RADIATION DOSE RATE EVALUATION IN KINGDOM OF BAHRAIN DUE TO A HYPOTHETICAL ACCIDENT IN A NUCLEAR POWER PLANT IN THE REGION

A Thesis

by

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ABSTRACT

The construction of new nuclear power plants in the Middle East region calls for an estimate of the radiation dose to the general members of public in the region due to an accidental radiological release, even though it is a highly unlikely scenario. The main objective of this thesis research is to perform radiation dose assessments for the Kingdom of Bahrain and the countries of the Arabian Gulf region for the case of a large radioactive material release due to a hypothetical accident in a regional nuclear power plant. This objective was accomplished by computing the radioactive source term by performing nuclear reactor core physics and fuel burnup simulations using Monte Carlo radiation transport code, MCNP. MCNP code was used to prepare the model of a fuel assembly used in one of the nuclear reactor cores in the Middle East region. The MCNP model was used to perform fuel burnup simulations for estimating the concentration of radionuclides in the burned nuclear fuel. Subsequently, the estimation of location-dependent radiation dose rates was carried out by using a material dispersion code, HOTSPOT. For fuel assembly and the corresponding burnup simulations, a model of the advanced pressurized water reactor (APWR) was used. A mixture of radioactive isotopes from the estimated source term was used to perform material dispersion simulation based on the Gaussian dispersion model. The atmospheric dispersion simulation of radioactive materials and the corresponding radiation dose rate estimates gave useful insights on the potential areas that will be affected, which should help in emergency planning and preparedness. The most probable dose rate was recorded at a wind speed of 6.8 m/s and ranged between 0.0085 mSv for atmospheric stability A and 4.3 mSv for atmospheric stability D, while the highest radiation dose recorded was 41 mSv in the Kingdom of Bahrain for the worst-case scenario studied, which involved the hypothetical accidental release of

10% of the core inventory and atmospheric conditions at a wind speed of 3 m/s and atmospheric stability F.

For the most probable scenario with a 10% of the nuclear source term activity released, for atmospheric stability classes from A, C, and D the radiation dose rates to the members of the public were calculated. The higher the letter, the more stable the situation. Before the fuel elements were cooled, the estimated TED ranged from 0.0085 mSv to 4.30 mSv. The maximum TED in this case is more than four times the permissible dose limit for public exposure, which is 1 mSv per year.

The highest estimated TED in the Kingdom of Bahrain was 41 mSv/year at 10% source term activity released when atmospheric stability was at its peak (Stability F). That is 41 times higher than the permissible dose limit for public exposure of 1 mSv/year, and nearly double the permissible dose limit for radiation workers per year, 20 mSv averaged over five years for a total of 100 mSv. An annual dose of 1000 mSv (1 Sv) may cause radiation sickness symptoms such as nausea and vomiting. A dose of 7000-10000 mSv (7-10 Sv), on the other hand, may result in death.

To obtain 41 mSv/year, I used a very conservative approach in the calculations in which all fuel pins are at maximum irradiation time, but in reality, the source term is predicted to be approximately 66% at any point in time, implying about 27 mSv/year, which is still higher than the public dose limit for a year (1 mSv). However, to bring this dose rate value to perspective, if 10000 members of the public received this amount of dose one in that group may develop cancer according to the radiation risk studies found in literature.

DEDICATION

To Latifa, Mahra and Amna

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I want to express my special thanks to my commanders in Bahrain Defense Force (BDF) for their trust and believes in my capabilities and sponsoring my academic endeavors at Texas A&M University.

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NOMENCLATURE

PWR	Pressurized Water Reactor
NPP	Nuclear Power Plant
NTP	Normal Temperature and Pressure
APR	Advanced Power Reactor
ALWR	Advanced Light Water Reactor
LWR	Light Water Reactor
OPR	Optimized Power Reactor
MCNP	Monte Carlo N-Particle
HOTSPOT	HOTSPOT health physics code
HYSPLIT	The Hybrid Single-Particle Lagrangian Integrated Trajectory model
JRTR	Jordan Research and Training Reactor
UAE	United Arab Emirates
TED	Total Effective (Radiation) Dose
TEDE	Total Effective Dose Equivalent
KML	A file format used to display geographic data in an Earth browser

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1. INTRODUCTION

1.1 Pressurized Water Reactor Overview

Nuclear energy is one of the clean electricity sources to minimize the climate challenge posed by the emission of greenhouse gases. Several countries around the world are switching gears from the use of fossil fuels as the main source of electricity to include nuclear fuel (uranium and plutonium) to their list. The pressurized water reactor (PWR) is the most used type of nuclear power plant (NPP) in the world. PWRs keep the reactor primary coolant water under pressure to prevent it from boiling at its normal temperature and pressure (NTP) boiling point temperature of 300^{o}C. The reactor primary coolant water gets heated up due to nuclear fission energy generated in the fuel. The heated primary coolant water the reactor exchanges it with the water in the secondary circuit and gets converted to steam in the steam generator, which in turn rotates the turbine blades to generate electricity. As a result, most of the radioactive materials produced in the fuel assembly during nuclear fission remains intact within the fuel assemblies inside the reactor vessel.

An NPP operates like that of a thermal electricity generation station converting the heat generated into electricity. The source of heat generation is the fundamental difference; in a thermal power station it is fossil fuel whereas in a nuclear power plant it is uranium/plutonium fuel. In a PWR-type NPP there are three cooling circuits: (i) primary circuit; (ii) secondary circuit or steam cycle; and (iii) tertiary circuit [1].

1.2 Advanced Power Reactor (APR1400) model

The newest NPP in the Middle East region being analyzed in this thesis study is the Barakah NPP, which has 4 nuclear reactor cores of Advanced Power Reactor (APR1400) model designed by South Korea. The APR1400 is an evolutionary Advanced Light Water Reactor (ALWR) based on the Optimized Power Reactor 1000 (OPR1000), which is in operation in South Korea. The APR1400 incorporated a variety of engineering improvements from its vast operational experience to enhance safety, economics, and reliability. [2] The advanced design features of the APR1400 design and the major reactor core and fuel characteristics are shown in table 1.

Table 1 Major Characteristics of APR1400 and Fuel. [2]

Parameters	Design Value
Number of Fuel Assemblies	241
Maximum Fuel Rod Burn-up	60,000 (MWD/MTU)
Fuel Assembly Type	16x16 rods
Number of Fuel Rods in a Fuel Assembly	236
Total number of Fuel Rods in the Core	56,876
UO_2 Fuel Pellet Radius	0.39398 cm
Number of Guide Tube in Fuel Assembly (Control element assemblies / in-core instrumentation)	5 (4/1) *
Fuel Clad Material	Zirlo
Cladding Radius (Inner/Outer)	0.40226 cm / 0.45972 cm
Pin Level Lattice Pitch	1.26678 cm

*Each of the five guide tubes occupies 4 fuel rods space

Accident in an NPP and the associated potential large release of radioactive materials from them are extremely rare due to the defense-in-depth measures incorporated in the design of reactor. However, it is essential to estimate the radioactive material source term in the reactor core for different states of the reactor to assess the potential radiation dose to the members of public and environment in the case of an unlikely accidental large release. The insights gained from the dose rate estimates can help us to plan and prepare for emergencies. Figure 1 shows the geographic location of Barakah NPP that is being analyzed in this thesis.

