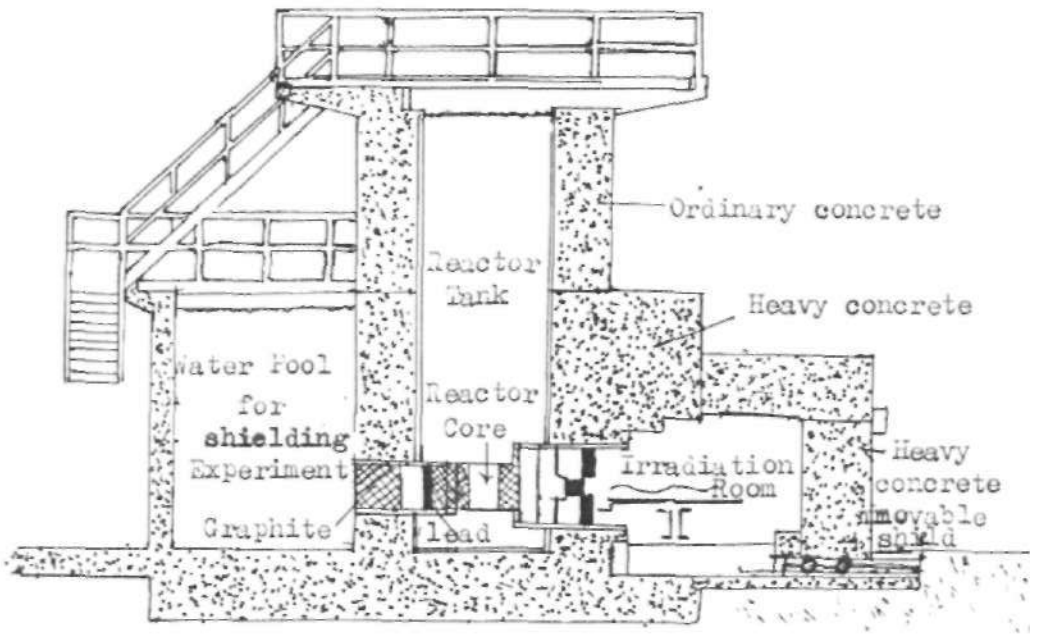


Figure B.2 A vertical section of a Triga Mark II reactor re-modelled to include an exposure room. From Ewa, 1982.

The inventory of possible fission products from such a reaction has been reported to include approximately 360 radionuclides (Hosemann et al, 1974). This large number is however, considerably reduced on the basis of yield and half-life (Lewis, 1977).

On certain occassions the release of such fission products from the point of production in fuel element cladding to outside the fuel element cladding and eventually to the reactor containment building may occur. These are generally refered to as accidents. Among these accidents Lewis (1978) has listed fuel cladding rapture, fuel melting, fuel mixing with concrete (or metals) and vapour explosion. He goes on to identify four types of fission product releases which will be summarised below.

Gap release: This is the release of fission products that occurs due to fuel element cladding rapture. Gap release materials are usually those fission products that are gaseous or in the vapour state which collect in fuel pellet spacing and fuel voids. During normal operation it is possible for a small number of fuel elements to rapture due to variations in cladding strength, core power distribution, build up in fuel rod internal pressure and so forth. After the occurrence of a rapture the rate of escape of gap release materials depends on

the size of the rapture and the pressure differential across the cladding at the rapture point.

The main fission products that easily escape through the rapture areas are the noble gases (Kr, Xe, Ar and so forth if they are present) due to their very negligible chemical reactivity. Following the noble gases are the halogens (iodine and bromine) and to a lesser extent the alkali metals. If any of the gap release materials happen to be in elemental form, then it may undergo chemical reactions with other fission products, for example the reaction between elemental iodine and cesium, zirconium or cladding material. Such reactions reduce the release fraction by reducing migration. As can be seen from table b.1 the less volatile fission products are hardly released due to cladding raptures accidents. On the whole, the amount of fission products released due to rapture depends on the temperature profile of the raptured fuel element, its exposured history and half-lives of the fission products involved. This type of release is the most occuring of all reactor fission product releases; because it does occur even when the fuel elements are fully submerged in collant. With loss of coolant accident the probability of rapture increases. The remaining classes of fission products releases, briefly discussed below, occur mainly as a result of loss of coolant accident.

Fission Product	Gap Release Fraction	Meltdown Release Fraction	Vaporization Release Fraction[4]	Steam Explosion Fraction[5]
Xe,Kr,Ar.	0.030	0.870	0.100	(X)(Y)0.90
I, Br	0.017	0.883	0.100	(X)(Y)0.90
Cs, Rb	0.050	0.760	0.190	---
Te[1]	0.0001	0.150	0.850	(X)(Y)(0.60)
Sr,Ba	0.00001	0.100	0.010	---
Ru[2]	-	0.030	0.050	(X)(Y)(0.90)
ha[3]	-	0.003	0.010	---

TABLE B.1 Fission product release source summary-best total core release fractions. (See Lewis, 1978).

1. Includes S1, Sb.
2. Includes Mo, Fd, Rb, Tc.
3. Includes Nd, Eu, Y, Ce, Fr, Pm,Sm, Np,Pu,Zr, Nb.
4. Exponential loss over two hours with half-time of thirty minutes. If a steam explosion occurs prior to this, only the core fraction not involved in the steam explosion can experience vaporitation.
5. X = Fraction of core involved in the steam explosion.
   Y = fraction of inventory remaining for release by oxidation.

Melt Down Release: Following a loss of coolant accident, the temperature of fuel elements in the reactor may become so excessively high that fuel melting occurs. This generally starts at "highest power density locations in the almost on a fuel pellet to pellet scale", which gives large surface-to-mass ratio of molten material. As a result large proportions of volatile fission product escape the molt. As melting progresses however, molten fuel pellets coalese into larger masses which enhances trapping of less volatile fission products in the molt. Those in the gaseous state may however form bubbles which will froth to the surface. The progressing of melting if not halted may eventually lead to the collapse of fuel pins, eventually leading to the next type of release.

Vaporisation Release: The collapse of fuel pins may mean formation of large molten mass including cladding material and contact between molten mass and remaining coolant, if there is any or to contact with structural materials. This gives rise to decomposition and vaporisation of the most volatile materials and the formation of water vapour, carbon dioxide (from the decomposition of concrete) and generally the release of aerosols containing fission products. This stage of the accident gives rise to what is referred to as vaporisation release. This stage and sometimes the preceeding one may be accompanied by the formation of substantial amounts of combustible gases like hydrogen. The occurance of such leads to what is discussed in the next section.

Oxidation Release: The presence of combustible gases and the high temperature may result in vapour explosion within the core at any stage of loss of coolant accident. This dangerous happenning leads to the release of about the total estimates of releases due to meltdown and vaporisation, if it occurs early in the loss of coolant accident. In addition to this, fine fragments of pulvirised fuel will also be produced and scattered by the explusion. These scattered fragments get oxidised in an oxidising atmosphere hence the name oxidation release.

It should be noted that a loss of coolant accident can occur with lots of variations from what is given above.

Nuclear excursions: Another major cause of release of activity from reactor core to containment is nuclear excursion. This is a class of accidents that is quite distinct from loss of coolant accident in liquid cooled reactors. Its major cause is "overpower transient, particularly superprompt critical power bursts" (Lewis, 1978). One of the major distinction between loss of coolant accident and nuclear excusion as has put by Lewis (1978) is that "at time that fuel melting or vaporisation is initiated, the reactor vessel is still filled with liquid and the primary system envelope is intact." Another is fuel melt or even its vaporisation may occur before melting temperature of cladding is reached. Which ever of these happens may create sufficient pressure for the eventual collapse of fuel elements. With radioactive

material now in the collant stream, "the possibility for escape of the fission products to the containment depends on the integrity of the primary system envelope and the partitioning of the radioactive materials between liquid and gas phase within the vessel." For more information on this Lewis (1977) or other suitable text may be consulted.

