RADIOLOGICAL SAFETY ASSESSMENT OF THE GHANA RESEARCH REACTOR-1 AT SHUTDOWN USING ATMOSPHERIC DISPERSION MODEL

A thesis presented to the:

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By

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In partial fulfillment of the requirements for the degree of

MASTER OF PHILOSOPHY

In

NUCLEAR ENGINEERING

July, 2016
DECLARATION

I hereby declare that, with exception of references to other peoples work which have duly been acknowledged, this work is the result of my own original research undertaken under supervision, and either in whole or in part has not been presented for any other degree at another university elsewhere.

..................................................... ................................................

Henry Kwame Obeng Date:
(Student)

Supervisors declaration:

We hereby declare that the preparation and presentation of the thesis were supervised in accordance with guidelines on supervision of thesis laid down by the University of Ghana.

..................................................... ................................................

DR. S. A. Birikorang Dr. R. G. Abrefah
(Principal Supervisor) (Co-supervisor)

Date:............................................ Date:............................................

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ABSTRACT

A radiological safety assessment of the GHARR-1 was evaluated by calculating approximately the TEDE of radionuclides release from the reactor at shutdown using atmospheric dispersion model before the commencement of the core conversion from HEU to LEU fuel. A condition essentially needed for safety and environmental impact assessment to obtain the core conversion (removal) program license. In doing so, a source term estimation and radiological safety assessment were initially performed. Radionuclide inventory of the HEU core was first determined by depleting the core using isotope depletion code ORIGEN-S. After the source term estimation and radiological safety assessment of the MNSR, atmospheric dispersion modeling was undertaken for a hypothetical severe accident scenario of the HEU core. Addressing the hypothetical accident scenario. Hotspot code which is based on Gaussians plume model was employed. The code was used to simulate the atmospheric dispersion of the released radionuclide and TEDE estimation as a function of distance downwind. The assumed methodological analysis was based on predominant site-specific meteorological condition statistics and dispersion modeling theories. Some radionuclides which are assumed to have health implications were selected among the estimated core inventories and doses estimated. Radiological health effect to on-site personnel and the public were assessed through dose estimation. The maximum TEDE was found to be 1.9E-01 mSv while the maximum ground deposition was also found to be 4.9E+00 kBq/m² at a distance of 200m, respectively. The values obtained were far far less than the regulatory recommended threshold of the 50 mSv for the on-site workers and 1mSv for the public.
DEDICATION

This thesis is dedicated first to the God Almighty for seeing me through the course, to Him be all the glory. Furthermore, I dedicate this work with my deepest gratitude and love to my family, and also to Mr. and Mrs. Opoku for their enormous support, patience and prayers in bringing me this far on the academic ladder. I love you all.
ACKNOWLEDGEMENT

My sincerest gratitude goes to the Almighty God for his unending mercies and support throughout my life and in the execution of this project. I am especially indebted to my project supervisors, Dr. S. A. Birikorang and Dr. R. G. Abrefah whose direction, criticisms and advice nurtured this work into fruition. I also take this opportunity to appreciate the Head of Department and all Lecturers of the Department of Nuclear Engineering for their assistance, advice and guidance throughout my stay in this University. My sincere appreciation also goes to Dr. J. K Gbadago, Mr. Kwame Gyamfi, and Mr. Edward Oscar Amponsah-Abu for their individual contributions towards the completion of this work. My special thanks also go to all the GHARR-1 Reactor Operating Team especially Mr. Philip Gasu and Mr. A.G.Ampong, whose support and corporation helped to carry out this work.My sincere appreciations also go to Mr. Isaac Baidoo, and Mr. Nicholas Opata for their time and contributions to this work. To Prof. B. J. B Nyarko, Prof. Shilo Osae, Prof. S. B. Dampare, I appreciate your encouragements.
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ABBREVIATIONS

GHARR-1 Ghana Research Reactor -1
MNSR Miniature Neutron Source Reactor
UO$_2$ Uranium dioxide
U-Al Uranium Aluminum
HEU Highly Enriched Uranium
LEU Low Enriched Uranium
ORIGEN Oak Ridge Isotope Generation
MCNP Monte Carlo N-Particle Simulation
SAR Safety Analysis Report
TEDE Total Effective Dose Equivalent
RERTR Reduced Enrichment for Research and Test Reactors
GTRI Global Threat Reduction Initiative
GPM Gaussian Plume Model
GAEC Ghana Atomic Energy Commission
GMet Ghana Meteorological Agency
<table>
<thead>
<tr>
<th>SYMBOL</th>
<th>DESCRIPTION</th>
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<tbody>
<tr>
<td>$\sigma_f$</td>
<td>Microscopic cross-section of fission</td>
</tr>
<tr>
<td>$\phi$</td>
<td>Position- and energy-averaged neutron flux</td>
</tr>
<tr>
<td>$\sigma_c$</td>
<td>Spectrum-averaged neutron absorption cross section</td>
</tr>
<tr>
<td>$\gamma_{ji}$</td>
<td>Fraction of radioactive disintegration by nuclide j which leads to formation of nuclide i;</td>
</tr>
<tr>
<td>$\varphi$</td>
<td>Neutron flux</td>
</tr>
<tr>
<td>$N_x$</td>
<td>Mass transfer per unit volume</td>
</tr>
<tr>
<td>$D_x$</td>
<td>Mass diffusivity area per unit time, in the x-direction</td>
</tr>
<tr>
<td>$\chi$</td>
<td>Concentration of gas in mass per unit volume</td>
</tr>
<tr>
<td>$A$</td>
<td>Cross-sectional area in the x-direction</td>
</tr>
<tr>
<td>$Q$</td>
<td>Uniform emission rate of pollutants</td>
</tr>
<tr>
<td>$H$</td>
<td>Height of the plume</td>
</tr>
<tr>
<td>$\sigma_y$</td>
<td>Horizontal deviations of plume</td>
</tr>
<tr>
<td>$\sigma_z$</td>
<td>Vertical deviations of plume</td>
</tr>
<tr>
<td>$y$</td>
<td>Cross-wind coordinates direction</td>
</tr>
<tr>
<td>$z$</td>
<td>Vertical coordinate measured from the ground</td>
</tr>
<tr>
<td>$\mu$</td>
<td>Mean wind velocity</td>
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CHAPTER 1

INTRODUCTION

This chapter deals with the general background of the thesis work. It also describes a brief overview of the core conversion process of GHARR-1 and the radiological assessment before the commencement of the conversion activity. The objectives and scope of the research are briefly described.

1.1 Background of thesis

There are increasing worries over the possible usage of Highly Enriched Uranium (HEU) in producing of nuclear weapons, with the rising worry about the potential of HEU-fueled research reactors becoming the primary source [1]. As such, IAEA and the international community are calling all HEU grade fuel to be converted to LEU grade fuel. Ghana has been compelled by the call to convert its Nuclear Research Reactor which fuel is composed of HEU fuel to LEU fuel. Hence the eminent need to convert GHARR-1 HEU grade fueled research reactor to LEU, it is also indispensable to perform critical analysis of possible discharge of radionuclides to the immediate environment before the commencement of the core conversion activity when the reactor has been shut-down for a period of time. Figure of merit of the core conversion project will hinge on the radiological and safety analysis which forms part of environmental impact assessment. The radiological assessment will involve a consideration or assumption of an accidental discharge of radionuclides to the environment. SAR of GHARR-1 but does not give a comprehensive account of radiological safety assessment [2]. The use of a better and reliable model can be of great interest in addressing radiological safety assessment in considering a postulated hypothetical accident scenario. One of the vital issues in safety assessment of nuclear reactors is the dealing with dispersion of release radionuclides during accident situation whether under normal and abnormal conditions. Modeling of atmospheric dispersion is the first step of such assessments [3], [4]. As an
effect of radiological accident, when there is a released of radionuclides, it is the weather condition that determines its concentration. In assessing the measure of the effect of such accident on the environment and populace the concentration levels are calculated. The precise estimate of effect of radiological accident is contingent upon the credibleness of the computational dispersion model. Hence the selection of computational model is important. Many codes have been developed and are internationally used to perform dose calculations and to simulate radiation dispersion of release radiation from the whole reactor system. In the past, hands-on calculations were used to predict the level of radiation releases effect, which were not very reliably. As such the interests were focused on developing system codes to perform overall plant simulations, including the source term and relevant components from where release are assumed to emanate, such as the core, the steam generators, the coolant pumps, etc. The best known codes such as RODOS [5]and RATCHET [6], which are all for accident analysis have been tried and tested. These codes have been used by researchers for large sets of calculations and tested over a long time; and therefore, have reached a considerable degree of maturity. The Hotspot Code which is a Gaussian dispersion model is employed in this work to assess the release of radionuclides from the Ghana Research Reactor-1 core at shut-down. Even though, system codes are able to produce fairly reliable results for reactor accident assessments, their capabilities are limited when considering detailed phenomena. Basically, this is due to the fact that most system codes are one-dimensional and lack certain detail input parameter as pertain to recent generation of nuclear reactors. Most recent reactor analysis principles are based on balance equations which are expressed in terms of cross section averaged variables which are factored in recent codes and has not been factored into most hands-on models, though there are drawbacks in most current generation of system codes [7].

1.2 Problem statement

The IAEA and US Department of Energy (DOE) have been working together for several years in converting nuclear reactors operating on Highly Enrich Uranium (HEU) core. Initial documentation on radiological safety assessment of radionuclide release to the atmosphere as a
result of radiological accident before the conversion process need to be addressed to safeguard the staff and the environs [8]. One other difficulty when it comes to assessing radiation release is lack of prior knowledge on radiation level in the environment when there is accident. Therefore prior knowledge is needed as a baseline data before the activities. And more importantly to calculate the dose to be received at different receptor locations downwind around the facility. Such an assessment will enable the management in addressing the public concern on the conversion activity.

1.3 Objectives

The process of converting one fuel to another requires a complete safety analysis. The estimation of radiological effect and doses from released radiation during accident is one aspect the of safety analysis. This kind of safety assessment is usually addressed by considering a possible postulated hypothetical accident scenario and the use of atmospheric dispersion model to simulate its consequences. The fate of any pollutant released to the atmosphere is decided by the phenomenon called atmospheric dispersion (the process by which contaminant is transported through the air and diffuses into the atmosphere). The aim is to simulate and analyze radionuclides dispersion in the atmosphere and estimate the released dose from GHARR-1, at shutdown. As a requirement by regulatory body, the operational organization must undertake postulated accident scenario prior to the commencement of such an activity. Hence the thesis aims is also to simulate a possible postulated hypothetical accident scenario after the reactor has been in a shut-down mode for a period of time before commencement of the core conversion program. One other motive is to access the dose level and analyze the severity of some selected radionuclide to safeguard the working personnel before the activity commence. It is also to prepare a safety document which will conform to the regulatory requirement. The document will then be submitted to the regulatory authority for approval and this will now give permit to the operating organization to commence the core conversion process. As much as this is important, the work seeks to address other related issues and also help to improve the safety analysis report for the new core. Some specific objectives are:
To estimate the radionuclide inventory using a depletion code.