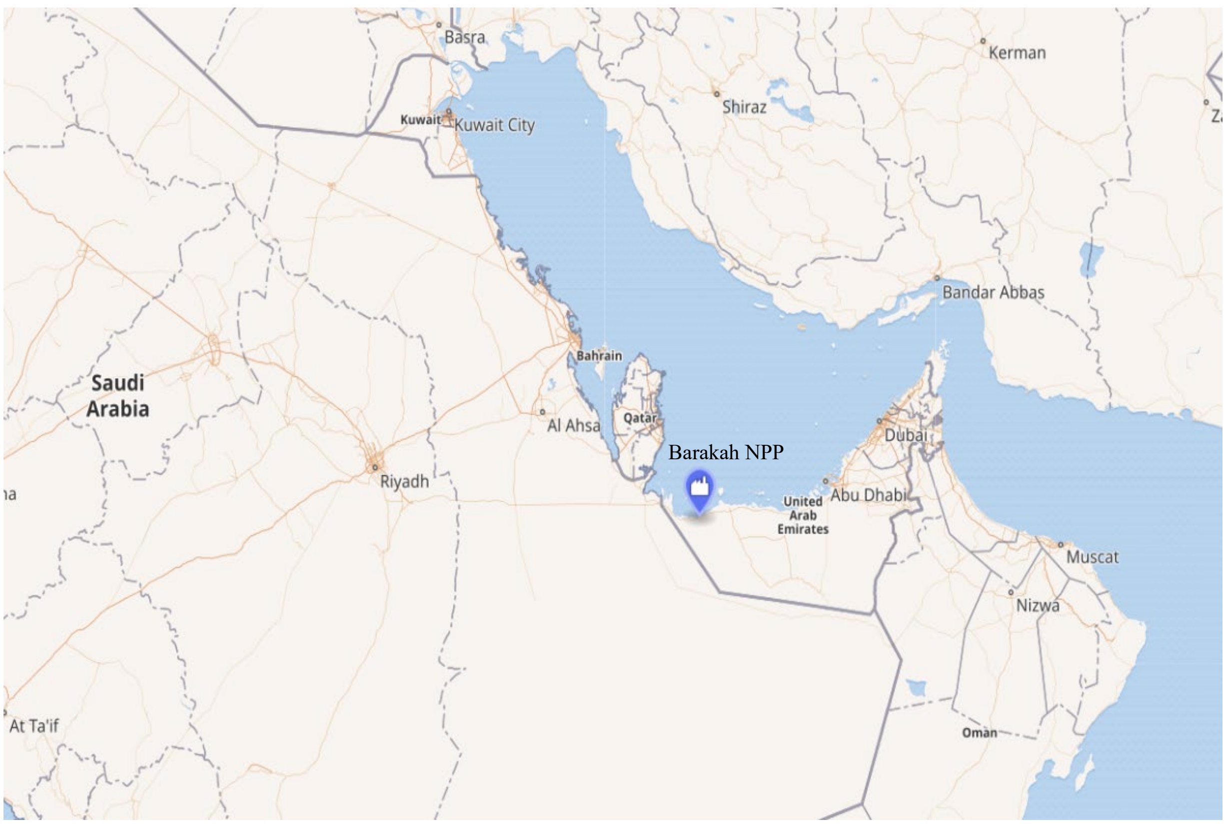

Fig. 1. Geographical location of Barakah NPP [3]

1.3 Objective Overview

The main objective of this thesis research is to perform radiation dose assessments for the Kingdom of Bahrain and the countries of the Arabian Gulf region for the case of a large radioactive material release due to a hypothetical accident in a regional nuclear power plant. This objective can be accomplished by computing the radioactive source term by performing nuclear reactor core physics and fuel burnup simulations using Monte Carlo radiation transport code, MCNP [4]. MCNP code was used to prepare the model of a fuel assembly used in one of the nuclear reactor cores in the Middle East region. Subsequently, the estimation of location-dependent radiation dose rates was carried out by using a material dispersion code, HOTSPOT [5]. For fuel assembly and the corresponding burnup simulations, a model of the advanced pressurized water reactor (APWR) was used. A mixture of radioactive isotopes from the estimated source term was used to perform material dispersion simulation based on the Gaussian dispersion model. The atmospheric dispersion simulation of radioactive materials and the corresponding radiation dose rate estimates can give useful insights on the potential areas that will be affected, which should help in emergency planning and preparedness.

The thesis will cover the fuel burnup simulation of a fuel assembly for various burnup and cooling time steps to estimate the source term of radioactive materials in an APWR. This calculated source term will enable the estimation of radiation dose rates for multiple reactor conditions as well as atmospheric conditions such as temperature, wind speed and directions, and atmospheric stability.

1.4 Basis for Current Research

Alrammah et al. has reported the information on the release of radioactive materials from a proposed NPP in Saudi Arabia [6]. In their methodology on estimating the release of radioactive materials, they applied Gaussian plume model and the Lagrangian particle model for dispersion calculations. HOTSPOT code, used in this thesis study, also uses Gaussian plume model for dispersion calculations. They also used HYSPLIT software to simulate ranges of dispersion, transport, and deposition of many types of airborne pollutants including the radioactive materials and GENII software to integrate internal dosimetry models. Shamsuddin et al. performed their research using HOTSPOT health physics code and they reported results on the postulated accidental dispersion of radionuclides, Cs-137 and I-131 in various wind directions [7].

Mistarihi and Kwan published research titled "Dispersion of radioactive materials from Jordan Research and Training Reactor (JRTR) following a postulated accident using HOTSPOT health physics code" [8], where they discussed the dispersion of radioactive materials from JRTR. The report's findings indicate that for a ground level release with an average speed of 3.6 m/s of hourly averaged meteorological data for one year with a dominant direction from the west, a person located 0.062 km from the reactor site will receive 0.25 Sv.

Malaysian researchers published a paper titled "Development of radionuclide dispersion modeling software based on Gaussian plume model" [9]. Their study used HOTSPOT health physics code to estimate the concentration of Cs-137. The highest Cs-137 concentration (3.6×10^{10} Bq-sec/m^3) is predicted at 1.0 km from the proposed nuclear power plant site.

Pirouzmand et al. performed research using HOTSPOT health physics code and published a paper titled "Dose assessment of radionuclides dispersion from Bushehr nuclear power plant stack under normal operation and accident conditions" [10]. They used HOTSPOT health physics code for their analysis to get the plume dispersion in 100 km radius from Bushehr NPP. The maximum value of TEDE was found is about 10 mSv/year near the center of the reactor site.

2. MONTE CARLO N-PARTICLE (MCNP) SIMULATION FOR LWR

2.1 Monte Carlo N-Particle (MCNP) overview

The Monte Carlo method is a numerical analysis technique which uses random sampling procedures to construct the solution of a physical problem. A stochastic model estimates the statistical numerical answers to the problem by sampling from appropriate probability distributions, in this case the Boltzmann Transport Equation.[11] The Monte Carlo method in MCNP code simulates the process of nuclear particle interactions with matter by sampling, via random numbers, probability distributions calculated from transport data.[12]

The MCNP code must have an abundant supply of random numbers uniformly distributed between 0 and 1. Each particle is followed from birth to the particle's death or escape from the system, with random sampling of probability distributions contained in the radiation transport equation to determine the outcome at each step of the particle's life.[11] Events in the life of a particle may include the distance between collisions, collision nuclide selection, and nuclear reaction selection. Probabilities at each event are calculated based on physics, transport data and the materials involved. A random number is selected at an event and applied to the probability distribution to determine the outcome of the event. This process is repeated along the particle's life with a particle's death coming from absorption or leakage from the system. Since many particle life histories are tracked, the average particle behavior better simulates the physical process.[12]

The envisaged tasks for completing the thesis study are to prepare the model of a 16x16 PWR fuel assembly of the APR1400 to perform fuel burnup simulations to estimate the radioactive materials source concentration in the fuel assemblies for different states of the reactor. An average

^{235}U enrichment of the fuel in the core will be used in the model. The concentration of fission products and actinides will be estimated using the fuel burnup simulations using the general-purpose MCNP neutronics code [4] for various fuel burnup and colling time steps to use in the atmospheric dispersion simulations.

2.2 LWR Fuel Pin Modeling

The estimation of the radioactive source term of a fuel rod is performed using MCNP simulation. The APR-1400 core has a total of 56,876 fuel rods. The dimensions of each fuel rod are shown in fig. 2 The radius of the cylindrical uranium dioxide fuel pellet (blue color) is 0.39398 cm with a height of 366 cm. Fuel Clad Material Zirlo (green color) has an inner radius of 0.40226 cm and an outer radius of 0.45972 cm, and both have a similar height of 366 cm. A cuboid pin plane grid measuring 1.26678 x 1.26678 x 366 cm is used.

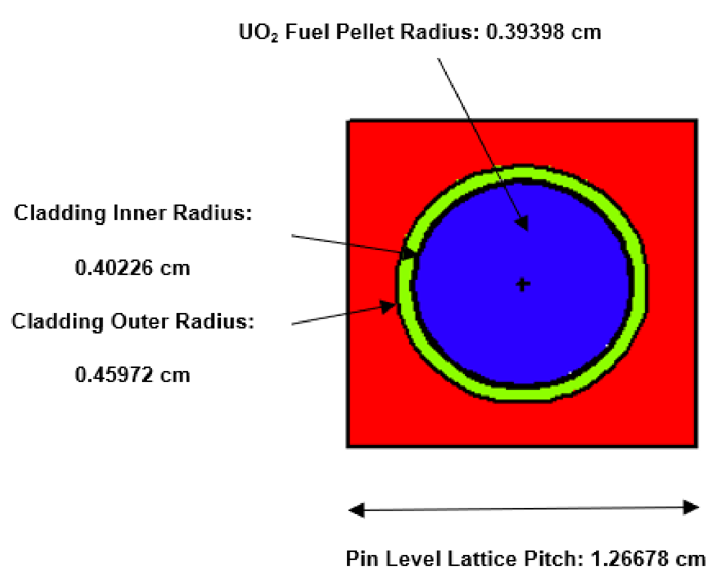

Fig. 2. Fuel pin components and dimensions.

The simulation was performed by creating an MCNP input file to burnup the UO_2 fuel over 1100 days and then cooling it for one year and this has been done over 32 burnup and three cooling time steps (see Table 2). The power of a single rod is 0.06722 MW. The fuel used in this modeling consists of 3.5% U^{235}, 96.46% U^{238} and 0.04% U^{234} (weight percent). The total fuel volume of each fuel rod is 178.4758 cm^3.

Table 2 Fuel Burnup and Cooling time Steps.