B.II Release From Containment Building To Outside Atmosphere.

Due to the possibility that radioactivity might reach the containment building, the following preventive steps are taken to minimize the contamination of the environment around it. This building and infact all others subject to radioactive contamination are kept at a negative pressure relative to all other adjacent buildings and the outside atmosphere (Edward, 1984). This ensures that air from these buildings does not get out through all available passages. Rather than that, the air is extracted from these buildings and passed through efficiency filteration units. These, filter out particulates and iodine from the extracted air. Further routing of the filtered air to a tall exhaust stack and employing the dispersive abilities of the atmosphere is done. Other special features of that may be encorporated to the containment building are very thick concrete walls, containment spray system,combustible gases and fire protection devices, radiation sampling and monitoring systems, emergency air exhaust and flooding systems and so forth (Edwards, 1984).

APPENDIX C: AIRBORNE EFFLUENT RELEASE FIGURES FOR THE TEXAS A & M UNIVERSITY REACTOR FOR THE PERIOD 1983-1985.

TABLE C.1- GASEOUS EFFLUENT RELEASES
ARGON-41
ANNUAL SUMMARY
1983

Month	Exhaust Volume (cc)	Concentration* (μCi/cc)	Concentration** (μCi/cc)	Ratio MPC**	Total Radio-activity (Ci)*
January	6.31 E 12	1.02 E-08	5.10 E-11	1.28 E-03	6.44 E-02
February	5.91 E 12	8.31 E-09	4.16 E-11	1.04 E-03	4.91 E-02
March	6.31 E 12	4.59 E-09	2.29 E-11	5.73 E-04	2.90 E-02
April	6.12 E 12	1.11 E-08	5.55 E-11	1.39 E-03	6.79 E-02
May	6.31 E 12	2.04 E-08	1.02 E-10	2.55 E-03	1.28 E-01
June	6.12 E 12	5.99 E-08	3.00 E-10	7.50 E-03	3.67 E-01
July	6.31 E 12	3.45 E-08	1.73 E-10	4.33 E-03	2.18 E-01
August	6.31 E 12	2.23 E-08	1.12 E-10	2.80 E-03	1.41 E-01
September	6.12 E 12	2.92 E-08	1.46 E-10	3.65 E-03	1.79 E-01
October	6.31 E 12	2.17 E-08	1.09 E-10	2.73 E-03	1.37 E-01
November	6.12 E 12	1.89 E-08	9.45 E-11	2.36 E-03	1.16 E-01
December	6.31 E 12	5.40 E-08	2.70 E-10	6.75 E-03	3.41 E-01

Total Volume: 7.45 E 13 cc

Annual Average Release*: 2.46 E-08 μCi/cc

Total Radioactivity Released*: 1.77 Ci

*As measured in the central exhaust stack.

**As determined at 100 meters, approximate boundary of exclusion area, with 200/1 dilution factor (SAR, pp. 117-119, June 1979).

(From Krohn, 1986).

TABLE C.2- PARTICULATE EFFLUENT RELEASES
ANNUAL SUMMARY
1983

Month	Exhaust Volume (cc)	Concentration (uCi/cc)	Total Radioactivity (uCi)	(Ci)
January	6.31 E 12	6.85 E-12	43.22	4.32 E-05
February	5.91 E 12	2.05 E-12	13.89	1.39 E-05
March	6.31 E 12	5.03 E-12	31.74	3.17 E-05
April	6.12 E 12	1.07 E-12	6.55	6.55 E-06
May	6.31 E 12	1.07 E-12	6.75	6.75 E-06
June	6.12 E 12	1.18 E-12	7.22	7.22 E-06
July	6.31 E 12	4.8 E-12	30.29	3.03 E-05
August	6.31 E 12	3.75 E-12	23.66	2.37 E-05
September	6.12 E 12	2.39 E-11	146.27	1.46 E-04
October	6.31 E 12	6.82 E-12	43.03	4.30 E-05
November	6.12 E 12	1.70 E-12	10.40	1.04 E-05
December	6.31 E 12	2.38 E-11	15.02	1.50 E-05

Total Volume: 7.45 E 13 cc

Annual Average Release: 6.86 E-12 uCi/cc

Total Radioactivity Released: 3.78 E-04

(From Krohn, 1986).

TABLE C.3- GASEOUS EFFLUENT RELEASES
ARGON-41
ANNUAL SUMMARY
1984

Month	Exhaust Volume(cc)	Concentration* (µCi/cc)	Concentration** (µCi/cc)	Ratio MPC	Total Radioactivity (Ci)*
January	6.31 E12	1.86 E-08	9.3 E-11	2.32E-03	1.17E-01
February	5.91 E12	1.92 E-08	9.6 E-11	2.4E-03	1.13E-01
March	6.31 E12	5.13 E-08	2.56 E-10	6.4E-03	3.23E-01
April	6.12 E12	1.63 E-08	8.1 E-11	2.0E-03	9.9E-02
May	6.31 E12	9.03 E-08	4.5 E-10	1.12E-02	5.69E-01
June	6.12 E12	1.09 E-08	5.4 E-11	1.3E-03	6.6E-02
July	6.31 E12	2.48 E-08	1.24 E-10	3.1E-03	1.56E-01
August	6.31 E12	3.06 E-08	1.53 E-10	3.8E-03	1.93E-01
September	6.12 E12	2.6 E-09	1.3 E-11	3.2E-04	1.59E-02
October	6.31 E12	6.1 E-10	3.0 E-12	7.5E-05	3.85E-03
November	6.12 E12	1.53 E-09	7.6 E-12	1.9E-04	9.36E-03
December	6.31 E12	1.47 E-08	7.3 E-11	1.82E-03	9.2E-02

Total Volume: 7.45 E13 cc

Annual Average Release:* 2.35 x 10^{-8} µCi/cc

Total Radioactivity Released:* 1.75 Ci

*As measured in the central exhaust stack

**As determined at 100 meters, approximate boundary of exclusion area, with 200/1 dilution factor (SAR, pp. 117-119, June 1979).

(from Krohn, 1986).

TABLE C.4- PARTICULATE EFFLUENT RELEASES
ANNUAL SUMMARY
1984

Month	Exhaust Volume (cc)	Concentration (μCi/cc)	Total Radioactivity (μCi)	(Ci)
January	6.31 E12	2.81 E-11	177	1.77 E-04
February	5.91 E12	4.09 E-12	24.1	2.4 E-05
March	6.31 E12	3.91 E-11	246	2.46 E-04
April	6.12 E12	5.9 E-12	36.1	3.61 E-05
May	6.31 E12	9.3 E-12	58.6	5.86 E-05
June	6.12 E12	1.79 E-11	109.5	1.09 E-04
July	6.31 E12	1.88 E-11	118.2	1.18 E-04
August	6.31 E12	1.38 E-11	87.1	8.71 E-05
September	6.12 E12	6.8 E-13	4.1	4.1 E-06
October	6.31 E12	2.3 E-11	145.7	1.45 E-05
November	6.12 E12	5.6 E-12	34.3	3.43 E-05
December	6.31 E12	5.1 E-12	32.2	3.22 E-05

Total Volume: 7.45 E 13cc

Annual Average Release: 1.43 E-11 μCi/cc

Total Radioactivity Released: 1.06 E-03 Ci

(From Krohn, 1986).