To estimate radiation dose using site-specific meteorological data.

To demonstrate radiation safety when converting the core from HEU to LEU.

To investigate the health effect from some selected radionuclides.

1.4 Justification

In assuming a possible hypothetical accident scenario during the core conversion process, radionuclides are expected to be emitted from the nuclear reactor if not handled with care. The idea of assessing atmospheric dispersion of radiation from any anticipated radiological accident is very much important to effectively know the effect it will have on on-site workers, off-site public, acceptable limit.

1.5 Scope of Research Work

This work is performed to ascertain the radiological safety assessment of GHARR-1. The assessment considered the design of a hypothetical accident scenario of the GHARR-1 reactor core. Estimation of core inventory release from the reactor was performed by using ORIGEN-S a reactor physic depletion code. A few radionuclides that could have radiological health effect to on site personnel and the public were estimated to determine their dose rate and ground dispersion concentration using site specific atmospheric conditions and an atmospheric dispersion model called Hotspot [9], [10], [11].

1.6 Structure of work

Chapter one provides the general introduction of the thesis. It also gives a summary on the core conversion process of GHARR-1, the objectives and scope of the research. Chapter two discusses literature review of the thesis work. Chapter three account for the theoretical equations behind
the two adopted codes and review of the theoretical development and application of computational material relevant to this thesis. Chapter four gives detail account for the methodology used, and how the codes simulations were performed. Chapter five gives a summary account on the results obtained from the simulations while chapter six discusses conclusions and recommendations of the research work. A review of Conversion of reactor cores from HEU to LEU, and related radiological safety studies of MNSR relevant to this thesis are presented in the next chapter.
CHAPTER 2

LITERATURE REVIEW

This chapter deals with the general description of the GHARR-1 reactor and the core conversion project. The GTRI core conversion program and the Jamaican SLOWPOKE core conversion are discussed. A review of atmospheric dispersion models used in radiological assessment as well as radiological safety analysis studies performed on MNSR are discussed.

2.1 GHARR-1 Facility

The GHARR-1 is a MNSR which belongs to the family of pool-in-tank type reactors [12]. It has a thermal power of the 30 kW with a corresponding peak thermal neutron flux of $1 \times 10^{12} \text{ncm}^{-2}\text{s}^{-1}$. Its cold clean excess reactivity is about 4 mk. The GHARR-1 core employs 90.2% enriched uranium-aluminum alloy admixed in aluminum matrix as fuel. Currently, the fuel assembly is made of HEU fuel elements arranged in ten concentric rings about a control rod. The control rod’s reactivity worth is about 7mk, providing a core shutdown margin of 3 mk of reactivity. Figure 2.1 shows a diagram of the lattice configuration of the GHARR-1 core. The safety features, stability of flux and moderate cost, provides the MNSR with several usefulness in many sectors of science. Most especially in trace elements analysis [13], soil fertility studies and geochemical isometry. Table 2.1 presents list of some technical specifications including the geometrical dimensions of the reactor fuel lattice of a typical MNSR
Figure 2.1: Lattice configuration of the HEU Core

Table 2.1: Technical specification of GHARR-1

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>Reactor design type</td>
<td>Tank in pool</td>
</tr>
<tr>
<td>Rated thermal power</td>
<td>30 kW</td>
</tr>
<tr>
<td>Excess Reactivity</td>
<td>3.4-4.0 mk</td>
</tr>
<tr>
<td>Fuel</td>
<td>U-Al</td>
</tr>
<tr>
<td>Enrichment</td>
<td>90.2%, HEU</td>
</tr>
<tr>
<td>U-235 loading</td>
<td>1kg</td>
</tr>
<tr>
<td>Core Diameter</td>
<td>23.0cm</td>
</tr>
<tr>
<td>Flux in inner channel</td>
<td>$1.0 \times 10^{12} \text{ncm}^{-2}\text{s}^{-1}$</td>
</tr>
</tbody>
</table>
2.2 GHARR-1 core conversion project

A coordinated research project of IAEA for the conversion of GHARR-1 started in the year 2006. Studies were performed on neutronic, thermal hydraulic and numerical computations of both the HEU and the proposed LEU. China Institute of Atomic Energy, the manufacturer of the GHARR-1 HEU core has developed a LEU core of high-density, low-enrichment UO\(_2\) fuel under the RERTR program. The fuel has a total density up to 10.6g/cm\(^3\) compared to the current HEU density of 3.456g/cm\(^3\). Total core loading of U-235 is 1358g compared to current core loading of 998g. U-235 enrichment has been reduced from 90.2% to 13%. HEU core has a nominal power of 30 kW, for the LEU core the nominal power is raised to 34 kW in order to meet the flux level of \(1.0 \times 10^{12}\)ncm\(^{-2}\)s\(^{-1}\) [14]. Table 2.2 shows the comparison of the HEU and LEU core composition and some key parameters of GHARR-1.

Table 2.2: Comparison of parameters for GHARR-1 HEU and LEU Core

<table>
<thead>
<tr>
<th>Parameter</th>
<th>HEU</th>
<th>LEU</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fuel Meat</strong></td>
<td>U-Al</td>
<td>UO(_2)</td>
</tr>
<tr>
<td><strong>U-235 Total Core Loading</strong></td>
<td>998</td>
<td>1358</td>
</tr>
<tr>
<td><strong>U-235 Enrichment, wt%</strong></td>
<td>90.2</td>
<td>13</td>
</tr>
<tr>
<td><strong>Density of Meat, g/cm(^3)</strong></td>
<td>3.456</td>
<td>10.6</td>
</tr>
<tr>
<td><strong>Meat Diameter, mm</strong></td>
<td>4.3</td>
<td>4.3</td>
</tr>
<tr>
<td><strong>Cladding Material</strong></td>
<td>Al-303-1</td>
<td>Zirc-4</td>
</tr>
<tr>
<td><strong>Number of Fuel Rods</strong></td>
<td>344</td>
<td>339</td>
</tr>
<tr>
<td><strong>Material for Grid Plates</strong></td>
<td>LT-21</td>
<td>Zirc-4</td>
</tr>
</tbody>
</table>

2.3 Global Threat Reduction initiative-Conversion program

Research and Test reactors globally that use HEU are being converted to LEU due to global threat. Efforts to convert research and test reactors to LEU have existed since the 1970’s. RERTR program was established in 1978 by the US Department of Energy, and its objective is to develop modalities and technology need to enable the conversion of civilian facilities with HEU to LEU fuels. The RERTR became an international program, establishing multiple collaborations leading to LEU fuel development and reactor conversion to LEU fuels [15]. In 2004, the DOEs National Nuclear
Security Administration (NNSA) established the Global Threat Reduction Initiative (GTRI) that incorporated the reactor conversion program as one of the main pillars for HEU minimization. Since then countries like United State and Russia have been in the forefront of the conversion process. Nuclear research reactors of both American and Russia origin fuel are being converted worldwide, with some in the conversion process while the fuel of already converted ones been sent back. Countries like Canada, China, Jamaica, etc have embarked on this conversion process. Since the inception of the Conversion Program, 76 research reactors with HEU fuel have undergone conversion or have shutdown prior to conversion [15]. The GTRI program conversion analysis includes performing studies on feasibleness of suitable LEU fuel assembly models for each reactor, performing the operational and safety analyses and resolving regulatory issues. The program has ensured the conversion to LEU of first set of Russian-supplied reactors in third world countries such as IRT-200 in Bulgaria and WWR-SM in Uzbekistan. Conversion of US-supplied research reactors such as SAFARI-1 in Pelindaba, South Africa. Current effort is toward conversion of Chinese- supplied MNSR reactor to countries such as Nigeria, Ghana, Pakistan, Iran, and Syria through the IAEA Coordinated Research Project (CRP).

2.4 Jamaican SLOWPOKE core conversion

The Jamaican SLOWPOKE research reactor is a 20 kW which was supplied by the Atomic Energy of Canada Limited (AECL). The reactor fuel was 1kg of highly enriched uranium (HEU) of 93% supplied by the U.S through a Project and Supply Agreement with the IAEA. The reactor achieved its first criticality in March 1984 and normally operates at an average power of 10 kW for approximately 1300 hours per year [16]. In an effort to keep with global trends together with call by the global threat reduction initiative and the growing international consensus to eliminate civil uses of HEU, a request was made in 2009 via the IAEA to the GTRI and the RERTR program to convert the reactor in Jamaica to LEU fuel. The AECL under the GTRI have developed LEU fuel fabricated from zircaloy-4 clad uranium oxide pellets and contained 1100g of 235U (total mass of U 5600g) with an enrichment of 19.9%, as the LEU fuel requires 20% more U-235 to achieve
the same reactivity as the HEU core. The estimated reactor neutronic parameters were performed using MNCP5 computational model. Results were in better agreement for both the HEU and LEU cores [17]. The conversion project was completed in September 2015.

2.5 Review of atmospheric Dispersion Models

Current pollution activities have heightened interest in computational modeling of time evolution of airborne particulate contaminants. These modeling can be useful for design and evaluating the efficiency of sensing element scheme systems. This would alert of something detrimental in the atmosphere, which will prompt the need for quarantine or evacuate during an actual occurrence. Furthermore, it helps to analyze what really transpired after an event [18]. The effective preparation for response nuclear accidents, require the knowledge to model the discharge of airborne particulate contaminants. Atmospheric plume dispersion modeling dates back to the 1920s. Following World War I, researchers tried to estimate chemical plume concentrations from poisonous gas attacks under various wind conditions [19]. The British conducted the Porton smoke experiments which provided on plume spread as a function of distance [20]. Current atmospheric dispersion models are computer programs models which uses various mathematical formulas that describe complex phenomena such as diffusion to calculate downwind species concentrations [21]. Several studies have been performed and compared on modeling gaseous dispersion in canyons using different models [22], [23], [24]. Open site studies conducted on gas and particles showed a varying correlation between the concentration of gases and particulates. Moon [25] demonstrated a poor correlational statistics among the outdoor PM$_{10}$ concentrations and NO$_2$ concentrations in an urban environment with a better correlation between PM$_{2.5}$ and NO$_2$. Models that underestimate plume concentrations are a threat to health of the populace as well as the environment, while models that overestimate plume concentrations may have serious economic consequences [26]. Basically, there are four models for describing atmospheric dispersion. The box model, Lagrangian model, Eulerian model and Gaussian model.
2.5.1  The Box model

The Box model is the most elementary of the models, which assumes a given volume of atmospheric air in the form of a box. It further assumes that the air pollutants inside the box are uniformly distributed and uses that assumption to calculate the mean pollutant concentrations anywhere within the airshed. Although very useful, this model is very confined in its ability to effectively determine dispersion of air pollutants over an airshed because the assumption of uniform pollutant distribution is much too simple [27].