Step Number	Duration (days)	Power Fractions	Fuel Burnup GWD/MTU (Giga-watt-day/ metric ton of uranium)
1	0.3	1	0
2	0.3	1	0.0124
3	0.4	1	0.0248
4	1	1	0.0413
5	3	1	0.0827
6	25	1	0.207
7-32	40 per step	1	44.32 (at end of step 32)
33	1	0	44.32
34	29	0	44.32
35	335	0	44.32

2.3 MCNP output file

Each burnup and cooling step performed MCNP produces the estimates of the concentrations of isotopes in the fuel. In this work, the focus is on step 32, the final fuel burnup time step before cooling, and step 35, which provides the isotope concentration in the fuel after 1 year of cooling. The radioactive source data was used to create an input file for the HOTSPOT health physics code, discussed in the next chapter.

2.4 Fuel Burnup Results

For this thesis, the objective is to estimate the source term of the whole core when it is at full operation, and after one year of cooling. The results of fuel burnup and the estimated reactor core inventory of selected isotopes for full operation (burnup time step 32) are shown in table 3.

Table 3 Core inventory of selected isotopes at full operation (burnup time step 32).

Isotope	Core Activity		10% of Core Activity		1% of Core Activity	
	Ci	Bq	Ci	Bq	Ci	Bq
I-130	2.76E+06	1.02E+17	2.76E+05	1.02E+16	2.76E+05	1.02E+15
I-131	1.07E+08	3.94E+18	1.07E+07	3.94E+17	1.07E+06	3.94E+16
I-135	1.98E+08	7.31E+18	1.98E+07	7.31E+17	1.98E+06	7.31E+16
Cs-134	2.57E+07	9.51E+17	2.57E+06	9.51E+16	2.57E+05	9.51E+15
Cs-136	6.43E+06	2.38E+17	6.43E+05	2.38E+16	6.43E+04	2.38E+15
Cs-137	1.29E+07	4.79E+17	1.29E+06	4.79E+16	1.29E+05	4.79E+15

The results of isotopic concentration in the core after 32 fuel burnup times steps and one year of cooling fuel burnup (time step 35) are shown in table 4. From table 4, it can be seen that I-131 has completely decayed away due to its short half-life of 8 days.

Table 4 Core inventory of selected isotope after one year of cooling (time step 35).

Isotope	Core Activity		10% of Core Activity		1% of Core Activity	
	Ci	Bq	Ci	Bq	Ci	Bq
Cs-134	1.84E+07	6.80E+17	1.84E+06	6.80E+16	1.84E+05	6.80E+15
Cs-137	1.26E+07	4.68E+17	1.26E+06	4.68E+16	1.26E+05	4.68E+15

3. HOTSPOT HEALTH PYSICS CODE

3.1 HOTSPOT health physics code overview

HOTSPOT health physics code is a hybrid of the well-established Gaussian plume model, widely used for initial emergency assessment or safety-analysis planning. Virtual source terms are used to model the initial atmospheric distribution of source material following an explosion, fire, resuspension, or user-input geometry [4]. The HOTSPOT health physics code provides a first-order approximation of the radiation effects associated with the atmospheric release of radioactive materials. This code uses a Gaussian plume to calculate the air concentration and the total effective dose equivalent (TEDE) from radionuclides released into the atmosphere. This program is designed for short-range and short-term predictions [13]. HOTSPOT health physics code allows to get a good estimation of plume shapes and direction in each case and for different weather and atmospheric conditions.

Figure 3 illustrates the methodology of the HOTSPOT code used for this thesis study. Source term of radioactive materials that were obtained using the MCNP simulation is utilized with other parameters of meteorology, topography, and the placement of receptors to create a complete dispersion model. In this study, Gaussian Plume Model has been used due to the accuracy and reliability of the results it provides. Appropriate completion of the HOTSPOT simulation will provide the results of the atmospheric concentration of radionuclides and the corresponding radiation dose at each spatial receptor the user provided.

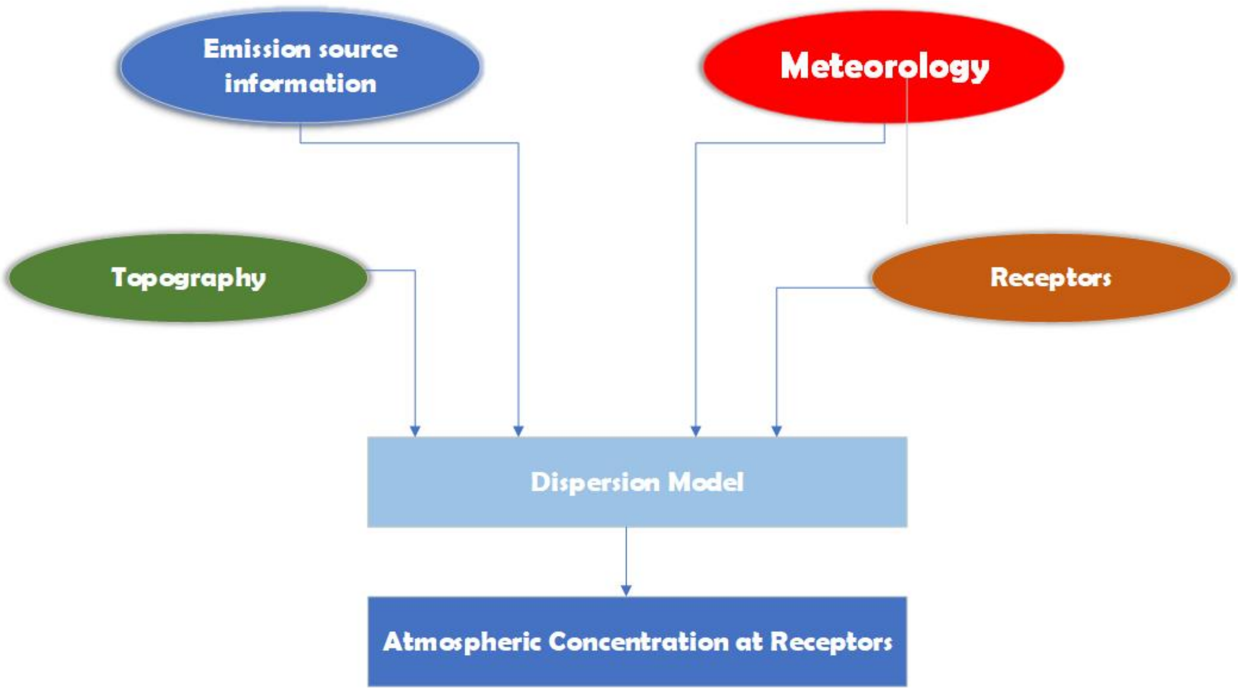

Fig. 3. TED calculation methodology.

3.2 HOTSPOT Methodology

3.2.1 Gaussian Plume Dispersion Model

There are many implementations of the Gaussian plume dispersion model and as such the following summary is included for completeness. The Gaussian plume dispersion model has been widely used and verified in the scientific community and is still the basic workhorse for initial calculations of atmospheric dispersion. The Gaussian plume dispersion model generally gives results that agree well with experimental data under simple meteorological and terrain conditions, and so has found its way into most government handbooks and is also used and accepted by the Environmental Protection Agency (EPA, 1978). The origin of the Gaussian plume dispersion model is found in work by Sutton (1932), Pasquill (1961, 1974), and Gifford (1961, 1968).

Additional background and supplemental information on the Gaussian plume dispersion model can be found in Turner (1969), Hanna, et al (1982, 1987, 1989), S. Pal Arya (1999). Figure 4 is an illustration of the HOTSPOT methodology of plume dispersion.