Table C.5- Gaseous Effluent Releases
Argon-41
Annual Summary
1985

Month	Exhaust Volume(cc)	Concentration* (μCi/cc)	Concentration** (μCi/cc)	Ratio MPC	Total Radioactivity (Ci)*
January	6.31 E12	2.45E-10	1.23E-12	3.08E-5	1.546 E-3
February	5.91 E12	4.9E-11	2.45E-13	6.13E-6	2.90 E-4
March	6.31 E12	7.35E-11	3.68E-13	9.20E-6	4.64 E-4
April	6.12 E12	1.4E-11	7.00E-14	1.75E-6	8.57 E-5
May	6.31 E12	3.52E-10	1.76E-12	4.40E-5	2.221 E-3
June	6.12 E12	3.52E-10	1.76E-12	4.40E-5	2.154 E-3
July	6.31 E12	1.31E-10	6.55E-13	1.64E-5	8.27 E-4
August	6.31 E12	1.65E-10	8.25E-13	2.06E-5	1.041 E-3
September	6.12 E12	3.92E-10	1.76E-12	4.40E-5	2.154 E-3
October	6.31 E12	1.76E-10	8.80E-13	2.20E-5	1.111 E-3
November	6.12 E12	1.97E-10	9.85E-13	2.46E-5	1.206 E-3
December	6.31 E12	1.75E-10	8.75E-13	2.19E-5	1.104 E-3

Total Volume: 7.45E13 cc

Annual Average Release*: 2.45×10^{-10} μCi/cc

Total Radioactivity Released*: .022 Ci

*As measured in the central exhaust stack.

**As determined at 100 meters, approximate boundary of exclusion area, with 200/1 dilution factor (SAR, pp. 117-119, June 1979).

(From Krohn, 1986).

Table C.6- Particulate Effluent Releases
Annual Summary
1985

Month	Exhaust Volume(cc)	Concentration (µCi/cc)	Total (µCi)	Radioactivity (Ci)
January	6.31 E12	2.4 E-11	151.44	1.514 E-4
February	5.91 E12	6.9 E-12	40.78	4.078 E-5
March	6.31 E12	1.81 E-14	.114	1.14 E-7
April	6.12 E12	1.72 E-13	1.05	1.05 E-6
May	6.31 E12	1.23 E-12	7.761	7.76 E-6
June	6.12 E12	1.45 E-13	.887	8.87 E-7
July	6.31 E12	1.25 E-13	.789	7.89 E-7
August	6.31 E12	1.98 E-13	1.25	1.25 E-6
September	6.12 E12	2.58 E-13	1.58	1.58 E-6
October	6.31 E12	1.98 E-13	1.25	1.25 E-6
November	6.12 E12	1.35 E-13	.826	8.26 E-7
December	6.31 E12	1.35 E-13	.852	8.52 E-7

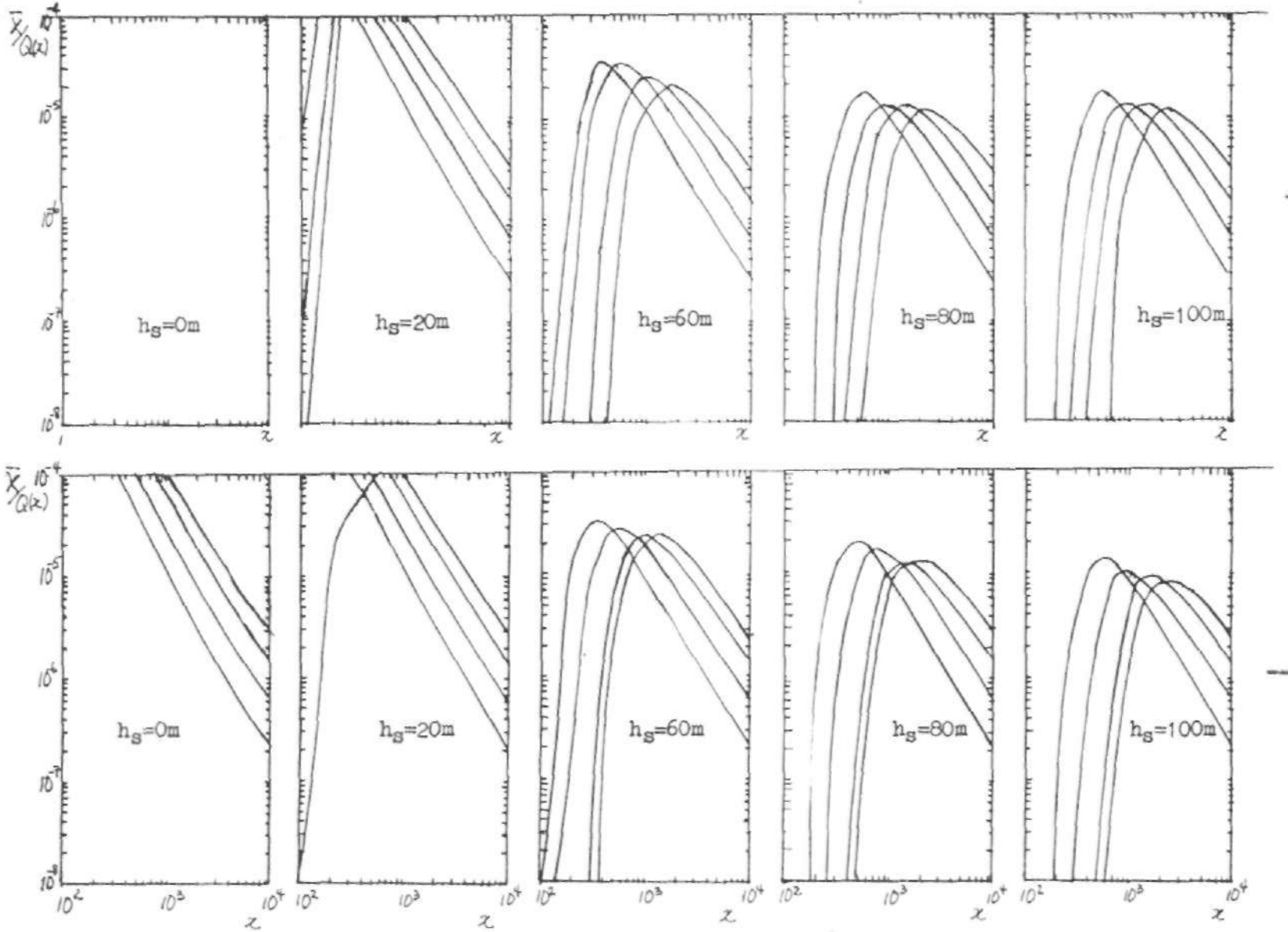
Total Volume: 7.45 E13 (cc)

Annual Average Release Rate: 1.25 E-12 µCi/cc

Total Radioactivity Released: 2.086 E-4 Ci

(From Krohn, 1986).