2.5.2  Lagrangian model

The Lagrangian method considers the concentration changes relative to the moving fluid. Lagrangian model performs well for uniform and static conditions over a level terrain [28], [29], [30], [31] and for non-uniform and unstable condition for the complex terrain [32], [33], [34]. Unfortunately, this method will not produce an exact solution for the mean concentration of a species in a fluid, necessitating the use of simplifying assumptions [35].

2.5.3  Eulerian model

The Eulerian dispersions model is analogous to a Lagrangian model in that it also tracks the mobility of a large number of pollution plume parcels as they migrate from their initial location. The difference between these two models is that the Eulerian model uses a fixed three-dimensional Cartesian grid as a frame of reference instead of a moving frame of reference. It is said that an observer of an Eulerian model watches the plume go by [27].

2.5.4  Gaussian models

Gaussian models are primarily based on a Gaussian distribution of the plume parcels in the vertical and horizontal directions under steady state conditions. The width of the plume is determined by y and z, which are defined either by stability classes of Pasquill and Gifford Jr [36], [37] or travel time
from the source. Gaussian models have been shown to consistently over predict concentrations in low wind conditions [38]. For good estimation of concentrations in low wind speed conditions, a modified version which is a combination of the Gaussian plume and puff models have been formulated [39], [40]. A further limitation of the Gaussian model is a result of the oversimplified treatment of turbulence and meteorology. The advantage of Gaussian models is that very fast and provides immediate response time. Their computation is primarily on solving a single formula equation developed by Hanna [41] for every receptor point. The Gaussian plume model has become a standard approach for studying the transport of airborne contaminants due to turbulent diffusion and advection by the wind.

2.6 Review of application of atmospheric dispersion models used in radiological assessment

Atmospheric dispersion models find application in many nuclear establishments most especial in the safety of nuclear facilities. They are a necessary part for studies such as siting, pre-operational planning, licensing, and the establishment of operational control [42]. Enormous amount of theoretical and experimental work on atmospheric dispersion and related topics have been undertaken over the years. Most of the works have been inspired by military concerns and the need to control radiation hazards and air pollution. Although there has been improvement in dispersion modeling computation power, not all models are applicable to situations associated with radionuclide release. Models applied to radiological release must consider the following [42]:

i Radionuclide discharges are normally from point sources;

ii The models developed especially for conventional air pollutants give short term concentrations (averages of hours to days) whereas because of the cumulative effect of radiation exposure, an essential quantity in the case of radionuclide discharges is the time-integrated concentration.

Radiological analysts for convenience have grouped the application of dispersion models into three
categories; these are local scale models (dispersion up to 10 km from source), regional scale models (From about 200 km to a few thousand kilometers) and global scale models (covering distances beyond the circumpolar latitudinal circumferences and where meridional mixing is more important than the zonal transport). In the nuclear industry, the interest has mainly centered on the local scale. The Gaussian plume model is probably the most used form amongst empirical models for estimating local range dispersion. The model accounts for puffs release (applicable to instantaneous releases) and the plume release (applicable to continuous releases). The Gaussian plume model also has capability for simulation release from point sources thus making it a very relevant model for radiological analysis. Other models have been used but they contain features which may be more appropriate when considering dispersion over longer distances.

2.7 Radiological safety analysis

The purpose of radiological safety analysis for research reactors is to establish the basis for items relevant to safety using appropriate analytical tools [43]. Radiological safety analysis assesses the performance of an accidental scenario using postulated initiating events in order to obtain a complete understanding of such circumstances. Performing radiological safety analysis will demonstrate that the core conversion can be kept within the radiological safety limits established by the regulatory body. In order to demonstrate the safety of workers, the public and the environment during transport, storage, and disposal of spent fuel an operating organization must provide methodology based on regulatory guides to estimate possible radiological releases by considering hypothetical accident.

2.8 Review of radiological safety analyses of MNSR

A radiological safety analysis for MNSR studies for a maximum hypothetical accident radiation release was conducted by Liaw and Matos [44]. The power history used for the HEU core was based on a power level of 30 kW. Calculations were performed for generic MNSR core to derive
the peak radionuclides activities for the HEU core using the ORIGEN-S code. The generic HEU core modeled with 345 fuel pins was established from existing HEU models for the NIRR-1 reactor in Nigeria and the GHARR-1 reactor in Ghana. Liaw and Matos calculated the dose from the radiation release through the reactor building at an assumed building leakage rate of 20 volume percent per hour as lower bound and 100 volume percent per hour to establish an upper bound. The estimated effective dose was based on an assumed receptor location of 300m from the reactor core. Liaw and Matos estimation does not account for transport of radionuclides and dose calculation after the accident through the use of detailed physical models such meteorological conditions which are paramount to radiation dispersion. Ground deposition assessment of radionuclides following a hypothetical release using atmospheric dispersion model which employs a Gaussian plume transport model was performed for GHARR-1 by Birikorang et al [45]. An extensive hypothetical accident of GHARR-1 has further been studied by Museuma et al [46].

2.9 Description of the study area

The GHARR-1 facility is installed at the site of GAEC. It is located at the north-western part of Accra, the capital city of Ghana at longitude 5° 40 N and latitude 0° 13 W. Figure 2.2 show the area view and location of GAEC and its surrounding communities. The location is also surrounded by a number of communities, including Dome, Kwabenya, Atomic residence, Haatso, Ashongman residential area and Taifa [2]. The Atomic residence is about 3km away from the site. The Ashongman residential area is the most nearest to the site, and it is about 500m to the site due to some encroachment activities that have transpired over the years.
2.9.1 GHARR-1 Reactor building

The reactor building of the facility has a height of 12m, length of 21m and a width of 16m. Access to the reactor hall is through the main corridor door and through the ramp door. The ramp door is always closed during reactor operation and it is only opened under special circumstances. The reactor hall is ventilated using a blower installed on the roof. It ensures that a negative pressure gradient is provided at the reactor hall. The vent air intake system is installed with adjustable louvers. A crane rail runs from the large access door over the reactor pool to the roof of the reactor hall. The rail carries a crane of lifting capacity of 3 tons and height 13.5 m from the bottom of the pool.
2.9.2 Site-Specific Conditions of GHARR-1 Site

The site meteoric information retrieved from GMet on-line database and the GAEC weather stations were studied [47]. The mean monthly wind speed data were compiled and ascertained for sixteen directional sectors using a cup anemometer at intervals of days. Measurements from different wind roses established that the frequent direction is the West (W), which occurs for 66.6% of the total time of the day. South West (SW) and South-South West (SSW) positions also have 16.6% of occurrence. The yearly average wind speed of 4.1 m/s was ascertained. however, a strong wind blows at the site during the heavy rainy season (that is within the month of July) whose speed may be an average of 18.2 m/s. Temperature variations for both daily and yearly period are quite minimal. The table below shows the meteorological condition for GAEC.

Table 2.3: Comparison of parameters for GHARR-1 HEU and LEU Core

<table>
<thead>
<tr>
<th>Month</th>
<th>Normal °C</th>
<th>Warmest °C</th>
<th>Coldest °C</th>
<th>Precipitation mm</th>
<th>Wind speed ms⁻¹</th>
<th>Sunshine hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>27.1</td>
<td>31.7</td>
<td>22.5</td>
<td>6</td>
<td>4.6</td>
<td>217</td>
</tr>
<tr>
<td>February</td>
<td>28.2</td>
<td>32.3</td>
<td>24.0</td>
<td>10</td>
<td>4.6</td>
<td>226</td>
</tr>
<tr>
<td>March</td>
<td>28.5</td>
<td>32.5</td>
<td>24.5</td>
<td>16</td>
<td>5.6</td>
<td>217</td>
</tr>
<tr>
<td>April</td>
<td>28.2</td>
<td>32.1</td>
<td>24.4</td>
<td>26</td>
<td>5.6</td>
<td>217</td>
</tr>
<tr>
<td>May</td>
<td>27.4</td>
<td>31.3</td>
<td>23.5</td>
<td>67</td>
<td>4.6</td>
<td>210</td>
</tr>
<tr>
<td>June</td>
<td>26.2</td>
<td>29.6</td>
<td>23.5</td>
<td>111</td>
<td>5.1</td>
<td>150</td>
</tr>
<tr>
<td>July</td>
<td>25.3</td>
<td>28.0</td>
<td>22.5</td>
<td>61</td>
<td>6.2</td>
<td>155</td>
</tr>
<tr>
<td>August</td>
<td>25.2</td>
<td>28.0</td>
<td>22.3</td>
<td>62</td>
<td>6.7</td>
<td>155</td>
</tr>
<tr>
<td>September</td>
<td>25.8</td>
<td>29.1</td>
<td>22.5</td>
<td>62</td>
<td>6.2</td>
<td>180</td>
</tr>
<tr>
<td>October</td>
<td>26.6</td>
<td>30.4</td>
<td>22.8</td>
<td>60</td>
<td>5.1</td>
<td>217</td>
</tr>
<tr>
<td>November</td>
<td>27.3</td>
<td>31.6</td>
<td>22.9</td>
<td>18</td>
<td>4.6</td>
<td>240</td>
</tr>
<tr>
<td>December</td>
<td>27.1</td>
<td>31.6</td>
<td>22.5</td>
<td>8</td>
<td>4.1</td>
<td>248</td>
</tr>
</tbody>
</table>

The atmospheric stability corresponds to the vertical temperature spatial relation and the horizontal wind speed. A large negative spatial relation leads to high turbulence conditions. Neutral conditions correspond to just negative temperature spatial relation while positive temperature spatial relation indicates low turbulence conditions. Data collected were processed from average daily wind speeds regarding the sun high in the sky. It is observed that stability class B is predominant with 50% of occurrence, followed by class C with 33.3%, and class A with 16.7% for
the 2010-2015 year period.

## 2.9.3 Atmospheric stability classification

Atmospheric stability categorization is needed to quantitate the dispersion capabilities of the ambient atmosphere in the air quality models for concentration predictions. There are several atmospheric stability classification schemes based on Monin-Obukhov length, bulk - gradient Richardson numbers and the Pasquill scheme [48]. The Pasquill scheme was used in this work since it provides explicit formulations for determining the lateral and vertical distribution of a contaminant as a function of downwind distance. To interrelate the condition of atmospheric temperature change to perceptible parameters, Pasquill formulated an uncomplicated scheme comprising of six stability classes grading from highly convective A to highly stable flow conditions F. These classes are summarized in Table 2.4. Pasquill scheme shows that an unstable conditions are represented by; A, strongly unstable; B, moderately unstable; C, slightly unstable; D, neutral; while stable conditions are; E, slightly stable; F, moderately stable.