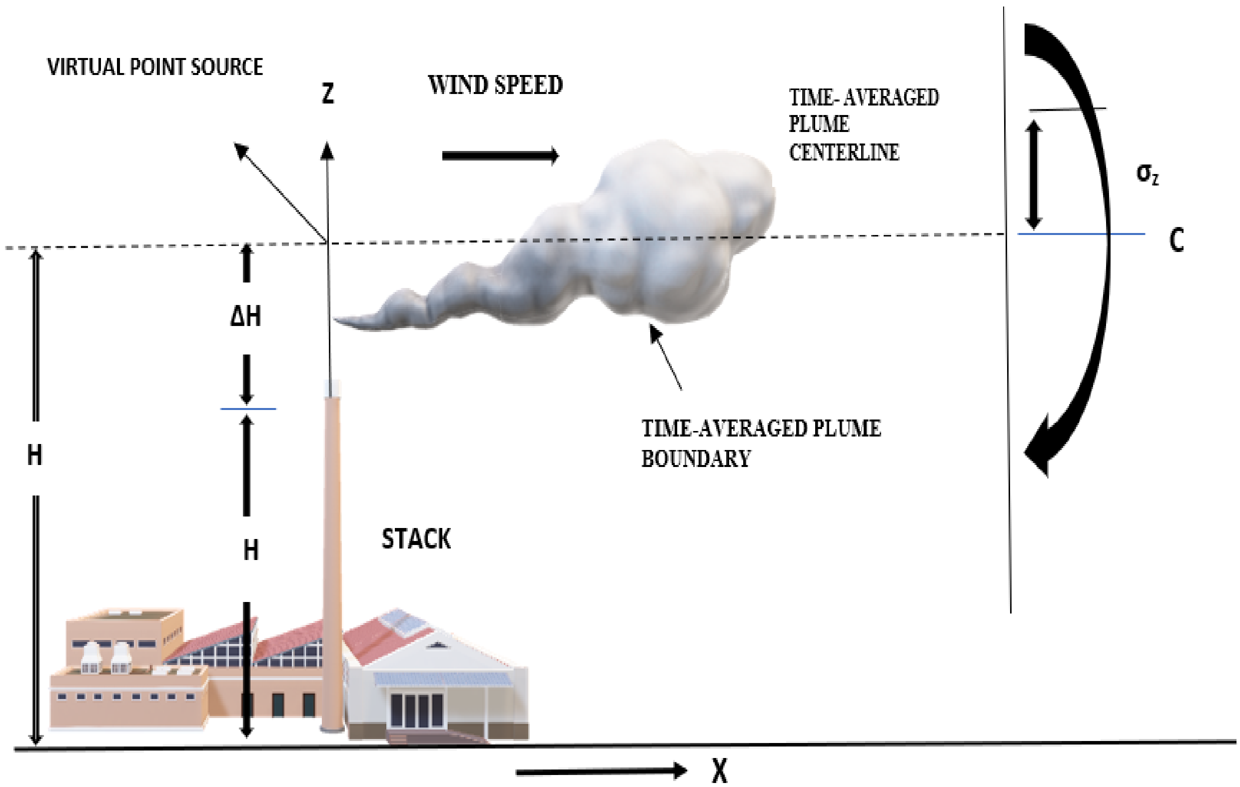

Fig. 4 Gaussian plume dispersion model.

In the HOTSPOT code, the coordinate origin is located at ground level, beneath the point of radionuclide release (x = 0, y = 0, z = 0). The x axis is the direction of the downwind, extending horizontally with the ground in the average wind direction. The y axis is in the direction of the crosswind, perpendicular to the downwind direction axis, also extending horizontally. The z axis extends vertically from the ground. A plume travels along, or parallel to the downwind axis, and reflects off the ground surface when the plume touches down [16].

3.2.2 Gaussian Plume Dispersion Model Equation

The following Gaussian model equations [16] determine the time-integrated atmospheric concentration of a gas or an aerosol at any point in space:

$$C(x,y,z,H) = \frac{Q}{2\pi\sigma_Y\sigma_z u}\exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right]\left\{\exp\left[-\frac{1}{2}\left(\frac{z-H}{\sigma_z}\right)^2\right] + \exp\left[-\frac{1}{2}\left(\frac{z+H}{\sigma_z}\right)^2\right]\right\}\exp\left[-\frac{\lambda x}{u}\right]DF(x) \qquad (1)$$

If the inversion layer option is in effect, and if z exceeds the inversion height (L), the following equation is used.

$$C(x,y,z,H) = \frac{Q}{\sqrt{2\pi}\sigma_Y L u}\exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right]\exp\left[-\frac{\lambda x}{u}\right]DF(x) \qquad (2)$$

To avoid the sharp transition between these two equations (1) and (2), the transition into the inversion layer equation begins when z equals 70% of L and is complete when z equals L. Between these two values, the two equations (1) and (2) are linearly interpolated.

Where:

C = Time-integrated atmospheric concentration (Ci-s)/(m3).

Q = Source term (Ci).

H = Effective release height (m).

λ= Radioactive decay constant (s^{-1}).

x = Downwind distance (m).

y = Crosswind distance (m).

z = Vertical axis distance (m).

y = Standard deviation of the integrated concentration distribution in the crosswind direction (m).

z = Standard deviation of the integrated concentration distribution in the vertical direction (m).

u = Average wind speed at the effective release height (m/s).

L = Inversion layer height (m).

DF(x) = Plume Depletion factor

3.3 HOTSPOT Inputs file

3.3.1 HOTSPOT Inputs file preparation

Preparation of input files that contain the data on release fraction of radioactive materials source term for various reactor states for simulations using atmospheric dispersion code, HOTSPOT. Simulation is to compute radiation dose rate around the nuclear power plant. Data for HOTSPOT input file are obtained from the burnup of a fuel pin by using MCNP software which was discussed in the previous chapter.

In addition to radionuclide source term, meteorology data such as wind speed, solar information, and actual atmospheric stability must be obtained. Moreover, receptors height and position are to be added. A total of 20 receptor can be used with a maximum distance of 200 miles (322km). Furthermore, the terrain type and complexity play an important role in this study. Lastly, exposure time and exposure parameters are adjusted to match the hypothetical scenario of this thesis.

3.3.2 Geography

Barakah NPP is in the western part of United Arab Emirates (UAE) as shown in Fig. 1 elsewhere in this thesis. Kingdom of Bahrain, Kingdom of Saudi Arabia, State of Qatar, and Sultanate of Oman are the nearby countries to UAE. Two of the major cities in the region Abu Dhabi and Dubai are also not too far from the NPP. Table 3 shows the list of cities around Barakah NPP with their distances from the Barakah NPP.

Table 5 Cities around Barakah NPP with their distances.

Country	City	Distance (Km)
Kingdom of Bahrain	Manama	300
Kingdom of Bahrain	Hawar Islands	232
Kingdom of Saudi Arabia	Damam	371
Kingdom of Saudi Arabia	Riyadh	565
Sultanate of Oman	Muscat	643
State of Qatar	Doha	163
UAE	Abu Dhabi (Center)	210
UAE	Dubai	343

3.3.3 Meteorology

As mentioned in section 3.2, meteorology data play a vital role in determining the outcome of radionuclide dispersion due to an accidental release and the corresponding radiation dose rate. Wind and weather statistics for Barakah, United Arab Emirates used in this thesis contains detailed information about average local wind speed and air temperature since 2012. Figure 5 shows a dominant wind direction and includes average data for the past 10 years and these statistics for Barakah are based on historical data observations.

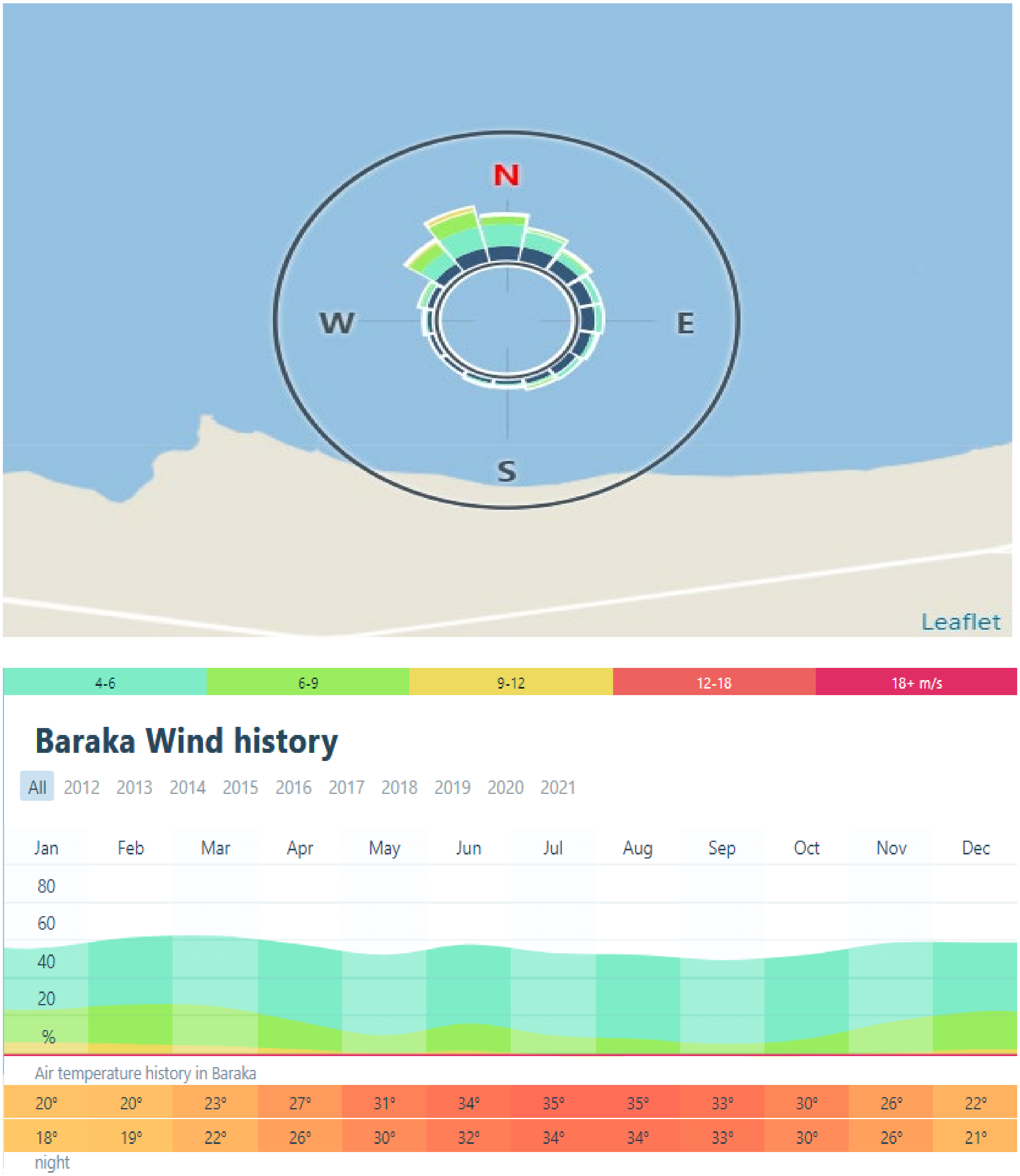

Fig. 5. Dominant wind direction and average data for the past 10 years [14]

Aside from wind speed and direction, atmospheric stability is critical for plume dispersion. The class of atmospheric stability ranges from A (very unstable) to F (stable). Many factors influence atmospheric stability class, including wind speed and time of day.