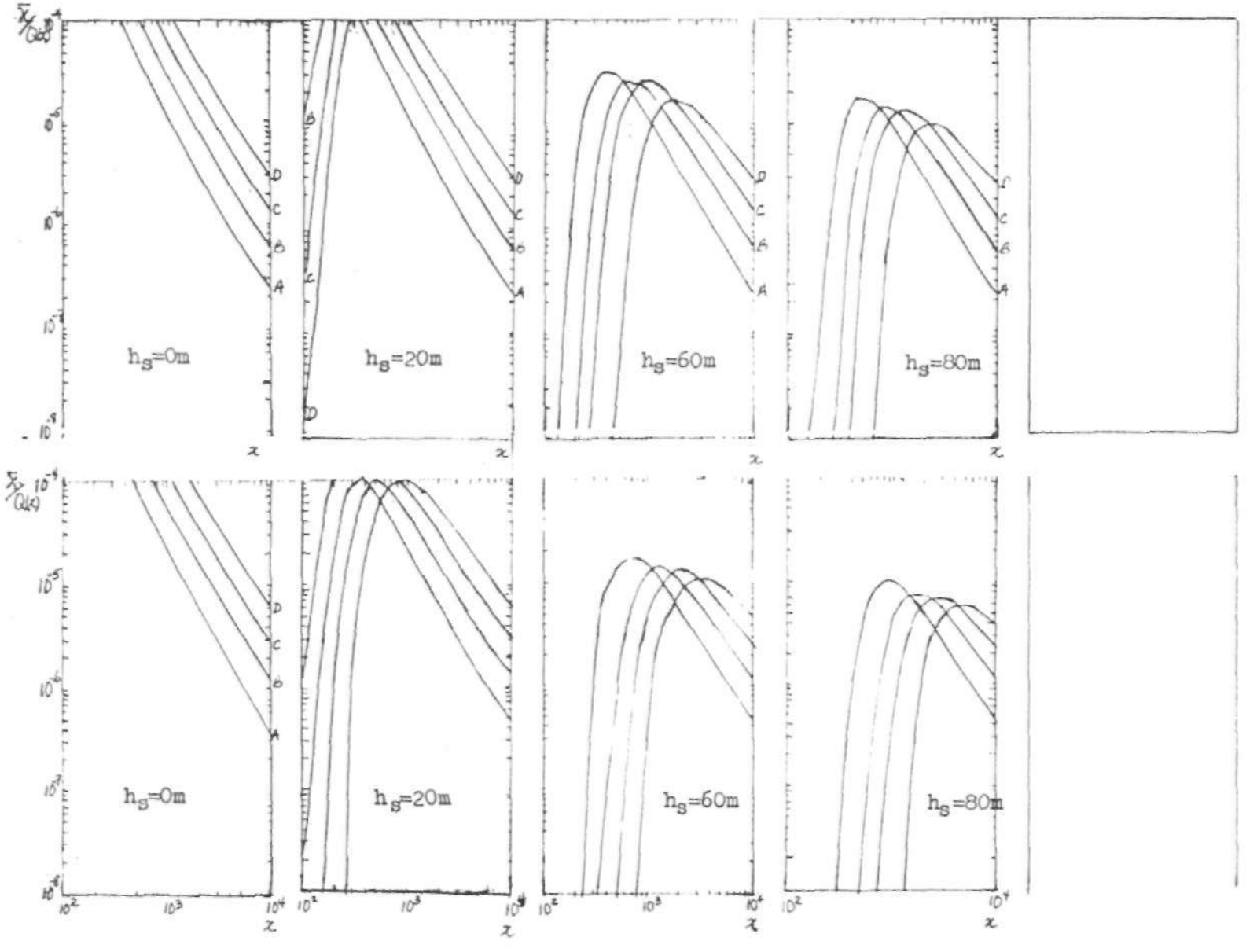
APPENDIX D: GRAPHICAL PRESENTATION OF RESULTS



(D.1.1)
---February results

(D.1.2)
—— November results

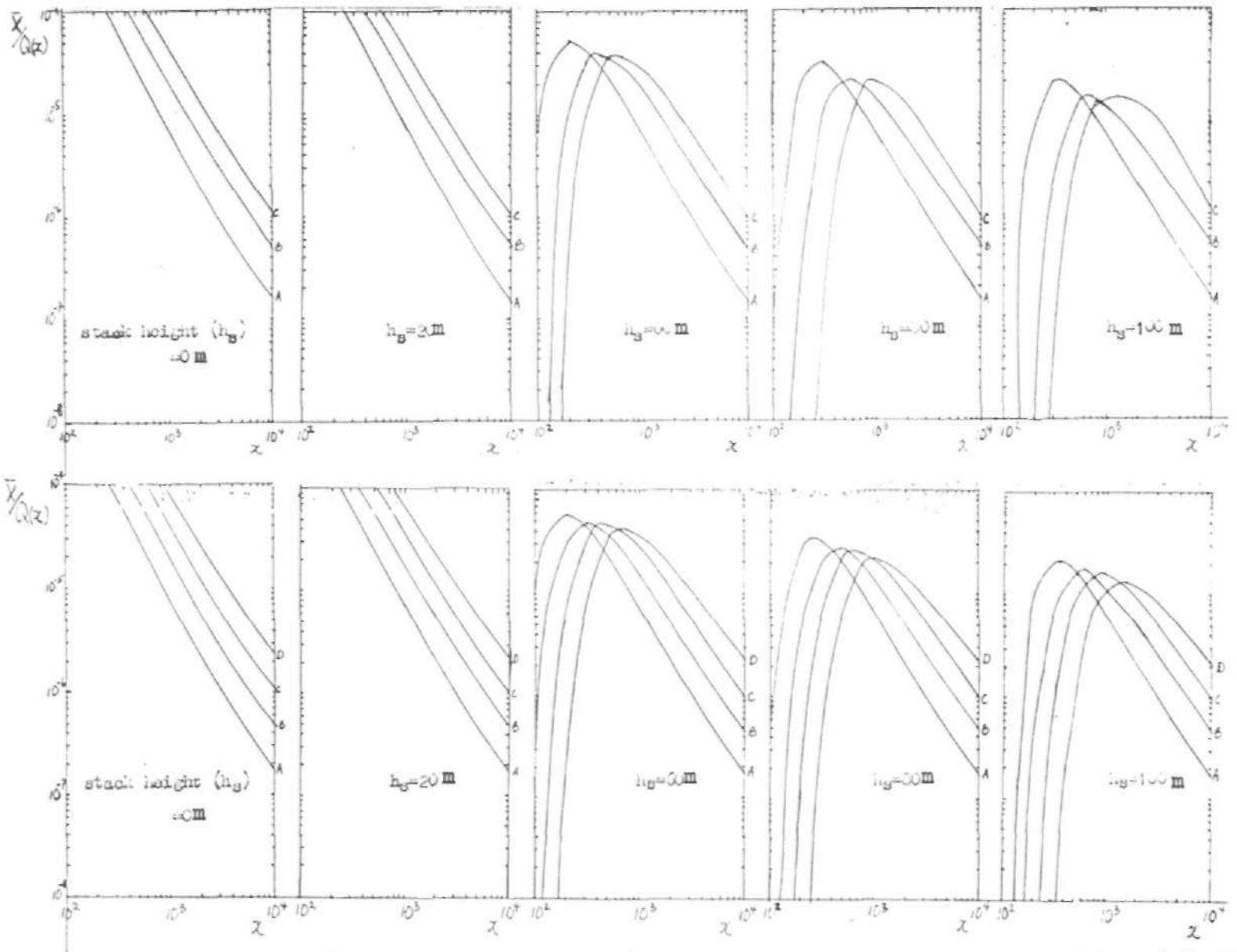
Figure D.1- Relative concentration of effluent, $\bar{\chi}/Q(x)$, at ground level as function of downwind distance, x, for selected stack heights. Vertical axis is $\bar{\chi}/Q(x)$, horizotal axis is downwind distance, x (m).