The next chapter deals with the theory and the mathematical formulations behind the codes used for the simulation and their respective assumptions.

### Table 2.4: Meteorological Pasquill Stability classes definition

<table>
<thead>
<tr>
<th>Description</th>
<th>Stability Class</th>
<th>Time of Day</th>
<th>Wind Speed (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strongly unstable</td>
<td>A</td>
<td>Sunny day</td>
<td>&lt;2</td>
</tr>
<tr>
<td>Moderately unstable</td>
<td>B</td>
<td>Sunny day</td>
<td>3-4</td>
</tr>
<tr>
<td>Slightly unstable</td>
<td>C</td>
<td>Sunny day</td>
<td>4-6</td>
</tr>
<tr>
<td>Neutral</td>
<td>D</td>
<td>Cloudy/Windy</td>
<td>3-5</td>
</tr>
<tr>
<td>Slightly stable</td>
<td>E</td>
<td>Cloudy/Windy</td>
<td>2-3</td>
</tr>
<tr>
<td>Moderately stable</td>
<td>F</td>
<td>Clear Night</td>
<td>&gt;6</td>
</tr>
</tbody>
</table>
CHAPTER 3

THEORY OF SOLUTION

This chapter deals with the theoretical or the mathematical aspect behind the two well-known validated computational tools, the ORIGEN-S and the HotSpot 3.0 used for the source term estimation and for the atmospheric dispersion of radionuclides release from the reactor respectively and its relevant importance to this research work.

3.1 The ORIGEN-S Code

The Oak Ridge Isotope Generation (ORIGEN-S) code is a computational code used for reactor core depletion analysis, buildup estimation and processing of radioactive materials. The ORIGEN-S code which is very comprehensive and very user friendly computational tool set for criticality assessment, reactor physics, spent fuel classification, radiation shielding analysis was developed as module of the Standardized Computer Analysis for Licensing Evaluation (SCALE) code system developed at Oak Ridge National Laboratory [49].

3.1.1 The computational expressions of ORIGEN-S

The ORIGEN-S code is capable of performing burnup calculations using the general expression for the formation and disappearance of a nuclide by nuclear transmutation and radioactive decay method. This method is used to calculate the time-dependent formation, destruction and decay of radionuclides. The ORIGEN-S code employs a matrix exponential method to solve linear, first-order ordinary differential equations with constant coefficients. In general, the rate at which the amount of nuclide \( N_i \) changes a function of time \( \frac{dN_i}{dt} \) is described by a homogeneous differential equation as follows:

\[
\frac{dN_i}{dt} = \text{Formation rate} - \text{Decay rate}
\]  

(3.1)
In the computational process the code uses radioactive disintegration and neutron absorption [50].

The time rate of change of concentration for particular nuclide, \(N_i\) can be expressed as

\[
\frac{dN_i}{dt} = \sum_j \gamma_{ji} \sigma_{f,j} N_j \phi + \sigma_{c,j-1} N_{i-1} \phi + \lambda_i' N_i' \phi - \sigma_{c,i} N_i \phi - \lambda_i N_i
\]  

(3.2)

Where \((i=1,...,I)\), and

\[
\sum_j \gamma_{ji} \sigma_{f,j} N_j \phi = \text{yield rate of } N_i \text{ due to fission of all nuclides } N_i.
\]

\[
\sigma_{c,j-1} N_{i-1} \phi = \text{rate of transmutation into } N_i \text{ due to radiactive decay of neutron capture by nuclide } N_{i-1}.
\]

\[
\lambda_i' N_i' \phi = \text{rate of formation of } N_i \text{ due to radioactive decay of nuclides } N_i.
\]

\[
\sigma_{f,j} N_j \phi = \text{destruction rate of } N_i \text{ due to fission.}
\]

\[
\sigma_{c,i} N_i \phi = \text{destruction rate of due to all forms of neutron capture } (n, \gamma, n, \alpha, n, p, n, 2n, n, 3n).
\]

\[
\lambda_i N_i = \text{radioactive decay rate of } N_i.
\]

\[
\phi = \text{position- and energy- averaged neutron flux } \sigma_c = \text{spectrum-averaged neutron absorption cross section of nuclide } c.
\]

\[
\gamma_{ji} = \text{fraction of radioactive disintegration by nuclide } j \text{ which leads to formation of nuclide } i.
\]

For homogeneous medium containing a spaced energy-averaged neutron flux, \(\phi\), with flux-weighted average cross sections, \(\phi_f\) and \(\phi_c\), representing the reaction probabilities.

### 3.1.2 The ORIGEN-S code assumptions

ORIGEN-S assumes a treatment that the space-energy-averaged flux can be regarded constant over a sufficient small time interval, \(\Delta t\). It is assumed that a single set of flux weighted neutron cross sections can be used over the same time step. The time-dependent varies in the flux and weighted cross sections are simulated in ORIGEN-S by provides the ability of updating the values for the space-energy-averaged flux and, hence, for the weighted cross sections for each successive time step, \(\Delta t_k, \Delta t_{k+1}, ..., \Delta t_n\). The values are deduced from lattice cell analyses using physics transport equations to update cross sections that typify the lattice geometry.
3.2 The Hotspot 3.0 Code

The considerable advancements achieved in computing power, with everyday increasing nuclear economy and in compliance with the requirements of 10 CFR 52.17 and 10 CFR Part 100, safety specialists are allowed to use Hotspot 3.0 Code for the analysis of radionuclide dispersion and dose calculation for nuclear reactors for a newly propose site. The Hotspot 3.0 code is a health physics code created by the Lawrence Livermore National Laboratory [51]. The merit of employing HotSpot 3.0 code in this research work is that the code is capable of estimating detailed accident condition, transport of radionuclides and dose calculation after the accident through the use of detailed physical models. One main reason why HotSpot 3.0 Code is useful to researchers in accident assessment field is the ability for the system code to perform two transport and diffusion computations for radiological releases.

3.2.1 The diffusion equation and the Gaussian plume model

The mass rate of diffusion $N_x$ of a gaseous species in the x-direction at some cross-sectional area $A$ is given by the expression

$$N_x = -A \left( \frac{\partial D_x \chi}{\partial x} \right)$$

(3.3)

$N_x$ is the mass transfer per unit volume

$D_x$ is the mass diffusivity area per unit time, in the x-direction

$\chi$ is the concentration of gas in mass per unit volume

$A$ is the cross-sectional area in the x-direction

Area under study is considered as a box in which pollutants are released and goes through physicochemical changes. The schematic diagram for the formulation GPM is shown below.
Equation 3.3 can be expressed as

$$N_x = -dydz \frac{\partial (D_x \chi)}{\partial x}$$

(3.4)

For a small change in $x$

$$N_{x+dx} = -dydz \frac{\partial (D_x \chi)}{\partial x} + \frac{\partial}{\partial x} \left[ \left( \frac{\partial (D_x \chi)}{\partial x} \right) dydz \right] dx$$

(3.5)

Subtracting equation 3.3 from 3.5 gives

$$N_{x+dx} - N_x = \frac{\partial}{\partial x} \left[ \left( \frac{\partial (D_x \chi)}{\partial x} \right) dydz \right] dx$$

(3.6)

Rate in bulk motion $R_{ibm}$ is given by

$$R_{ibm} = \chi \mu dydz$$

(3.7)
Rate out bulk motion $R_{obm}$ is given by

$$R_{obm} = \chi \mu dydz + \frac{\partial}{\partial x}(\chi \mu dydz) dx$$  \hfill (3.8)

The net rate (bulk motion) $R_{net}$ is expressed as $R_{net} = R_{ibm} - R_{obm}$

$$R_{net} = -\frac{\partial}{\partial x}\chi \mu dx dydz$$  \hfill (3.9)

Rate of change within $dx dydz$, is given by

$$R_{net} = \frac{\partial \chi}{\partial t} dx dydz$$  \hfill (3.10)

The time rate of change in concentration is

$$\frac{\partial \chi}{\partial t} = -\frac{\partial}{\partial t}(\chi \mu) + \frac{\partial}{\partial x}\left(\frac{\partial (D_x \chi)}{\partial x}\right) + \frac{\partial}{\partial y}\left(\frac{\partial (D_y \chi)}{\partial y}\right) + \frac{\partial}{\partial z}\left(\frac{\partial (D_z \chi)}{\partial z}\right)$$  \hfill (3.11)

Where:

- $x$ - Along–wind coordinate measured in wind direction from the source [m]
- $y$ - Cross-wind coordinates direction [m]
- $z$ - Vertical coordinate measured from the ground

$\chi(x,y,z)$ - Mean concentration of diffusing substance at a point $(x,y,z)$ [kg/m$^3$]

$D_xD_z$ - Mass diffusivity in the direction of the $y$ - axis and $z$ - axis [m$^2$/s]

$\mu$ - Mean wind velocity along the $x$ - axis [m/s]

The time rate of change and advection of the cloud by the mean wind is

$$\frac{\partial \chi}{\partial t} + \frac{\partial}{\partial t}(\chi \mu)$$  \hfill (3.12)

The turbulent diffusion of material to the centre of the pollutant cloud (the cloud will expand over time due to these terms); is given by
\[ \frac{\partial}{\partial x} + \left( \frac{\partial (D_x \chi)}{\partial x} \right) \]  

(3.13)

Assumptions:

- Mass transfer due to bulk motion in \( x \)-direction far out shadows the contribution due to mass diffusion. That is the second term on the right side of Equation 3.9 is far smaller than the first term and may be dropped from the equation.

- We are primarily interested in the steady-state solution to the dispersion of the pollutants in the atmosphere. Hence the \( \frac{\partial \chi}{\partial t} \) quantity is zero.

- Even though the wind speed does vary in the three coordinate directions, the variation is relatively small. Therefore it is appropriate to assume that the wind speed \( \mu \) is constant.

- The major transport direction due to the wind is chosen to lie along the \( x \)-axis.

- \( D_x, D_y \) and \( D_z \) are constant.