3.3.4 Topography

Studying the shapes and characteristics of land surfaces is known as topography. The topography of a region can either refer to the actual land formations and features or to a description of them. Plume dispersion behavior is dependent upon the topography of the area. For example, plume dispersion in open areas is different from mountainous area. Similarly, plume dispersion in a standard rural area will vary from that of a metropolitan or large city. For the region selected in this study, the plume dispersion area is in open areas with some exceptions.

3.3.5 Receptors

The distance between Barakah NPP and Manama, the capital of Kingdom of Bahrain is around 300 km. In this study, several receptors are placed up to 322 km from area of incident. The height of receptors is set at 1.5m to match the real-life receptor at chest height of a human being.

3.4 HOTSPOT Output

HOTSPOT code uses Gaussian plume model for atmospheric dispersion calculations. Based on the input data provide by the user, HOTSPOT code produces table of outputs that include distances with their relative data such as total effective dose (TED) and arrival time of such radiation dose. In addition, TED graphs can be retrieved for the same data. Similarly, ground deposition contour plots can also be produced.

In general, the goal of this study is to estimate the plume dispersion for a given radionuclide source term by calculating the plume depth and direction on the map. HOTSPOT code produces a ".kml" filetype that can be used with map software such as Google earth to view plume progression in the exact location.

4. TED ESTIMATION FOR HYPOTHETICAL ACCIDENTAL RADIOACTIVE MATERIAL RELEASE SCENARIOS CONSIDERING THE MOST PROBABLE METEOROLOGICAL CONDITIONS

In Chapter 2, we discussed the results of radio nuclide source term estimation using MCNP simulation of APWR. In Chapter 3, we discussed about the methodology to calculate TED using the HOTSPOT software. For this study, we assumed a hypothetical accidental release of 10% of the source term activity for one scenario and 1% source term activity for a second scenario. Analysis of the results of these two scenarios will aid in comparison of TED values.

For many years meteorological data continues to be collected for the space around Barakah NPP. The data are shown in table 6 are for the most probable meteorology conditions.

Table 6 Most probable meteorology conditions in Barakah area. [15]

Median wind velocity (m/s)	Min Value (m/s)	Max value (m/s)	Wind direction
6.8	3	18.9	NW 324º

HOTSPOT code was supplied with the accidental release source term for each scenario based on the results of the radionuclide concentration estimated in the APWR core using MCNP simulation. In this work we have studied a variety of isotopes activities and meteorological data. To be as appropriate as possible, we used both most probable and worst-case scenarios of meteorological conditions with respect to plume dispersion in atmosphere. In this chapter, the most probable scenario is discussed while chapter 5 discusses the worst-case scenario.

4.1 HOTSPOT results and discussions at 10% of source term activity release

4.1.1 Estimated TED for a fully operational core (Burnup Step 32 with no cooling time)

Table 7 in this section lists the HOTSPOT calculated TED values for different atmospheric stability classes and as a function of distance from the radionuclides release point. The atmospheric stability is referred to when there are differences in activity levels throughout the day. Sun-high in the sky (stability class A) results in lower plume concentration when it occurs. The concentration is higher over the same distances at night when atmospheric stability class is D. The variation of TED values for three atmospheric stability classes, A, C, and D as a function of distance from the source is shown in Fig. 6.

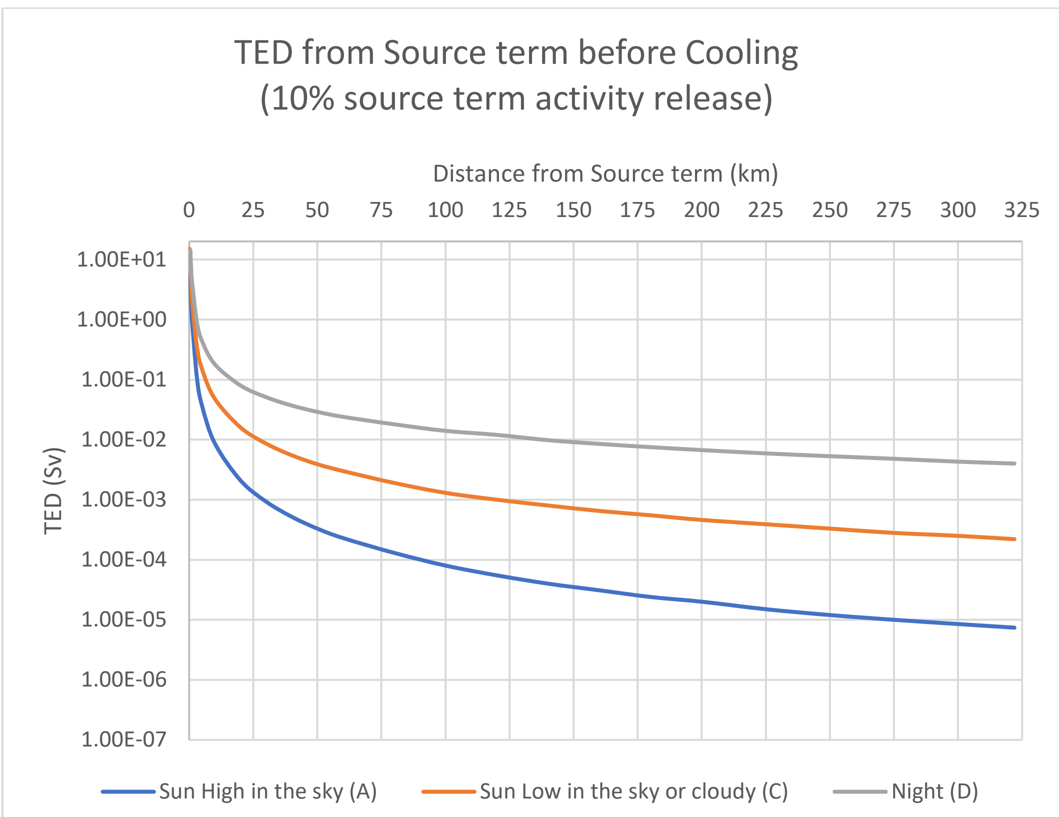

Fig 6. Variation of TED values for three atmospheric stability classes, A, C, and D as a function of distance from the source (10% source term release from burnup simulation step 32 is assumed without considering any cooling time).

Table 7 Variation of TED values for three atmospheric stability classes, A, C, and D as a function of distance from the source (10% source term release from burnup simulation step 32 is assumed without considering any cooling time)

Distance (km)	TED (Sv) for three atmospheric stability classes		
	Sun High in the sky (A)	Sun Low in the sky or cloudy (C)	Night (D)
0.2	1.40E+01	1.50E+01	6.40E+00
0.4	6.30E+00	1.10E+01	1.40E+01
0.6	3.00E+00	5.80E+00	9.70E+00
0.8	1.70E+00	3.60E+00	6.70E+00
1	1.10E+00	2.40E+00	4.80E+00
3	1.10E-01	3.60E-01	9.10E-01
5	3.70E-02	1.50E-01	4.40E-01
10	8.70E-03	4.80E-02	1.80E-01
20	2.10E-03	1.60E-02	8.00E-02
30	9.30E-04	8.60E-03	5.10E-02
40	5.20E-04	5.50E-03	3.70E-02
50	3.30E-04	3.90E-03	2.90E-02
60	2.30E-04	3.00E-03	2.40E-02
80	1.30E-04	1.90E-03	1.80E-02
100	8.00E-05	1.30E-03	1.40E-02
120	5.50E-05	1.00E-03	1.20E-02
140	4.00E-05	8.00E-04	9.80E-03
160	3.10E-05	6.50E-04	8.50E-03
180	2.40E-05	5.50E-04	7.50E-03
200	2.00E-05	4.60E-04	6.70E-03
225	1.50E-05	3.90E-04	5.90E-03
250	1.20E-05	3.30E-04	5.30E-03
275	1.00E-05	2.80E-04	4.80E-03
300	8.50E-06	2.50E-04	4.30E-03
322	7.40E-06	2.20E-04	4.00E-03

4.1.2 Estimated TED for 10% source term released after one year of cooling (Fuel Burnup Step 35)

Table 8 lists TED values for three atmospheric stability classes for the 10% source release after the reactor is cooled for one year. The fluctuations in TED values during the day are due to the changes in atmospheric stability. When the sun is high in the sky (stability A) leads to a lower plume concentration. However, air stability is better at night (stability D) and across the same distances. Figure 7 depicts the variation of TED values for three atmospheric stability classes as a function of distance from the accidental release point.