(D.1.3)
— May results

(D.1.4)
— July results

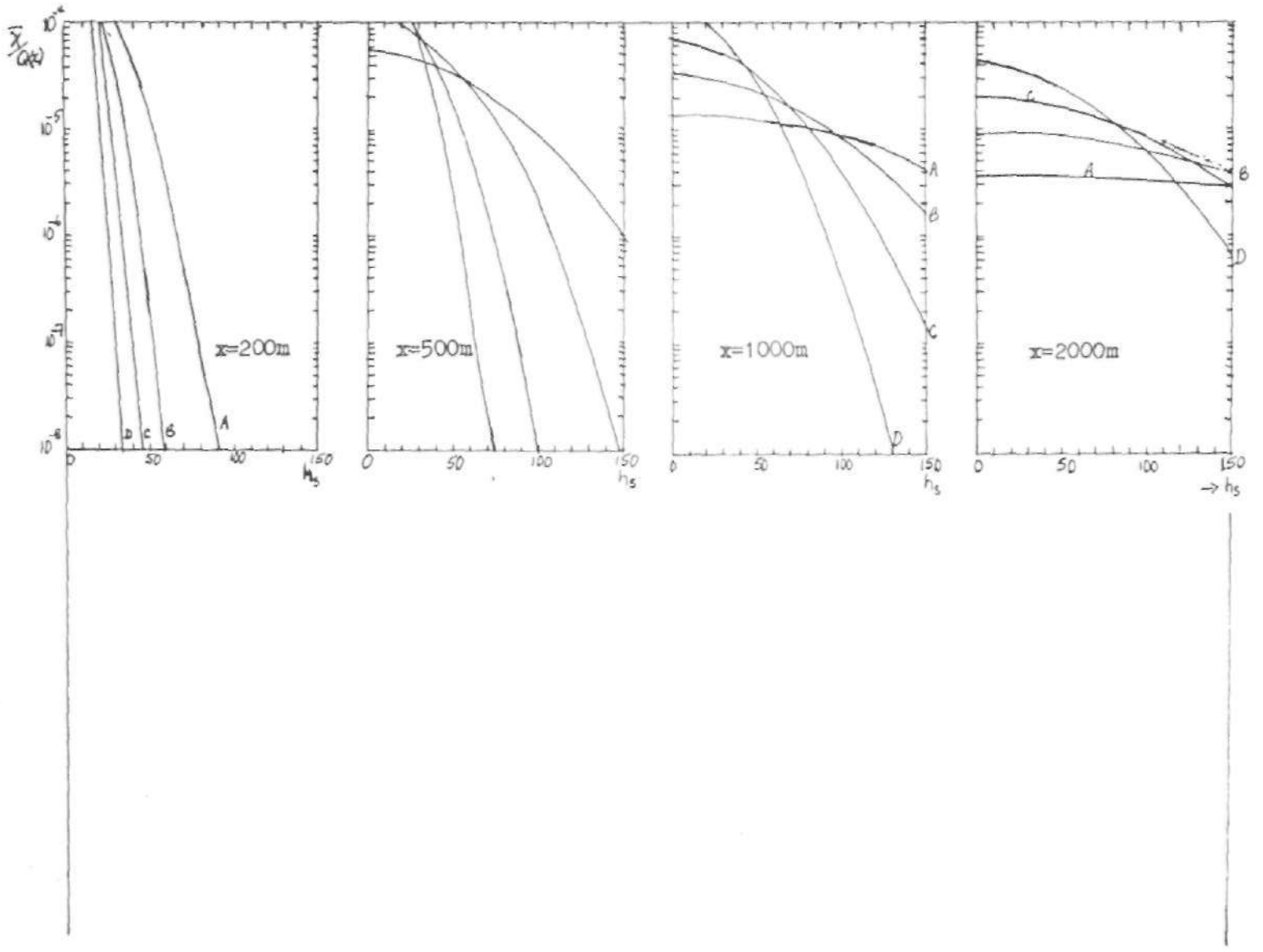
Figure D.1 - Relative concentration of effluents, $\bar{\chi}/Q(x)$, at ground level as a function of downwind distance, x, for selected stack heights.



(D.1.5) — September results

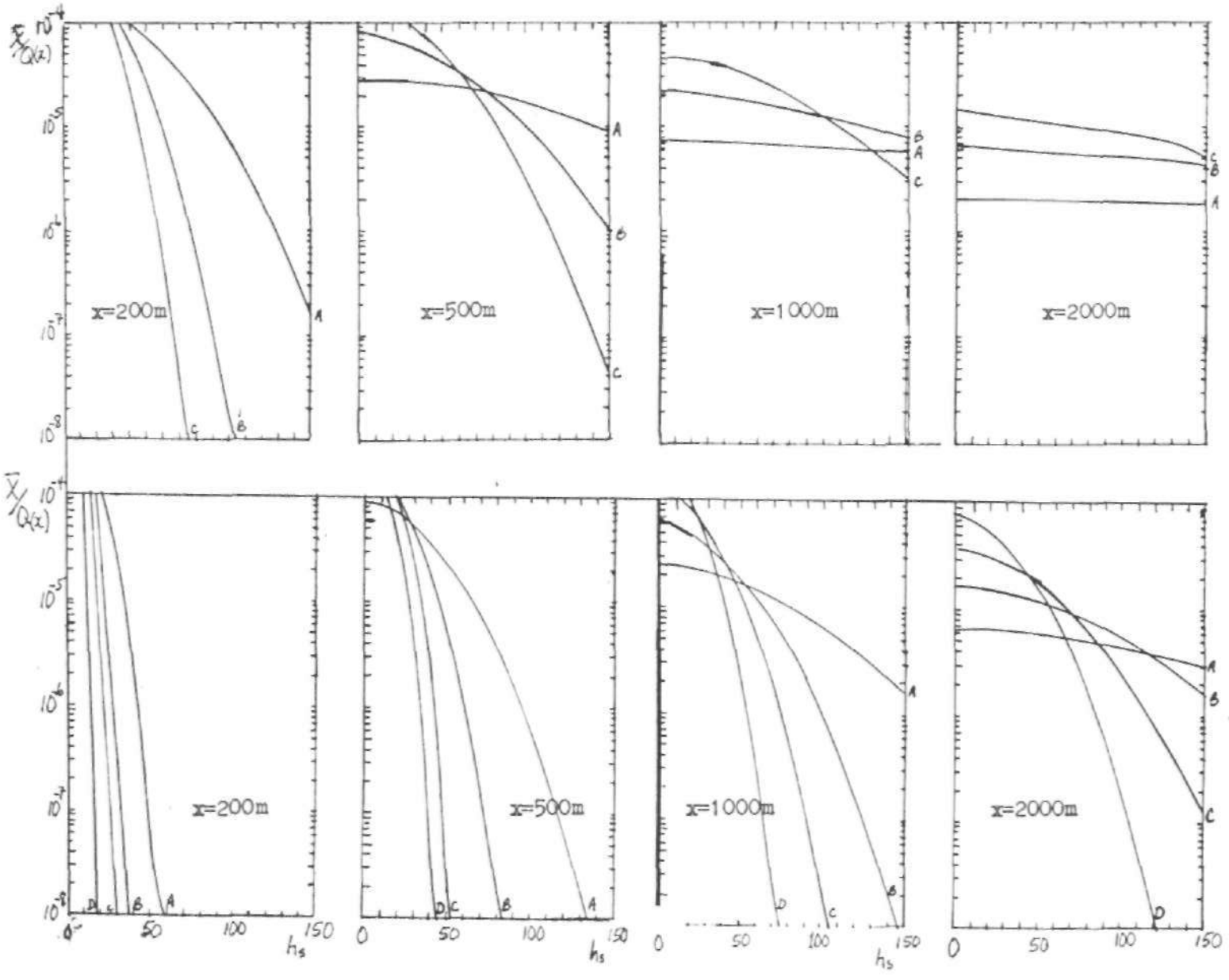
(D.1.6) — Main Campus side (September) results

Figure D.1- Relative concentration of effluent, $\bar{\chi}/Q(x)$, at ground level as a function of downwind distance, x, for some selected stack heights.



(D.2.1)
— February results

Figure D.2- Relative concentration of effluent, $\bar{\chi}/Q(x)$, at ground level as a function of stack height, h_s, for some selected downwind distances, x. Vertical axis is $\chi/Q(x)$, horizontal axis is stack height ..ht, h_s(m).



(D.2.2) — July results

(D.2.3) — September results

Figure D.2 - Relative concentration of effluent, $\bar{\chi}/Q(x)$, at ground level as a function of stack height, h_s, for some selected downwind distances, x.