Hence equation 3.9 can be expressed as

\[ \mu \left( \frac{\partial \chi}{\partial x} \right) = D_y \left( \frac{\partial^2 \chi}{\partial y^2} \right) + D_z \left( \frac{\partial^2 \chi}{\partial z^2} \right) \]  

(3.14)

The general solution to this second-order partial differential equation is

\[ \chi = K x^{-1} \exp \left\{ - \left[ \left( \frac{y^2}{D_y} \right) + \left( \frac{z^2}{D_z} \right) \right] \frac{\mu}{4x} \right\} \]  

(3.15)

Where:

\( K \) - is an arbitrary constant whose value is determined by the boundary conditions. The rate of transfer of pollutant through any vertical plane downwind from the source is a constant in steady
state, and this constant must equal the uniform emission $Q$ rate.

$$Q = \int \int \mu \chi dydz$$  \hspace{1cm} (3.16)

Generally, the limits of integration on $dy$ are minus to plus infinity and for a point source at Elevation $H$ above the ground level the limits of integration on $z$ are taken from $-\infty$ to $\infty$

$$Q = \int \int Kx^{-1} \exp \left[ - \left( \frac{y^2}{D_y} + \frac{z^2}{D_z} \right) \right] \frac{\mu}{4x}$$  \hspace{1cm} (3.17)

After integrating

$$K = \frac{Q}{4\pi(D_yD_z)^{1/2}}$$  \hspace{1cm} (3.18)

Where:

$Q$ - is the strength of the emission source, mass emitted per unit time

$$\chi(x,y,z;H) = \frac{Q}{4\pi(D_yD_z)^{1/2}} \exp \left[ - \left( \frac{y^2}{D_y} + \frac{z^2}{D_z} \right) \frac{\mu}{4x} \right]$$  \hspace{1cm} (3.19)

Gaussian parameters

$$\sigma_y = \sqrt{2D_y \frac{x}{\mu}} \quad \text{and} \quad \sigma_z = \sqrt{2D_z \frac{x}{\mu}}$$  \hspace{1cm} (3.20)

Making $D_y$ and $D_z$ the subject of the formula from equation 3.20

$$D_y = \sigma_y^2 \mu \frac{1}{2x}$$  \hspace{1cm} (3.21)

$$D_z = \sigma_z^2 \mu \frac{1}{2x}$$  \hspace{1cm} (3.22)

Substituting equations 3.21 and 3.22 the contaminant in the ambient air resulting from a point
steady state concentration of an air is given by general equation:

$$\chi(x,y,z;H) = \frac{Q}{2\pi \mu \sigma_y \sigma_z} \left[ \exp \left( \frac{y^2}{2\sigma_y^2} \right) \right] \left\{ \exp \left[ \frac{-(z - H)^2}{2\sigma_z^2} \right] + \exp \left[ \frac{-(z + H)^2}{2\sigma_z^2} \right] \right\}$$

(3.23)

Figure 3.2: Typical plume boundary and time-average plume envelope

where;

$H$ - Height of the plume [m]

$\sigma_y$ and $\sigma_z$ - horizontal and vertical deviations of plume concentration distribution [m]

$Q$ - uniform emission rate of pollutants [kg/s]

$x$ - Along-wind coordinate measured in wind direction from the source [m]

$y$ - Cross-wind coordinates direction [m]

$z$ - Vertical coordinate measured from the ground [m]

$\chi(x,y,z)$ - Mean concentration of diffusing substance at a point $(x,y,z)$ [kg/m$^3$]

$\mu$ - Mean wind velocity affecting the plume along the $x$ - axis [m/s]

The plume boundary and time averaged plume envelope as well as the coordinate system of the Gaussian distribution in the vertical and horizontal direction [52] are shown in Figures 3.2 and 3.3
3.2.2 **Hotspot code model assumptions**

In studying the Gaussian plume model, certain assumptions are normally considered [53].

- The emission rate is constant.
- Material diffused is a stable gas or aerosol.
- Dispersion is negligible in the downwind (x) direction.
- Plume is infinite with no plume history.
- Horizontal meteorological conditions are homogeneous and stationary.
- The terrain is relatively flat.
• Background pollution is negligible.

The GAEC geographical area which is flat matched the default terrain in the Hotspot code which assumes a relatively flat geographical area.

The next chapter discusses the method that was employed in this work and how the codes were used to obtained various results.
CHAPTER 4

METHODOLOGY

4.1 Accident Scenario

A scenario of lifting the core from the reactor vessel using the overhead crane was assumed. It was further assumed that the crane hook swung resulting in the core hitting the metal rail, causing mechanical damage to several of the 344 fuel pins. It was assumed that the incident resulted in a release of radionuclide to the reactor hall which had its exhaust ventilation system turned on. It was assumed that fission product was released through the ventilation exhaust vent, with failing of gas purge system due to error in operation of gas purge pump system. Radioactivity of reactor core escaped through stack in the form of gas and particulate, and then dispersed into the atmosphere. No core melts down was assumed since the reactor has been shut down for more than a month and with the assumption that only decay heat from Photo neutrons which has insufficient heat to cause core melt down was available. Since the reactor has been shut down for months, we assume minimal fission products do exist in the core.

4.2 Simulation and method of analysis

The isotopic inventory generation code ORIGEN-S was used to perform simulations of the depletion of the reactor core to generate the isotopic source term inventory. The Hotspot atmospheric dispersion code was used to simulate the atmospheric and ground level concentration.

4.2.1 Determination of isotopic inventory

The ORIGEN-S input deck was set up in order to determine the isotopic source term inventory of the GHARR-1 core. The ORIGEN-S deck is divided into blocks (each block contains important information that helps in depleting the core). The core depletion takes into consideration the
composition of decay nuclides and activation products as well as light elements as a result of burnup. Key parts of the input deck include the nuclide identity, composition of nuclide, and the results desirable as well as specific neutron and gamma energies desirable (that is all these pieces of information are vital and used to set up the input deck). The nuclide composition and continuous nuclide feed rate were specified for nuclides of interest. The cut off fraction was over ridden to give way for output summary table. Two vectors were set up in the deck and nuclide concentration data in one vector were moved into the other vector depending on the calculation of interest. The decay and cross section libraries were specified so that the code works with those selected data. The code was instructed to control the printing of only relevant input data libraries. The deck was also set up to track photon production rate in 39 energy groups. Since the code was written for nuclear power plants, the code was instructed to read nuclide identifiers for replacement decay and cross section data cards in order to suit the MNSR. The average burnup, flux and specific power for an irradiation was calculated. Neutron flux and power were specified for irradiation of a single interval. Decay of a single interval was also specified. The table type to be printed (element, nuclides or summary) was specified for actinides, activation products and fission products. The power history of GHARR-1 used was 15kW. It was assumed to operate for four hours a day, four days a week, four weeks a month and 11 months in a year. A cumulative number of operating days was used. The decay time in steps of ten was used in order to monitor the short lived radionuclides. The average of running power especially the historic operation was determined and used. Near the end of life of the fuel, finer detail depletion is desirable but the historic operation would have lost its entire short lived isotope; hence coarse detail depletion is more convenient (20 years, 10 months, 10 weeks, 1 week and the last five days to the core removal). The flux spectrum of the reactor which is obtained from a pre-processed cross section from MCNP was used. The flux spectrum in the MCNP output has many groups as defined in the corresponding MCNP flux tally in the input deck. COUPLE has cross section libraries for the different nuclides and reactions arranged by energy groups. Available libraries have 44, 49, 200 or 238 groups. The most accurate or finely partitioned library (238 groups) according to the energy spectrum was used. This should provide more than
enough precision for most practical purposes.

### 4.2.2 Evaluation of radiation dose

Some important isotopic inventory was selected immediately after the core was depleted with the depletion generation code. They were selected based on their harmful nature to human health [8]. The isotopic inventory selected from the output of the depletion code was used as part of the input deck of the Hotspot atmospheric dispersion code for radiological dose calculations. In setting up the Hotspots code input deck; the Hotspot code Source term Model unit was modified to correspond to the radionuclides activity generated in the ORIGEN-S code. Plume raise information was specified; such as stack height (30m), stack diameter (0.32m), exit velocity of effluent (75 m3/hr), temperature of effluent (30°C) were all modified in the Source term Model unit. In the Meteorology unit of the Hotspot code; the wind speed, wind direction and the atmospheric stability class was also specified as well as the coordinated location designations. The Setup Model unit provided input for site topography and source geometry specification. Boundary conditions were selected, in terms of TEDE and ground deposition. The Hotspot code was simulated for the atmospheric concentrations and the TEDE at ground level. The Figure 4.1 below shows flow chart of the method used.

The results obtained from the simulations with emphasis on observations are discussed in the next chapter.
Figure 4.1: Flow chart of the codes simulation
CHAPTER 5

RESULT AND DISCUSSION

This chapter deals with the results obtained from the ORIGEN-S and the Hotspot code. The chapter emphasizes on observations or summary of the tables and figures in the text.

5.1 Isotopic inventory

The ORIGEN-S input deck was prepared and simulated. A large quantity of output was available from the ORIGEN-S code simulation; however only a few ones which are very useful in the studies were selected primarily on their radiotoxicity and the harmfulness they to human health. The Table 5.1 below shows some of the generated radionuclides after the ORIGEN-S simulations of the reactor core had been performed. From the results, Strontium-90, Cesium -137 and Xenon-133 were found to have the highest radioactivity level. Results obtained from the ORIGEN code were analogized to other publications on MNSRs and other research reactor, which had used burn up codes under connatural assumptions. In previous ORIGEN-S simulations of the GHARR-1 HEU reactor core as reported by Birikorang et al [45] and simulations performed on a 10MW research reactor by IAEA [54] the radionuclide activities estimated were much higher than the estimated radioactivity obtained in this work as compared in Table 5.2 below. The differences in results are due to the fact that this work was performed at reactor shut-down mode as Birikorang et al performed their work in reactor operation mode while the IAEA work was performed on a reactor with higher power of 10 MW.
Table 5.1: Selected radionuclides inventory in the core

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Group</th>
<th>Activity Curies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kr-83 m</td>
<td>Noble gas</td>
<td>2.290E-04</td>
</tr>
<tr>
<td>Kr-85m*</td>
<td>Noble gas</td>
<td>5.081E-09</td>
</tr>
<tr>
<td>Kr-87</td>
<td>Noble gas</td>
<td>2.265E-12</td>
</tr>
<tr>
<td>Xe-129</td>
<td>Noble gas</td>
<td>1.090E-10</td>
</tr>
<tr>
<td>Xe-130</td>
<td>Noble gas</td>
<td>1.715E-07</td>
</tr>
<tr>
<td>Xe-135</td>
<td>Noble gas</td>
<td>3.088E-07</td>
</tr>
<tr>
<td>Xe-133*</td>
<td>Noble gas</td>
<td>3.707E-04</td>
</tr>
<tr>
<td>I-129</td>
<td>Halogen</td>
<td>2.328E-04</td>
</tr>
<tr>
<td>I-130</td>
<td>Halogen</td>
<td>2.492E-11</td>
</tr>
<tr>
<td>I-131 *</td>
<td>Halogen</td>
<td>2.406E-06</td>
</tr>
<tr>
<td>I-132</td>
<td>Halogen</td>
<td>5.018E-08</td>
</tr>
<tr>
<td>I-135</td>
<td>Halogen</td>
<td>7.728E-08</td>
</tr>
<tr>
<td>Sr-87</td>
<td>Br-Sr group</td>
<td>5.712E-10</td>
</tr>
<tr>
<td>Sr-86</td>
<td>Br-Sr group</td>
<td>5.712E-10</td>
</tr>
<tr>
<td>Sr-89</td>
<td>Br-Sr group</td>
<td>1.031E-08</td>
</tr>
<tr>
<td>Sr-90*</td>
<td>BrSr group</td>
<td>1.928E-03</td>
</tr>
<tr>
<td>Te-131 m</td>
<td>Tellurium group</td>
<td>2.222E-10</td>
</tr>
<tr>
<td>Rh-101</td>
<td>Nobel metal</td>
<td>7.551E-13</td>
</tr>
<tr>
<td>Cs-137*</td>
<td>Alkali metal</td>
<td>2.065E-03</td>
</tr>
<tr>
<td>Ce-141</td>
<td>Cerium group</td>
<td>7.832E-06</td>
</tr>
<tr>
<td>Pr-146</td>
<td>Lanthanide</td>
<td>3.619E-07</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>4.843E-03</td>
</tr>
</tbody>
</table>