Table 8 Variation of TED values for three atmospheric stability classes, A, C, and D as a function of distance from the source (10% source term release from burnup simulation step 35 is assumed with one year cooling time)

Distance (km)	TED (Sv) for three atmospheric stability classes		
	Sun High in the sky (A)	Sun Low in the sky or cloudy (C)	Night (D)
0.2	4.80E+00	5.10E+00	2.10E+00
0.4	2.10E+00	3.60E+00	4.70E+00
0.6	1.00E+00	2.00E+00	3.30E+00
0.8	5.70E-01	1.20E+00	2.30E+00
1	3.60E-01	8.30E-01	1.60E+00
3	3.60E-02	1.20E-01	3.10E-01
5	1.20E-02	5.10E-02	1.50E-01
10	2.90E-03	1.60E-02	6.10E-02
20	7.20E-04	5.50E-03	2.70E-02
30	3.10E-04	2.90E-03	1.70E-02
40	1.80E-04	1.90E-03	1.30E-02
50	1.10E-04	1.30E-03	1.00E-02
60	7.80E-05	1.00E-03	8.30E-03
80	4.40E-05	6.60E-04	6.10E-03
100	2.80E-05	4.70E-04	4.80E-03
120	1.90E-05	3.60E-04	4.00E-03
140	1.40E-05	2.80E-04	3.40E-03
160	1.10E-05	2.30E-04	3.00E-03
180	8.60E-06	1.90E-04	2.60E-03
200	6.90E-06	1.60E-04	2.40E-03
225	5.50E-06	1.40E-04	2.10E-03
250	4.40E-06	1.20E-04	1.90E-03
275	3.70E-06	1.00E-04	1.70E-03
300	3.10E-06	8.90E-05	1.60E-03
322	2.70E-06	8.00E-05	1.50E-03

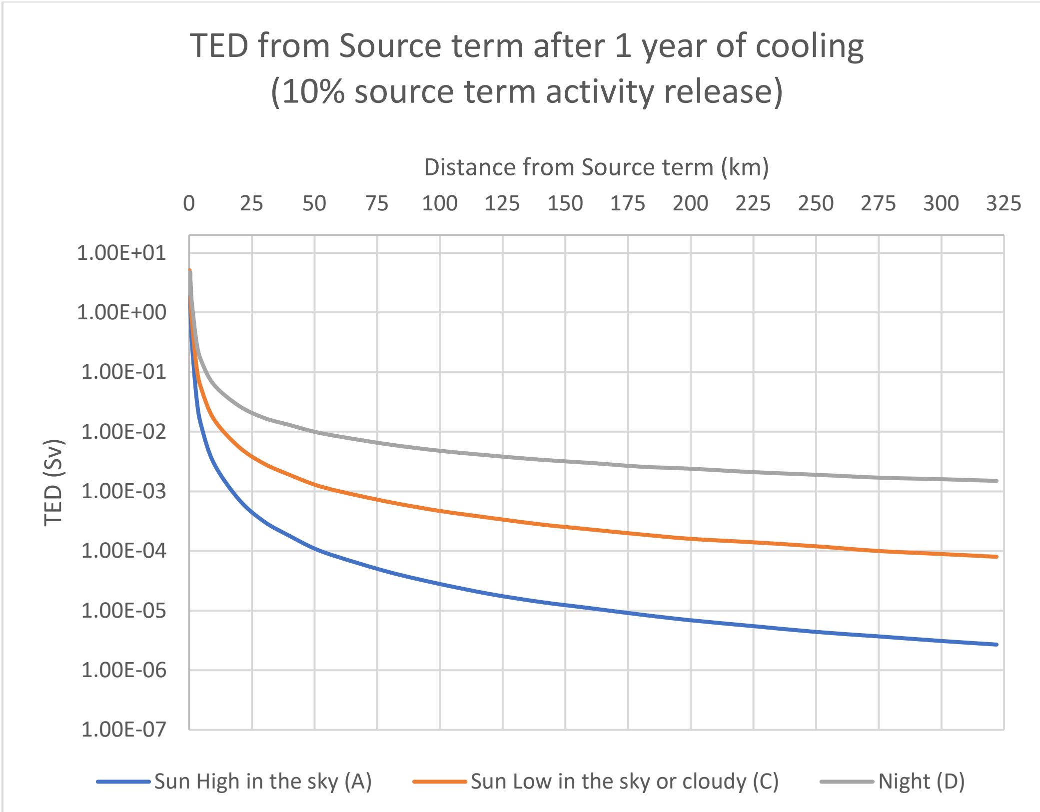

Fig. 7. Variation of TED values for three atmospheric stability classes, A, C, and D as a function of distance from the source (10% source term release from burnup simulation step 35 is assumed with one year cooling time).

4.2 HOTSPOT results and discussions for 1% of source term activity release

4.2.1 Estimated TED for a fully operational core (Burnup Step 32 with no cooling time)

Table 9 lists the values of TED as a function of distance for three atmospheric stability classes A, C, and D. The variation of TED values for this case is also shown in fig. 8.

Table 9 Variation of TED values for three atmospheric stability classes, A, C, and D as a function of distance from the source (1% source term release from burnup simulation step 32 is assumed without considering any cooling time)

Distance (km)	TED (Sv) for three atmospheric stability classes		
	Sun High in the sky (A)	Sun Low in the sky or cloudy (C)	Night (D)
0.2	1.40E+00	1.50E+00	6.40E+00
0.4	6.30E-01	1.10E+00	1.40E+00
0.6	3.00E-01	5.80E-01	9.70E-01
0.8	1.70E-01	3.60E-01	6.70E-01
1	1.10E-01	2.40E-01	4.80E-01
3	1.10E-02	3.60E-02	9.10E-02
5	3.70E-03	1.50E-02	4.40E-02
10	8.70E-04	4.80E-03	1.80E-02
20	2.10E-04	1.60E-03	8.00E-03
30	9.30E-05	8.60E-04	5.10E-03
40	5.20E-05	5.50E-04	3.70E-03
50	3.30E-05	3.90E-04	2.90E-03
60	2.30E-05	3.00E-04	2.40E-03
80	1.30E-05	1.90E-04	1.80E-03
100	8.00E-06	1.30E-04	1.40E-03
120	5.50E-06	1.00E-04	1.20E-03
140	4.00E-06	8.00E-05	9.80E-04
160	3.10E-06	6.50E-05	8.50E-04
180	2.40E-06	5.50E-05	7.50E-04
200	2.00E-06	4.60E-05	6.70E-04
225	1.50E-06	3.90E-05	5.90E-04
250	1.20E-06	3.30E-05	5.30E-04
275	1.00E-06	2.80E-05	4.80E-04
300	8.50E-07	2.50E-05	4.30E-04
322	7.40E-07	2.20E-05	4.00E-04

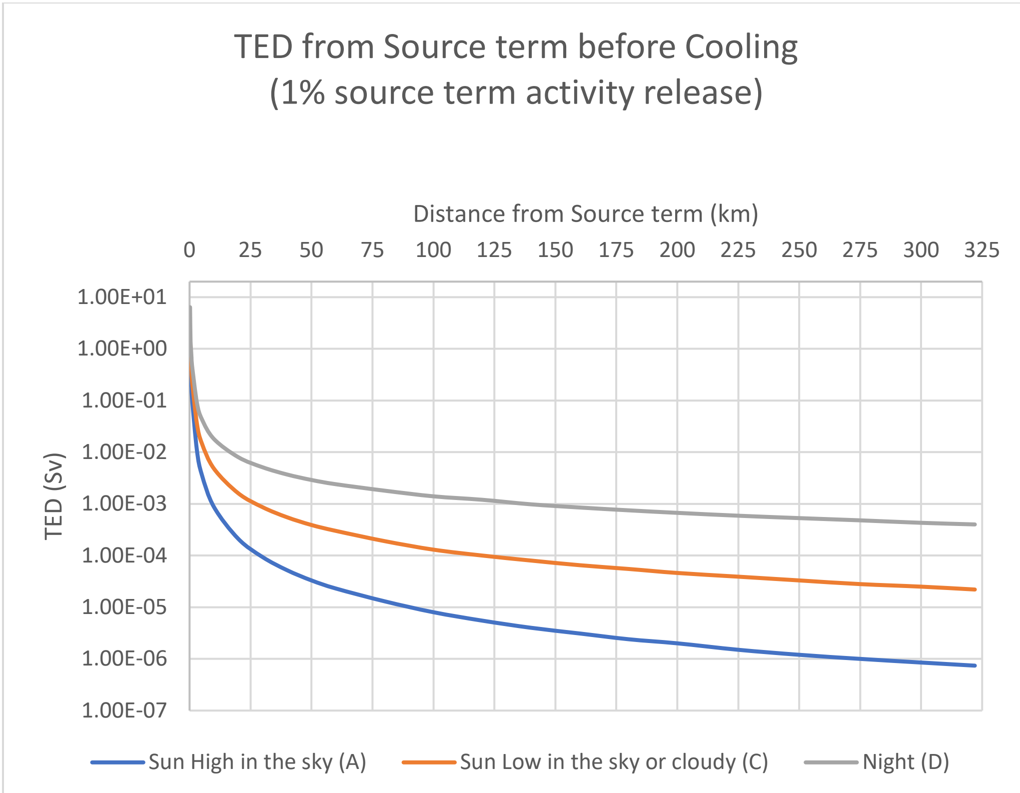

Fig 8. Variation of TED values for three atmospheric stability classes, A, C, and D as a function of distance from the source (1% source term release from burnup simulation step 32 is assumed without considering any cooling time).