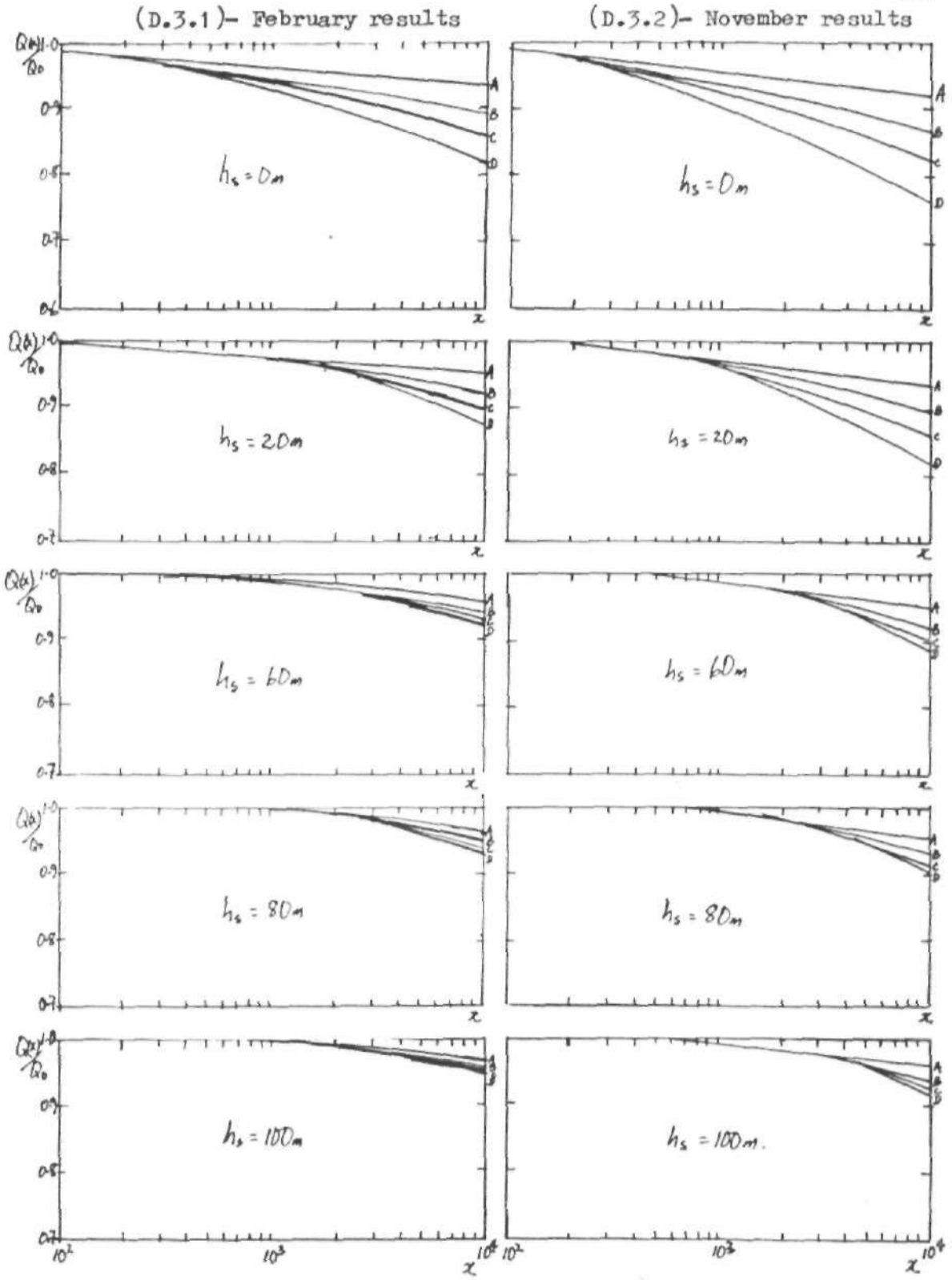


Figure D.3- Plume depletion fraction, $Q(x)/Q_o$, as function of downwind distance, x, for some selected stack heights. Vertical axis is $Q(x)/Q_o$, horizontal axis is downwind distance travelled, x(m).

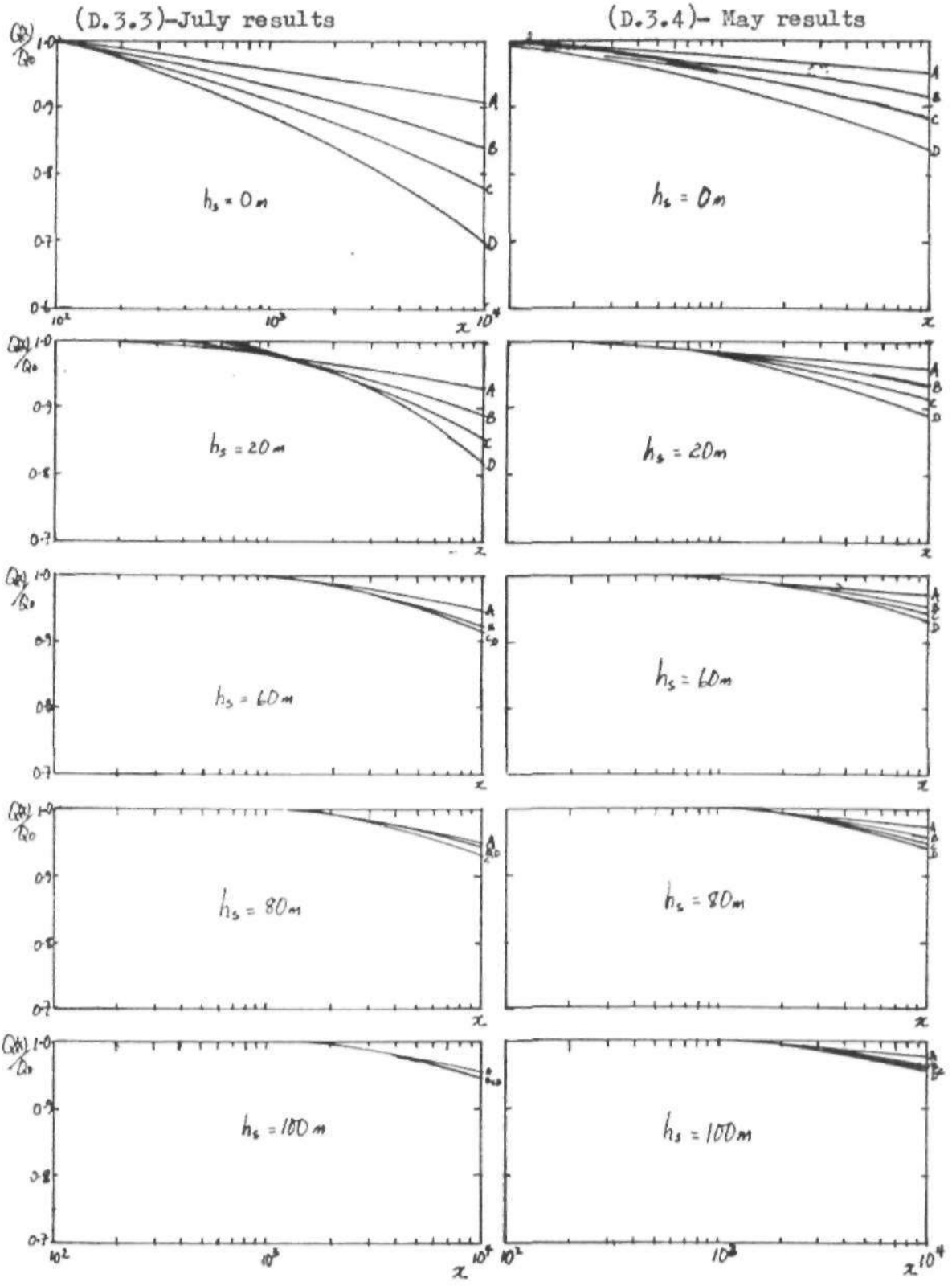


Figure D.3- Plume depletion fraction, $Q(x)/Q_o$, as a function of downwind distance, x, for some selected stack heights.