*Radionuclides used as part of the Hotspot code input deck
Table 5.2: Comparison of core inventory with the standard data published

<table>
<thead>
<tr>
<th>Radionuclide</th>
<th>Activity (Bq)</th>
<th>Activity (Bq)</th>
<th>Activity (Bq)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>This work</td>
<td>Published work [45]</td>
<td>IAEA [54]</td>
</tr>
<tr>
<td></td>
<td>(Shutdown mode)</td>
<td>(Operational mode)</td>
<td>(Shutdown mode)</td>
</tr>
<tr>
<td>Kr-85m</td>
<td>1.880E+02</td>
<td>1.12E+09</td>
<td>4.10E+13</td>
</tr>
<tr>
<td>Xe-133</td>
<td>4.517E+07</td>
<td>—</td>
<td>2.10E+16</td>
</tr>
<tr>
<td>I-131</td>
<td>8.902E+04</td>
<td>—</td>
<td>8.81E+17</td>
</tr>
<tr>
<td>Cs-137</td>
<td>7.640E+07</td>
<td>9.44E+09</td>
<td>2.21E+14</td>
</tr>
<tr>
<td>Sr-90</td>
<td>7.133E+07</td>
<td>9.10E+09</td>
<td>2.19E+14</td>
</tr>
</tbody>
</table>

5.2 Dose estimation

The Hotspot code generated plots of the atmospheric and ground level concentration does. After the hypothetical accident, TEDE which includes external and internal contributions for the whole absorbed dose on an individual in various atmospheric stability classes were calculated. Calculations were performed for TEDE received by populace residing within 1 km radius from the GHARR-1 site and beyond; for an average wind speed of 4 m/s. Much of the result analysis was emphatic on the atmospheric stability class B range since it is the dominant stability class at the GHARR-1 site. All simulations were performed under the assumption of unit release; thus simulating the isotopic source term individually.

5.2.1 TEDE dose from Noble gases

Kr-85 and Xe-133 are generally the first radionuclides noble gases to be released in a nuclear accident due to the low potential of these elements for retention in the damaged reactor core. The characteristics that makes noble gases dissimilar from other radionuclide releases is the fact that they do not react chemically with surrounding materials and hence atmospheric dispersion calculations for noble gases needed to be performed as it contribute to the TEDE of a whole body dose. The health effect of radiation from noble gases is determined by the gamma ray energy which
penetrates a person’s body and its likely impact on human tissues.

5.2.1.1 Dose estimation of Kr-85

The results for estimated TEDE for Kr-85 at different downwind distances from GHAR-1 site in different atmospheric stability classes (AF) are shown in Table 5.3. The maximum TEDE of 7.0E-16Sv was estimated at maximum distance of 0.11 km from GHARR-1 site for stability class A at an arrival time under a minute. A maximum estimated 5.6E-16Sv was observed for unstable stability class B at a downwind distance of 0.2 km from point of release. Stability class C and D which represent the slightly unstable and neutral stability class both had their maximum doses at downwind distance of about 0.3km from release point. Which show a value of 5.2E-16Sv and 4.1E-16Sv respectively. For stability class E and F which are the stable atmospheric conditions. The maximum TEDE values were 4.1E-16Sv and 6.2E-17Sv which were observed at a distance of 0.5km and 1km respectively. TEDE has been found to decrease with distance in power-law form. It was observed that due to the fanning nature of plume dispersion of stability class F, TEDE was registered at a downwind distance of 0.6km and beyond. This implies that people within a distance range of 0.0km- 0.6km will not be affected with immediate plume dispersion.
Table 5.3: Krypton-85 TEDE for stability class A-F

<table>
<thead>
<tr>
<th>Stability class</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance (km)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.030</td>
<td>&lt;00:01</td>
<td>0.00E+00</td>
<td>0.00E+00</td>
<td>0.00E+00</td>
<td>0.00E+00</td>
<td>0.00E+00</td>
</tr>
<tr>
<td>0.100</td>
<td>&lt;00:01</td>
<td>7.00E-16</td>
<td>2.20E-16</td>
<td>1.00E-17</td>
<td>0.00E+00</td>
<td>0.00E+00</td>
</tr>
<tr>
<td>0.200</td>
<td>&lt;00:01</td>
<td>7.00E-16</td>
<td>5.60E-16</td>
<td>4.30E-16</td>
<td>9.50E-17</td>
<td>9.50E-17</td>
</tr>
<tr>
<td>0.300</td>
<td>0:01</td>
<td>2.10E-16</td>
<td>3.90E-16</td>
<td>5.20E-16</td>
<td>4.10E-16</td>
<td>3.30E-16</td>
</tr>
<tr>
<td>0.400</td>
<td>0:01</td>
<td>1.30E-16</td>
<td>2.50E-16</td>
<td>4.20E-16</td>
<td>4.10E-16</td>
<td>3.30E-16</td>
</tr>
<tr>
<td>0.500</td>
<td>0:01</td>
<td>8.20E-17</td>
<td>1.70E-16</td>
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<td>4.00E-16</td>
</tr>
<tr>
<td>0.600</td>
<td>0:02</td>
<td>5.80E-17</td>
<td>1.30E-16</td>
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<td>3.60E-16</td>
<td>3.60E-16</td>
</tr>
<tr>
<td>0.700</td>
<td>0:02</td>
<td>4.30E-17</td>
<td>9.50E-17</td>
<td>1.90E-16</td>
<td>3.20E-16</td>
<td>3.20E-16</td>
</tr>
<tr>
<td>0.800</td>
<td>0:03</td>
<td>3.30E-17</td>
<td>7.40E-17</td>
<td>1.60E-16</td>
<td>2.80E-16</td>
<td>3.20E-16</td>
</tr>
<tr>
<td>0.900</td>
<td>0:03</td>
<td>2.60E-17</td>
<td>5.90E-17</td>
<td>1.30E-16</td>
<td>2.40E-16</td>
<td>1.30E-16</td>
</tr>
<tr>
<td>1.000</td>
<td>0:03</td>
<td>2.20E-17</td>
<td>4.80E-17</td>
<td>1.10E-16</td>
<td>2.10E-16</td>
<td>2.10E-16</td>
</tr>
</tbody>
</table>

The distribution of target organ committed dose to some selected organs as a function of downwind for the predominant site stability class B is shown in Figure 5.1. From estimated result it shows that the skin is the body tissue to be most affected under the release of Kr-85, followed by surface bone and the brain and lung respectively. The dose profile shows that TEDE on thyroid gland is very minimal. TEDE for a given exposure depended on the manner of the intake and retention of various nuclides, the possibility of concentration in the body organs and the radiological half-life of the nuclide.
Figure 5.1: Kr-85 Profile for Target organ committed equivalent dose as a function of downwind distance for stability class B

The plume contour distribution for stability class B, D and F which represent typical unstable, neutral and stable stability are shown in Figures 5.2 – 5.4 below. The contour distribution illustrates the severity of the radionuclide dose distribution. Where areas within the red zone indicate higher risks, the blue and the green areas shows zones of less dose risk.
It was observed that each stability class produce a varying shape from each other with stability class A having a wider contour and stability class F with a much narrow and long contour. This is due to the dispersion coefficients, sigma $\sigma$, which defines the spread of the plume. The magnitude of $\sigma$ is ascertained by the value of the turbulence in the atmosphere. Bigger eddies and bigger values of $\sigma$, will be detected during periods of high turbulence in the atmosphere. Smaller eddies and smaller values of $\sigma$, will be detected when the turbulence in the atmosphere is low. The parameters $\sigma_y$ and $\sigma_z$ are the standard deviations of the Gaussian distributions, which indicate the spread of the plume in the y and z directions, respectively.
The shapes of the contours depend on the value of $\sigma_y$ and $\sigma_z$, which in turn are a function of the atmospheric stability A-F. Unstable stability class A produces the largest and therefore wider contours. Stability class F sigma is the smallest and results in narrow contours. An increase in the dispersion coefficient results in a decrease of the concentration value of the pollutant plume center line. However, total amount of the pollutant in the plume show no significant change and thus; it is merely spread out over a wider range and hence the concentration changes.
It was observed that for stable stability atmospheric condition inhibits the vertical spread of the plume; thus the plume tends to move in a straight line and moves great distances away from the source before reaching the ground. This making the ground-level concentrates to be very low. The plume centerline illustrates the trend for TEDE graph. The predominant stability classes B are compared to all other stability classes. Figure 5.5 below, shows that the doses from class A increases from 1.0E-18Sv to a peak height of say 1.5E-15Sv at a distance of 0.11 km and decreases slowly downwards. The results also show the decrease in the maximum TEDE values when meteorological stability conditions become more stable and these maxima are shifted at longer distances consequently. The trend further shows that the unstable atmosphere produces the highest peak downwind concentration. The turbulence in the unstable atmosphere brings the plume to the ground very quickly. An unstable atmosphere increases the amount of vertical spreading and creates loops that move the plume up and down in the atmosphere, increasing the ground concentration every time the plume reaches the ground. Farther downwind, however, concentrations drop off very quickly. The stable atmosphere, on the other hand, has a much lower
peak. The TEDE for a given exposure depended on the manner of the intake and retention of various nuclides, the possibility of concentration in the body organs and the radiological half-life of the nuclides. Some of the inhaled material may concentrate in particular organs such as the lungs or thyroid and thus become a special threat to those organs.