4.2.2 Estimated TED for 1% source term released after one year of cooling (Fuel Burnup Step 35)

Table 10 lists the TED values for this case as a function of distance for three stability classes, A, C, and D. The variation of TED values for this case is also shown in fig. 9.

Table 10 Variation of TED values for three atmospheric stability classes, A, C, and D as a function of distance from the source (1% source term release from burnup simulation step 35 is assumed with one year cooling time)

Distance (km)	TED (Sv) for three atmospheric stability classes		
	Sun High in the sky (A)	Sun Low in the sky or cloudy (C)	Night (D)
0.2	4.80E-01	5.10E-01	2.10E-01
0.4	2.10E-01	3.60E-01	4.70E-01
0.6	1.00E-01	2.00E-01	3.30E-01
0.8	5.70E-02	1.20E-01	2.30E-01
1	3.60E-02	8.30E-02	1.60E-01
3	3.60E-03	1.20E-02	3.10E-02
5	1.20E-03	5.10E-03	1.50E-02
10	2.90E-04	1.60E-03	6.10E-03
20	7.20E-05	5.50E-04	2.70E-03
30	3.10E-05	2.90E-04	1.70E-03
40	1.80E-05	1.90E-04	1.30E-03
50	1.10E-05	1.30E-04	1.00E-03
60	7.80E-06	1.00E-04	8.30E-04
80	4.40E-06	6.60E-05	6.10E-04
100	2.80E-06	4.70E-05	4.80E-04
120	1.90E-06	3.60E-05	4.00E-04
140	1.40E-06	2.80E-05	3.40E-04
160	1.10E-06	2.30E-05	3.00E-04
180	8.60E-07	1.90E-05	2.60E-04
200	6.90E-07	1.60E-05	2.40E-04
225	5.50E-07	1.40E-05	2.10E-04
250	4.40E-07	1.20E-05	1.90E-04
275	3.70E-07	1.00E-05	1.70E-04
300	3.10E-07	8.90E-06	1.60E-04
322	2.70E-07	8.00E-06	1.50E-04

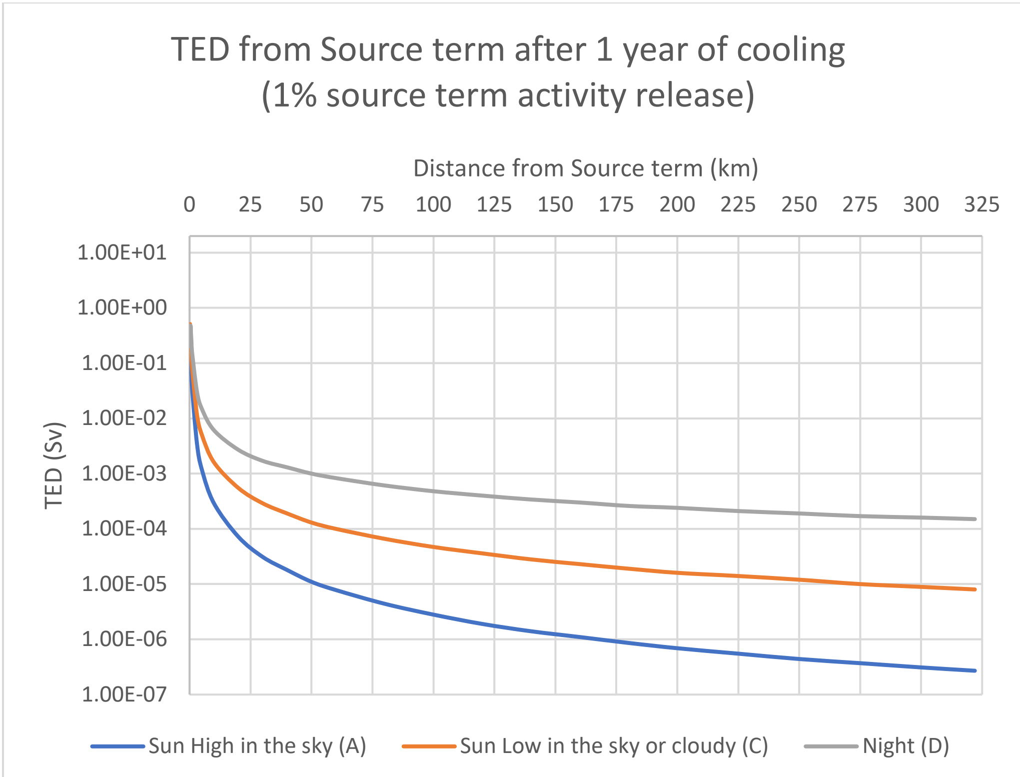

Fig. 9. Variation of TED values for three atmospheric stability classes, A, C, and D as a function of distance from the source (1% source term release from burnup simulation step 35 is assumed with one year cooling time).

In this chapter we studied the variation of TED values for three atmospheric stability classes, A, C, and D as a function of distance from the source up to 322 km for both 10% and 1% source term release from the source (for both burnup simulation at step 32 is assumed without considering any cooling time and step 35 is assumed with one year cooling time).

For the same step, we discovered that the relationship between 10% and 1% source term release is linear. That is, once one case is calculated using the gaussian dispersion equation, source term activity release can be calculated mathematically for the same source term at any different percentage.

5. TED ESTIMATION FOR HYPOTHETICAL ACCIDENTAL RADIOACTIVE MATERIAL RELEASE SCENARIOS CONSIDERING THE WORST-CASE METEOROLOGICAL CONDITIONS

5.1 Meteorology Conditions

When the wind speed is 3 m/s [15] with atmospheric stability (F), that is the worst-case scenario for the Barakah area plume dispersion given the historical meteorological data gathered. The plume is less dispersive in this worst-case scenario, which leads to higher values of TED. Along with the wind speed, atmospheric stability is a major factor in determining TED. Another element to consider is the change in wind direction.

The goal of this chapter is to estimate the TED values for the scenario where worst-case meteorological conditions exist during the hypothetical accidental radioactive material release. This section has been composed under the presumptions of constant wind speed, atmospheric stability, and wind direction.

5.2 Estimated TED for a fully operational core (Burnup Step 32 with no cooling time) and after one year of cooling (Fuel Burnup Step 35) for 10% release of source term.

A comparison of TED values as a function of distance for a fully operational core and the same fuel elements after one year of cooling is shown in Table 11 and Fig. 10. The fact that the TED for a fully operational core is roughly three times that of the cooled fuel elements illustrates the significance of cooling in the nuclear energy sector.

Table 11 TED as a function of distance for a fully operational core (Fuel Burnup Step 32) and the same fuel elements after one year of cooling (Fuel Burnup Step 35) for 10% source term activity release

Distance (km)	Total Effective Dose (TED) in (Sv)	
	Fully operational (Step 32)	After 1 year of Cooling (Step 35)
0.8	1.60E+01	5.20E+00
1	1.50E+01	5.00E+00
3	5.70E+00	1.90E+00
5	3.20E+00	1.10E+00
10	1.50E+00	5.10E-01
20	7.20E-01	2.40E-01
30	4.70E-01	1.60E-01
40	3.50E-01	1.20E-01
50	2.70E-01	9.40E-02
60	2.30E-01	7.80E-02
80	1.70E-01	5.80E-02
100	1.30E-01	4.60E-02
120	1.10E-01	3.80E-02
140	9.20E-02	3.30E-02
160	8.00E-02	2.90E-02
180	7.10E-02	2.50E-02
200	6.30E-02	2.30E-02
225	5.60E-02	2.00E-02
250	5.00E-02	1.80E-02
275	4.50E-02	1.70E-02
300	4.10E-02	1.50E-02
322	3.80E-02	1.40E-02