(D.3.5)- September results

(D.3.6)-Main Campus (Sept.)results

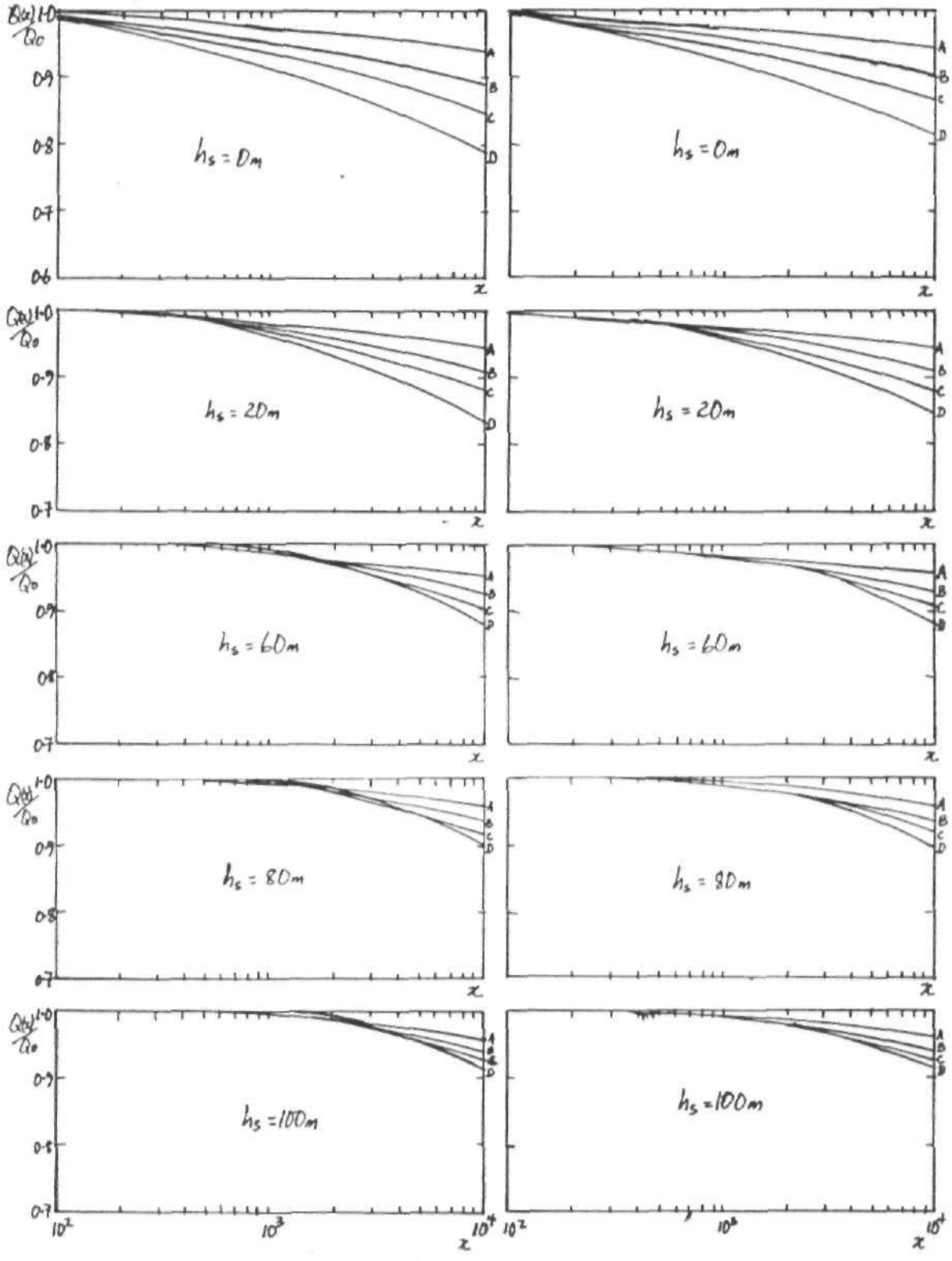
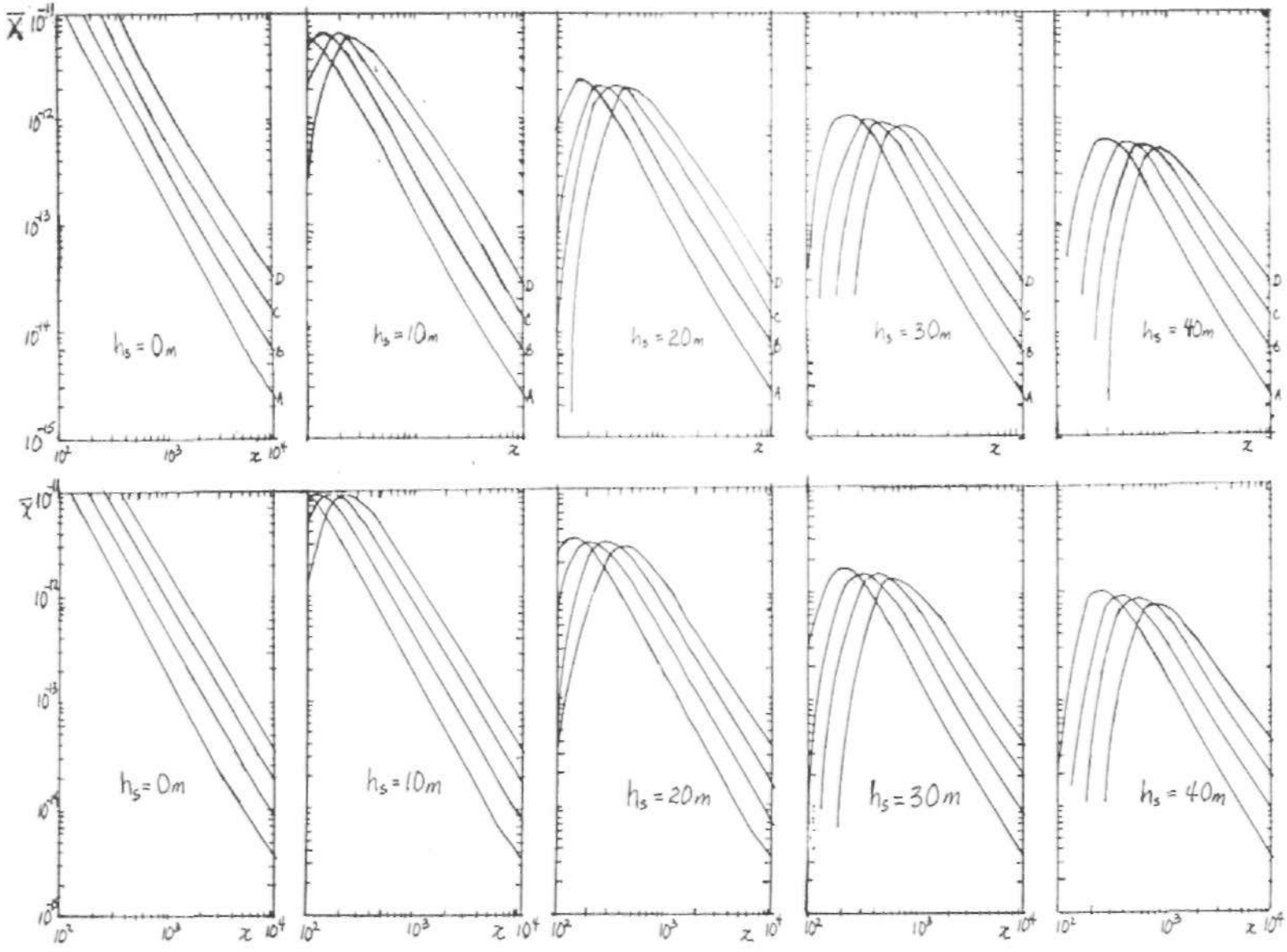


Figure D.3- Plume depletion fraction, Q(x)/Q , as a function of downwind distance, x, for some selected stack heights.



(D.4.1)
— February results

(D.4.2)
— November results

Figure D.4 – Mean concentration, $\bar{X}$, of stack effluents at ground level as a function of downwind distance, x. Vertical axis is mean concentration ($\mu Ci/cm^3$), horizontal axis is downwind distance (m).