![Figure 5.5: Plume centerline TEDE of Kr-85 as a function of receptor downwind distance for stability class A-F](image)

### 5.2.1.2 Dose estimation of Xe -133

Estimating of Xe-133 TEDE and atmospheric concentrations with respect to downwind distance has been calculated for the various stability classes as shown in Table 5.4 below. Maximum calculated concentration of TEDE occurred in less than one minute at a downwind distance of 0.11 km for stability class A at 3.89E-12Sv. Stability class B which is the dominant stability class at the site observed a maximum TEDE of 3.22E-13Sv at a downwind distance of 0.18 km. Stability class C, D, E and F had a maximum TEDE of 2.9E-12Sv, 2.2E-12Sv, 1.3E-12Sv and 2.5E-12Sv at a downwind distance of 0.3 km, 0.5 km, 0.8 km and 0.9 km respectively. It was observed that as the stability class continues to a more stable condition the maximum TEDE concentrations was shifting more away from the point of release. The maximum targeted organ committed doses
for stability class B were 1.0E-11Sv, 1.0E-11Sv and 3.1E-12Sv which occurred in a downwind distance of 0.20 km respectively for skin, surface bone and thyroid glands. Figure 5.4 below shows the Xe-133 Profile for Target Organ committed equivalent dose as a function of downwind distance for class B.

Table 5.4: Xenon-133 TEDE for stability class A-F

<table>
<thead>
<tr>
<th>Stability class</th>
<th>A (Sv)</th>
<th>B (Sv)</th>
<th>C (Sv)</th>
<th>D (Sv)</th>
<th>E (Sv)</th>
<th>F (Sv)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance (km)</td>
<td>Arrival Time (hr:mm)</td>
<td>TEDE</td>
<td>TEDE</td>
<td>TEDE</td>
<td>TEDE</td>
<td>TEDE</td>
</tr>
<tr>
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<td>9.0E-16</td>
<td>0.0E+00</td>
<td>0.0E+00</td>
<td>0.0E+00</td>
<td>0.0E+00</td>
</tr>
<tr>
<td>0.100</td>
<td>&lt;00:01</td>
<td>3.9E-12</td>
<td>1.2E-12</td>
<td>5.5E-14</td>
<td>1.3E-16</td>
<td>0.0E+00</td>
</tr>
<tr>
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<td>5.3E-13</td>
<td>9.4E-17</td>
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<td>1.8E-12</td>
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</tr>
<tr>
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<td>1.8E-12</td>
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</tr>
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<td>1.8E-12</td>
<td>2.2E-12</td>
<td>7.3E-13</td>
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<tr>
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<td>1.0E-12</td>
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<td>5.4E-13</td>
<td>1.1E-12</td>
<td>1.8E-12</td>
<td>1.2E-12</td>
</tr>
<tr>
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<td>4.2E-13</td>
<td>8.8E-13</td>
<td>1.6E-12</td>
<td>1.3E-12</td>
</tr>
<tr>
<td>0.900</td>
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<td>3.4E-13</td>
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<td>1.4E-12</td>
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<td>2.7E-13</td>
<td>6.0E-13</td>
<td>1.2E-12</td>
<td>1.2E-12</td>
</tr>
</tbody>
</table>

Ground level concentration was not calculated, as it is assumed that all the noble gas isotopes are released into the atmosphere and not deposited on the ground below. This important characteristic behavior of noble gases is that they do not deposit following release to the atmosphere. Generally, it was observed that plume under unstable conditions affect vicinity immediately near release points with high concentrations. Stable conditions cause the plume to reach ground level further away but with lower concentrations.
Plume centerline air concentration of atmospheric transport and deposition of Xe-133 source term is shown in Figure 5.6. Stability Class A had an initial minimum TEDE of about 1.0E-16Sv and a maximum of about 1.0E-12Sv at a distance of about 0.1km. The concentration falls off quickly as the plume travel further from the point of release. Stability class B had it maximum TEDE a little lower than stability class B at a distance of about 0.2 km from the point of release. The maximum TEDE for stability class C, D, E, and F follows this same trend. It is observed that both plume centerlines diminish exponentially with downwind distance.
5.2.2 Dose estimation of I-131

The simulation of I-131 was performed. The total amount of I-131 released was estimated to be approximately 8.902E+04Bq. The decay term of I-131 was not considered. The radiological hazardous nature of Iodine retention in any radiological accident is of primary concern. Iodine released to the atmosphere is transported downwind and dispersed by atmospheric mixing process. Personnel and the local individuals are irradiated internally due to inhalation and externally by gamma radiation. Table 5.5 below indicates the summary of the TEDE estimated for I131 for various stability classes. The maximum of 1.6E-11Sv was estimated at distance of about 0.1km for stability class A at an arrival time of less than a minute. A maximum estimated 1.3E-11Sv was observed for unstable stability class B at a downwind distance of 0.2km. Stability class C and D which represent the slightly unstable and neutral stability class both had their maximum doses at a downwind distance of about 0.3km and 0.5km; which show a value of 1.2E-11Sv and 9.4.1E-12Sv respectively. For stability class E and F which are the stable atmospheric conditions. The maximum TEDE values were 5.4E-12Sv and 1.5E-12Sv which were observed at a distance of 0.8 km and 1 km respectively.
Table 5.5: Iodine-131 TEDE for stability class A-F

<table>
<thead>
<tr>
<th>Stability class</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
</tr>
</thead>
<tbody>
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<td>Arrival Time (hr:mm)</td>
<td>TEDE (Sv)</td>
<td>TEDE (Sv)</td>
<td>TEDE (Sv)</td>
<td>TEDE (Sv)</td>
<td>TEDE (Sv)</td>
</tr>
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<td>0.0E+00</td>
<td>0.0E+00</td>
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<td>7.4E-12</td>
<td>5.1E-12</td>
</tr>
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<td>6.5E-12</td>
<td>5.4E-12</td>
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<td>5.7E-12</td>
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<td>2.5E-12</td>
<td>5.0E-12</td>
<td>5.2E-12</td>
</tr>
</tbody>
</table>

Ground surface deposition concentrations for various stability classes are summarized in Table 5.6 below. The ground surface doses are due to the radioactive particles deposited on the ground. Unstable stability class A had its maximum estimated ground deposition dose at a distance of 0.2 km at a value of 1.3E-11kBq/m². The highest estimated deposition for stability class B was estimated at 0.1 km with a dose of 1.6E-11kBq/m² in less than a minute. The dose concentration was reduced as the plume moves away from the point of release. High concentrations of ground deposition at the unstable stability class is due to inversion which inhibited diffusion as well as horizontal transport and turbulent diffusion which are limited in low wind situation. Simulated result for the slightly unstable and the neutral stability class (C and D) estimated its maximum ground deposition dose at distance between 0.2 km to 0.4 km at a value of 1.2E-11kBq/m². The ground deposition dose for the slightly unstable and the neutral stability depends of the coning
nature of plume dispersion. For stability class E and F which are the stable atmospheric conditions, ground deposition for stability class E had an initial value of 3.7E-16kBq/m² but had a maximum dose at a distance of 0.7km at a value of 5.4E-12kBq/m² and stability class F had an estimated maximum value of 1.5E-12 kBq/m² at a distance of 1km. The initial distance 0.3 km had no ground deposition this is due to the plume behavior in the unstable stability class.

Table 5.6: Iodine-131 Ground surface deposition for stability class A-F

<table>
<thead>
<tr>
<th>Stability class</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
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<tr>
<td>Arrival Time (hr:mm)</td>
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<td></td>
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<td></td>
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</tr>
<tr>
<td>Ground surface deposition (kBq/m²)</td>
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</tr>
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<td></td>
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</tr>
</tbody>
</table>

The distribution of target organ committed dose to some selected organs as a function of downwind is shown in Figure 5.8. The estimated result shows that the thyroid gland and the skin are the body tissues to be most affected under the release of I-133. The dose profile shows that TEDE on thyroid gland is very minimal. TEDE for a given exposure depended on the manner of the
intake and retention of various nuclides, the possibility of concentration in the body organs and the radiological half-life of the nuclide.

Figure 5.8: I-131 dose profile for Target organ committed equivalent dose as a function of downwind distance for class

Plume center line air concentration of atmospheric transport and deposition of I-131 source term emitted from the point of release is shown in Figure 5.9 below. The I-131 emitted into the atmosphere may be deposited onto the surface of the earth due to gravitational settling and dry deposition. It is observed that plume center line diminishes exponentially with downwind distance.
5.2.3 Dose estimation of Aerosols

Two of the most typical aerosols radionuclides found during most reactor accidents are cesium and strontium. Isotopes of these radionuclide such as Cs-137 and Sr-90 are relatively volatile and have the potential of contaminating large areas. These volatile aerosol Cs-137 and Sr-90 are among the dangerous radionuclides to the environment with respect to their long-term effect. Their respective half-life of about 30 years implies that they are not highly radioactive. However they have a long enough half-life to be around for hundreds of years. These aerosols particulate once airborne can
change their size and composition by condensation of vapour species or by chemical reactions. Therefore, quantitative estimation of this isotope dose as a function of their release and transport behavior from a release point has been determined by simulation. The total amount of Cs-137 and Sr-90 released was estimated to be approximately 7.64+07Bq and 7.13+07Bq. The decay terms of Cs-137 and Sr-90 were not considered.

5.2.3.1 Dose estimation of Cesium-137

The results for the estimated TEDE for Cs-137 simulated at various stability classes are summarized in Table 5.7. The highest TEDE estimated for stability class A was observed at 0.1km at a valve of 1.5E-08Sv. The dose level reduces as the plume travels further way from the point of release. Stability class B simulated results estimated 1.2E-08Sv at a distance of 0.2 km. It was observed that for unstable stability classes (A and B) all doses exceeded their respective normal distance range preset in the model; in excess ranging from 0.18 km-0.25 km. The results indicate that a relatively small amount of Cs-137 has the potential to contaminate a relatively large area. Estimated TEDE value of 1.1E-08Sv and 8.7E-9Sv was obtained for a distance of 0.3 km and 0.4 km respectively for stability class C and D. Due to the fanning dispersion behavior stable stability class E and F, the maximum TEDE was estimated 0.9 km and 1 km away from the point of release at a value of 4.9E-09Sv and 1.3E-09Sv respectively.
### Table 5.7: Cesium -137 TEDE for stability class A-F