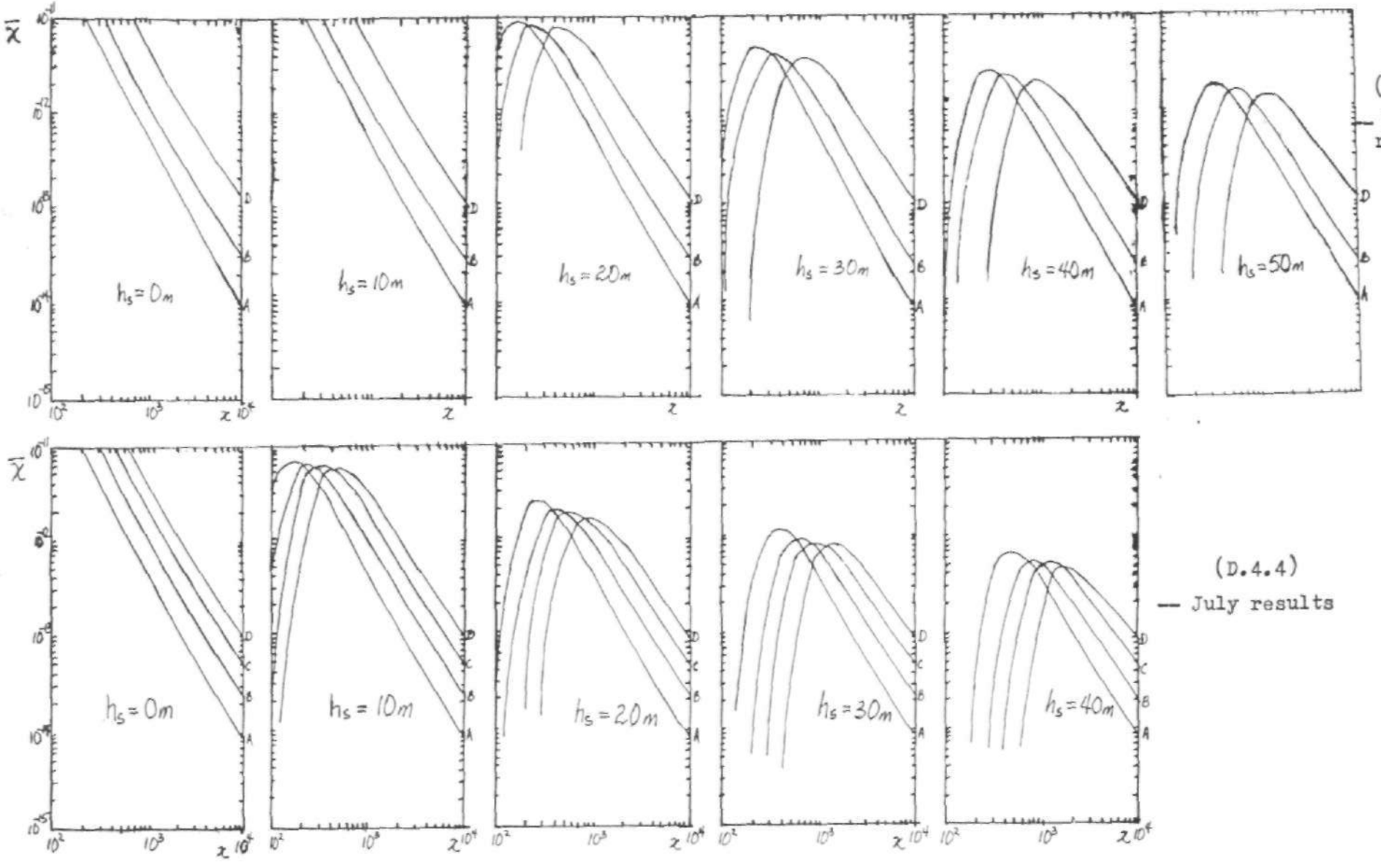
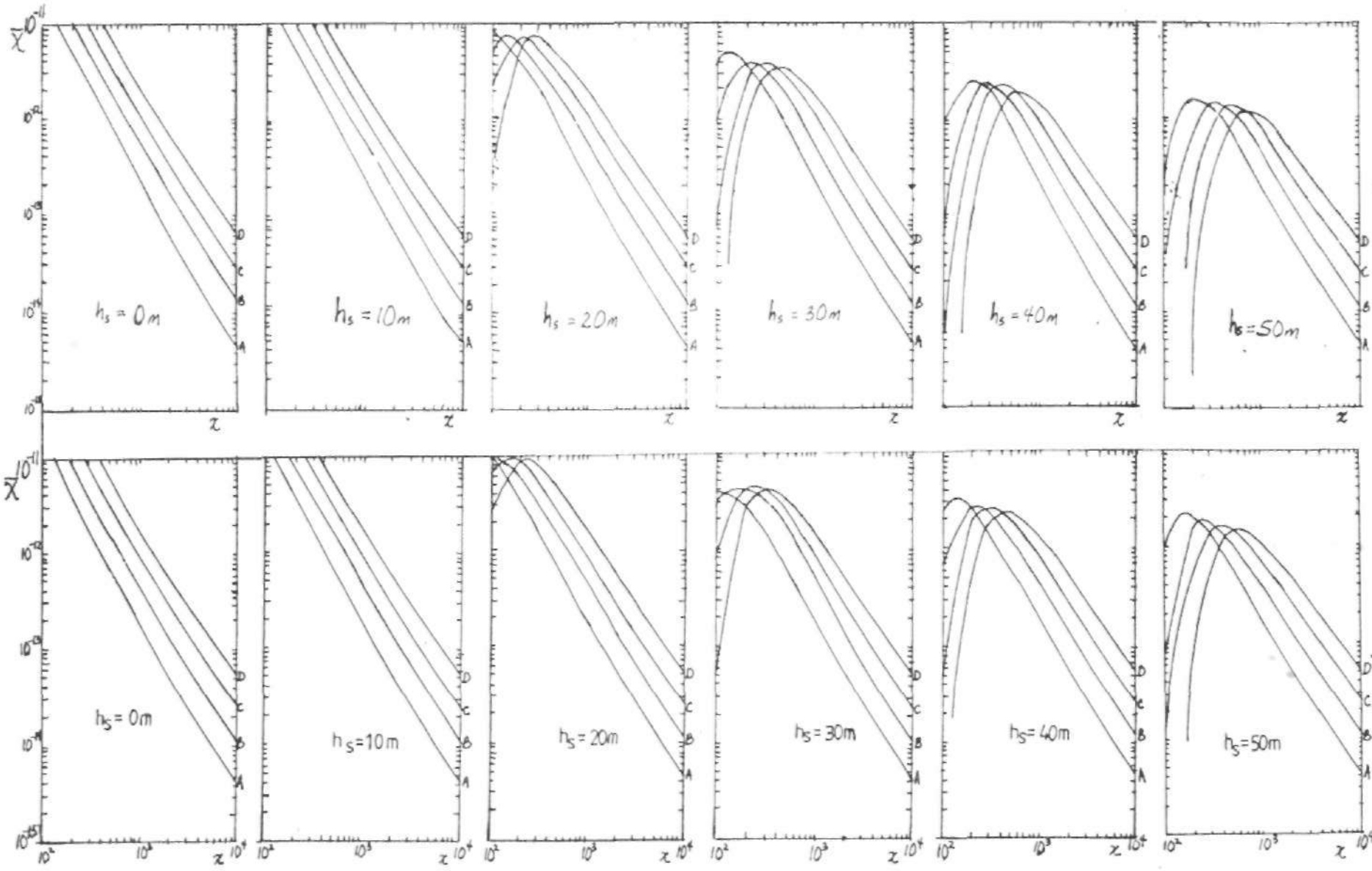


Figure D.4 – Mean concentration, $\bar{\chi}$, of stack effluents at ground level as a function of downwind distance, x.



(D.4.5) -September results.

(D.4.6) -Main Campu (Sept.) results.

Figure D.4 - Mean concentration, $\bar{\chi}$, of stack effluents at ground level as a function of downwind distance, x.