<table>
<thead>
<tr>
<th>Stability class</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
</tr>
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<td>Arrival Time (hr:mm)</td>
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</tr>
<tr>
<td>TEDE (Sv)</td>
<td>TEDE (Sv)</td>
<td>TEDE (Sv)</td>
<td>TEDE (Sv)</td>
<td>TEDE (Sv)</td>
<td>TEDE (Sv)</td>
<td>TEDE (Sv)</td>
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<td>0.0E+00</td>
</tr>
<tr>
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<td>3.3E-13</td>
<td>0.0E+00</td>
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<td>4.7E-09</td>
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Ground surface deposition concentrations for various stability classes are summarized in Table 5.8 below. The highest estimated deposition for stability class A was estimated at 0.1 km with a dose of 1.3E-02kBq/m$^2$ in less than a minute. The dose concentration was reduces as the plume moves away from the point of release. Unstable stability class B had its maximum estimated ground deposition dose at a distance of 0.2 km at a value of 1.3E- 02kBq/m$^2$. Simulated result for the slightly unstable C and the neutral stability class D estimated its maximum ground deposition dose at distance 0.3 km and 0.4 km at a value of 9.4E-03kBq/m$^2$ and 7.4E-03kBq/m$^2$ respectively. Ground deposition for stability class E had maximum value of 4.2E- 03kBq/m2at a distance of 0.8km. Stability class F had an estimated maximum value of 1.1E-03 kBq/m$^2$ at a distance of 1km.
Table 5.8: Cesium -137 Ground surface deposition for stability class A-F

<table>
<thead>
<tr>
<th>Distance (km)</th>
<th>Arrival Time (hr:mm)</th>
<th>Stability class</th>
<th>A (kBq/m²)</th>
<th>B (kBq/m²)</th>
<th>C (kBq/m²)</th>
<th>D (kBq/m²)</th>
<th>E (kBq/m²)</th>
<th>F (kBq/m²)</th>
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</thead>
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<tr>
<td>0.100</td>
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<td>0.0E+00</td>
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<td>Ground deposition</td>
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<td>1.0E-02</td>
<td>7.7E-03</td>
<td>1.6E-03</td>
<td>1.5E-07</td>
<td>0.0E+00</td>
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<tr>
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<td>Ground deposition</td>
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<td>4.0E-03</td>
<td>1.1E-03</td>
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</table>

The distribution of target organ committed dose to some selected organs as a function of downwind is shown in Figure 5.10. From estimated result, it was observed that the skin is the body tissue to be mostly affected, followed by the lung, thyroid gland, surface bone and the brain respectively under the release of Cs-137. TEDE for a given exposure depended on the manner of the intake and retention of various nuclides, the possibility of concentration in the body organs and the radiological half-life of the nuclide.
Figure 5.10: Cs-137 profile for Target organ committed equivalent dose as a function of downwind distance for class B

Plume centerline air concentration of atmospheric transport and deposition of Cs-137 source term is shown in Figure 5.11. Stability class A had the maximum peak, followed by stability class B, C, D, E, F. It is observed that the plume center line diminishes exponentially with downwind distance.
5.2.3.2 Dose estimation of Strontium -90 Source

The estimated TEDE for Sr-90 at various atmospheric stability classes (AF) are shown in Table 5.9 below. The maximum TEDE of 2.4E-04Sv was estimated at maximum distance of 0.1 km from the point of release for stability class A at an arrival time of less than one minute. The preset distance in the Hotspot 3.0 model reveals that the spread of Sr-90 exceeded their preset limit in terms of the area of dispersion. An excess distance of about 40 km was observed. This indicated that Sr-90 had the potential to spread over a wider area. A maximum estimated TEDE of 1.96E-04Sv was observed for unstable stability class B at a downwind distance of 0.2 km. Stability class B also exceeded the preset distance by about of 67 km.

Stability class C and D which represent the slightly unstable and neutral stability class both had their maximum doses at a downwind distance of about 0.3km and 0.4km. This had a value of 1.8E-04Sv and 1.4E-04Sv, respectively. The stability class E and F TEDE simulated results estimated 8.0E-05Sv and 1.5E-05Sv at respective distances of 0.8 km and 0.9 km. Stability class C, D, E and F all exceeded their preset distance to about 200 km.
Table 5.9: Strontium -90 TEDE for stability class A-F

<table>
<thead>
<tr>
<th>Stability class</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance (km)</td>
<td>TEDE (Sv)</td>
<td>TEDE (Sv)</td>
<td>TEDE (Sv)</td>
<td>TEDE (Sv)</td>
<td>TEDE (Sv)</td>
<td>TEDE (Sv)</td>
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<td>5.5E-08</td>
<td>2.3E-16</td>
<td>0.0E+00</td>
<td>0.0E+00</td>
<td>0.0E+00</td>
</tr>
<tr>
<td>0.100</td>
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<td>2.4E-04</td>
<td>7.7E-05</td>
<td>3.4E-06</td>
<td>8.1E-09</td>
<td>0.0E+00</td>
</tr>
<tr>
<td>0.200</td>
<td>&lt;00:01</td>
<td>1.4E-04</td>
<td>1.9E-04</td>
<td>1.5E-04</td>
<td>3.3E-05</td>
<td>5.8E-09</td>
</tr>
<tr>
<td>0.300</td>
<td>00:01</td>
<td>7.3E-05</td>
<td>1.3E-04</td>
<td>1.8E-04</td>
<td>1.1E-04</td>
<td>2.6E-06</td>
</tr>
<tr>
<td>0.400</td>
<td>00:01</td>
<td>4.3E-05</td>
<td>8.7E-05</td>
<td>1.1E-04</td>
<td>1.4E-04</td>
<td>2.0E-05</td>
</tr>
<tr>
<td>0.500</td>
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<td>2.9E-05</td>
<td>6.0E-05</td>
<td>8.6E-05</td>
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</tr>
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<td>1.2E-04</td>
<td>6.5E-05</td>
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<td>3.3E-05</td>
<td>6.7E-05</td>
<td>1.1E-04</td>
<td>7.6E-05</td>
</tr>
<tr>
<td>0.800</td>
<td>00:03</td>
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<td>5.4E-05</td>
<td>9.6E-05</td>
<td>8.0E-05</td>
</tr>
<tr>
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<td>4.4E-05</td>
<td>8.4E-05</td>
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</tr>
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<td>3.7E-05</td>
<td>7.4E-05</td>
<td>7.7E-05</td>
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</tbody>
</table>

Sr-90 ground surface deposition concentrations for various stability classes are summarized in Table 5.10 below. The highest estimated deposition for stability class A was estimated at 0.1km from the point of release with a dose of 6.1E+00kBq/m² in less than a minute. The dose concentration was reduces as the plume moves away from the point of release. Unstable stability class B had its maximum estimated ground deposition dose at a distance of 0.2km at a value of 4.9E+00kBq/m². Simulated result for the slightly unstable C and the neutral stability class D estimated its maximum ground deposition dose at distance 0.3km and 0.4km at a value of 3.7E+00kBq/m² and 3.6E+00kBq/m² respectively. For stability class E and F which are the stable atmospheric conditions. Ground deposition for stability class E had maximum value of 20E+00kBq/m² at a distance of 0.9 km. Stability class F had an estimated maximum value of 3.8E+04kBq/m² at a distance of 0.7 km.
Table 5.10: Strontium - 90 Ground surface deposition for stability class A-F

<table>
<thead>
<tr>
<th>Stability class</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance (km)</td>
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<td>Arrival Time (hr:mm)</td>
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<tr>
<td>Ground surface deposition (kBq/m²)</td>
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</tr>
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<td>3.9E-13</td>
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<td>0.0E+00</td>
<td>0.0E+00</td>
<td>0.0E+00</td>
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<tr>
<td>0.100</td>
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<td>0.200</td>
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<td>0.700</td>
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<td>1.000</td>
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</tbody>
</table>

The distribution of target organ committed dose to some selected organs as a function of downwind is shown in Figure 5.12. From estimated result it shows that the Lung is the body tissues to be mostly affected, followed by the surface bone and the Skin respectively under the release of Sr-90. TEDE for a given exposure depended on the manner of the intake and retention of various nuclides, the possibility of concentration in the body organs and the radiological half-life of the nuclide.
Figure 5.12: Sr-90 profile for Target organ committed equivalent dose as a function of downwind distance for class B

The plume center line TEDE graph indicates plots of trends for maximum distances of deposition curves downwind. The distribution of concentration as a function of distance reveals that higher peak values are obtained for class A and B as shown in Figure 5.13. The plume release attained a gradual raise from around 1E-12Sv and had a peak value around 1E-06Sv, this peak value decrease as the plume moves away from the origin.
Figure 5.13: Plume centerline TEDE of Sr-90 as a function of receptor downwind distance for stability class A-F
CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

Radiological safety assessment of the GHARR-1 at shutdown was performed using ORIGEN-S a reactor physics depletion code and a mostly validated atmospheric dispersion code called Hotspot based on a hypothetical accident scenario. The research work was performed by firstly estimating the GHARR-1 core inventory at shutdown using the depletion code. The estimated results produce by the depletion code proves to agree with other research finding [45]. The slight differences in the estimated core inventory as compared to other findings may be due to the fact that this work was perform when the reactor had been shut down for months as compared to finding when the reactor is in operation. After the core inventory estimation, few radionuclides that could have radiological health effect to on-site personnel and the public were analyzed to determine their dose rate and ground dispersion concentration from the release point to the populace at designated receptor location at downwind distances. Five of such kinds of radionuclides were selected and evaluated. Kr-85 and Xe-133 isotopes which are noble gases, Cs-137 and Sr-90 isotopes which are aerosols and I-131 isotope which is highly volatile were used to build the input deck of the atmospheric dispersion code. The result shows that the Sr-90 and Cs-137 which are aerosols resulted in highest dose rate, followed by I-131 and noble gas Kr-85 and Xe-133 respectively. All the estimated results indicated that the maximum TEDE value of 1.9E-01 mSv and maximum ground deposition value of 4.9E+00 kBq/m² occurred at a distance of 200 m from the reactor site. It was observed that airborne noble gases Kr-85 and Xe-133 neither deposited on the ground; hence acts basically as a source of direct external radiation. The distribution of committed equivalent dose to different organs as a function of downwind distance reveals that higher values are obtained for the lung, followed by the thyroid, bone surface, skin and brain respectively. The result obtained from the Hotspot code was found to be in agreement with other research findings. The results
also compares well with the findings in the following NRC documents (US-NRC, 2000, ICRP 66, 1994; ICRP 72, 1996 and NRC 10 CFR) which forms the bases of this study. The maximum TEDE values obtained at various stability classes and downwind distances are below the acceptable limit of the 1 mSv for the public and 50 mSv for the radiation worker in a year. Since the dose values calculated are very low the approximations and the margin of error due to the simulation should not significantly alter the final results. At the conclusion of this study, with a good degree of reliability, the hypothetical accident scenario as the one proposed would constitute events without any radiological significance for the population and for the workers.

6.2 Recommendations

- It is recommended that the results of this thesis should be adopted as part of radiological accident response plan during the core conversion.

- It is recommended that further studies be conducted on them impact of radionuclides released when gas purge system is activated.

- It is recommended that further studies be conducted on the dose levels on plants and animals that may be under the plume of released radionuclides.

- It is recommended that encroaching activities on the GAEC exclusion area boundary should be prohibited.
REFERENCES