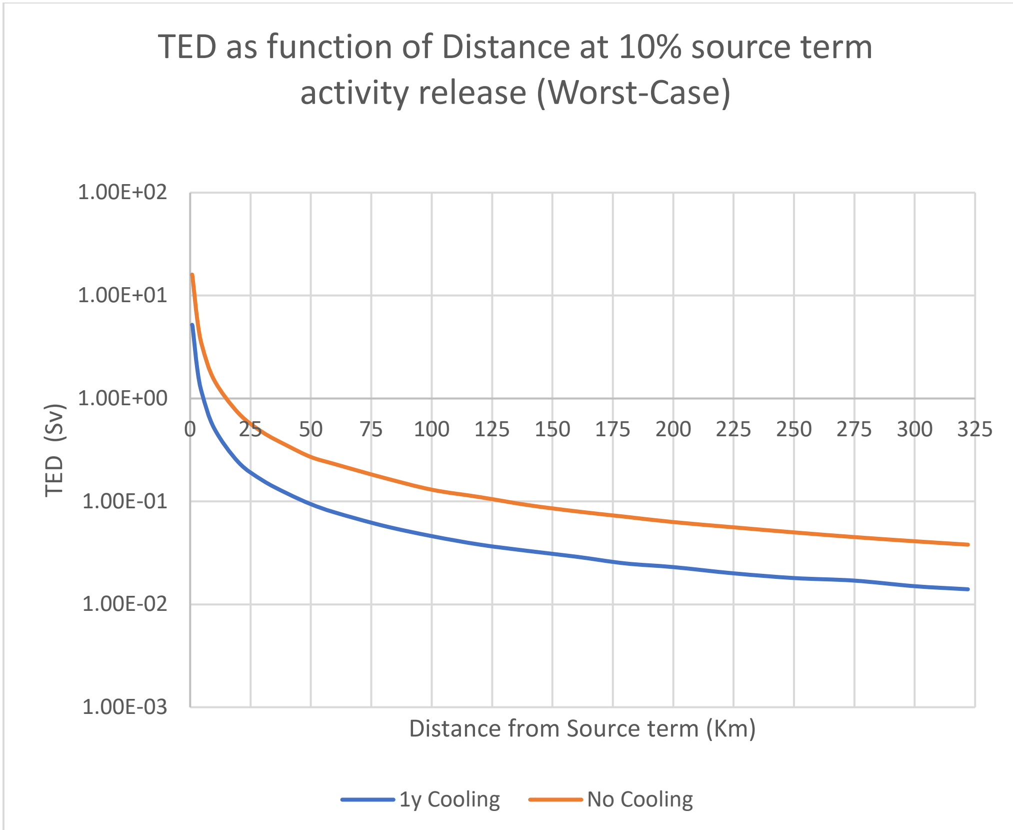

Fig. 10. TED as a function of distance of a fully operational core (Fuel Burnup Step 32) and after one year of cooling (Fuel Burnup Step 35) for 10% source term activity release.

5.3 Estimated TED for a fully operational core (Burnup Step 32 with no cooling time) and after one year of cooling (Fuel Burnup Step 35) for 1% release of source term.

Table 12 and Fig. 11 shows the comparison of TED values as a function of distance for a fully operational core and identical fuel elements after one year of cooling. The TED values in this scenario are found to be 10 times lower than the values in section 5.2 where the release considered was 10 times higher. Hence, these results show that the TED values for a given set of meteorological condition is linear with respect to the amount of radioactive material released.

However, the TED values for release scenario for a fully working core is nearly three times higher than that of the release scenario for one year cooled core.

Table 12 Estimated TED for a fully operational core (Burnup Step 32 with no cooling time) and after one year of cooling (Fuel Burnup Step 35) for 1% release of source term

Distance (km)	Total Effective Dose (TED) in (Sv)	
	Fully operational (Step 32)	After 1 year of Cooling (Step 35)
0.8	1.60E+00	5.20E-01
1	1.50E+00	5.00E-01
3	5.70E-01	1.90E-01
5	3.20E-01	1.10E-01
10	1.50E-01	5.10E-02
20	7.20E-02	2.40E-02
30	4.70E-02	1.60E-02
40	3.50E-02	1.20E-02
50	2.70E-02	9.40E-03
60	2.30E-02	7.80E-03
80	1.70E-02	5.80E-03
100	1.30E-02	4.60E-03
120	1.10E-02	3.80E-03
140	9.20E-03	3.30E-03
160	8.00E-03	2.90E-03
180	7.10E-03	2.50E-03
200	6.30E-03	2.30E-03
225	5.60E-03	2.00E-03
250	5.00E-03	1.80E-03
275	4.50E-03	1.70E-03
300	4.10E-03	1.50E-03
322	3.80E-03	1.40E-03

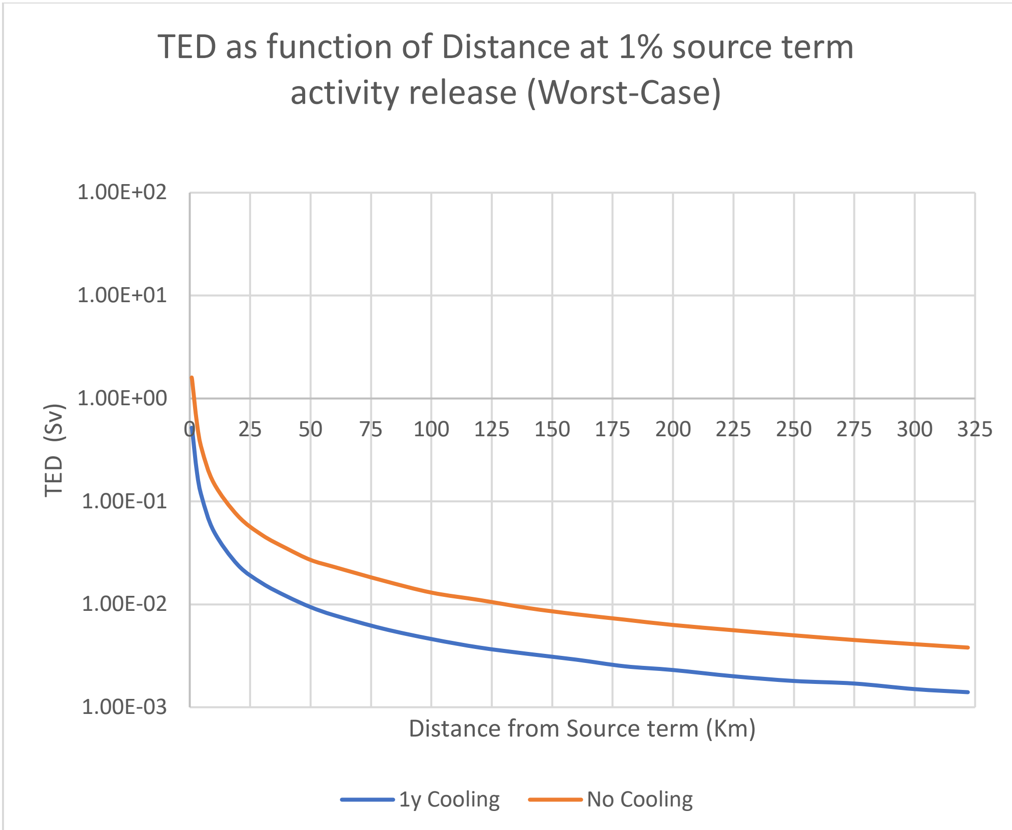

Fig. 11. Estimated TED for a fully operational core (Burnup Step 32 with no cooling time) and after one year of cooling (Fuel Burnup Step 35) for 1% release of source term.

6. PLUME DISPERSION ANALYSIS FOR THE MOST PROBABLE AND WORST-CASE SCENARIO METEOROLOGICAL CONDITIONS

6.1 Most Probable Scenario

This section discusses the dispersion of the plume. The range of distances from the hypothetical accident release source point covered in this thesis is up to 200 km. The application of contour level legends in plume dispersion used is shown in Table 12. The blue plume indicates 0.1 mSv, the green plume 1 mSv, and the red plume shows a TED threshold of 10 mSv.

Table 13 Contour levels legend for plume dispersion.

Contour Levels
1.00E-02 Sv
1.00E-03 Sv
1.00E-04 Sv

This study focused on two primary phases for the scenario that was most likely. Studying the plume dispersion for a fully functional core assuming the source term from the APR fuel burnup simulation of step 32 in the first scenario, while case two is for fuel elements that have been cooled for a year (fuel burnup step 35). Table 6 displays the parameters of the most likely scenario. Results of two hypothetical accidental radioactive material release scenarios for release fractions of 10% and 1% of the reactor core source term.

6.1.1 Plume dispersion of 10% of source term activity release

6.1.1.1 Plume dispersion analysis for activity released from a fully operational core (Fuel Burnup Step 32 with no cooling)

Three different atmospheric stability classes were analyzed. When the sun is high in the sky, we examine the first case (atmospheric stability A). The atmospheric stability in this situation is insufficient to maintain the plume's coherence. The TED drops below 10 mSv at around 4.5 km, but it takes longer—more than 28 km—to decrease below 1 mSv, as shown in Fig. 12.

Fig 12. Plume dispersion for 10% source term activity released before cooling (Fuel burnup step 32) for most probable scenario with atmospheric stability class, A

When atmospheric stability class is C, the TED value drops to below 10 mSv in less than 28 km, but it takes approximately 120 km to drop below 1 mSv, as illustrated in Fig. 13.

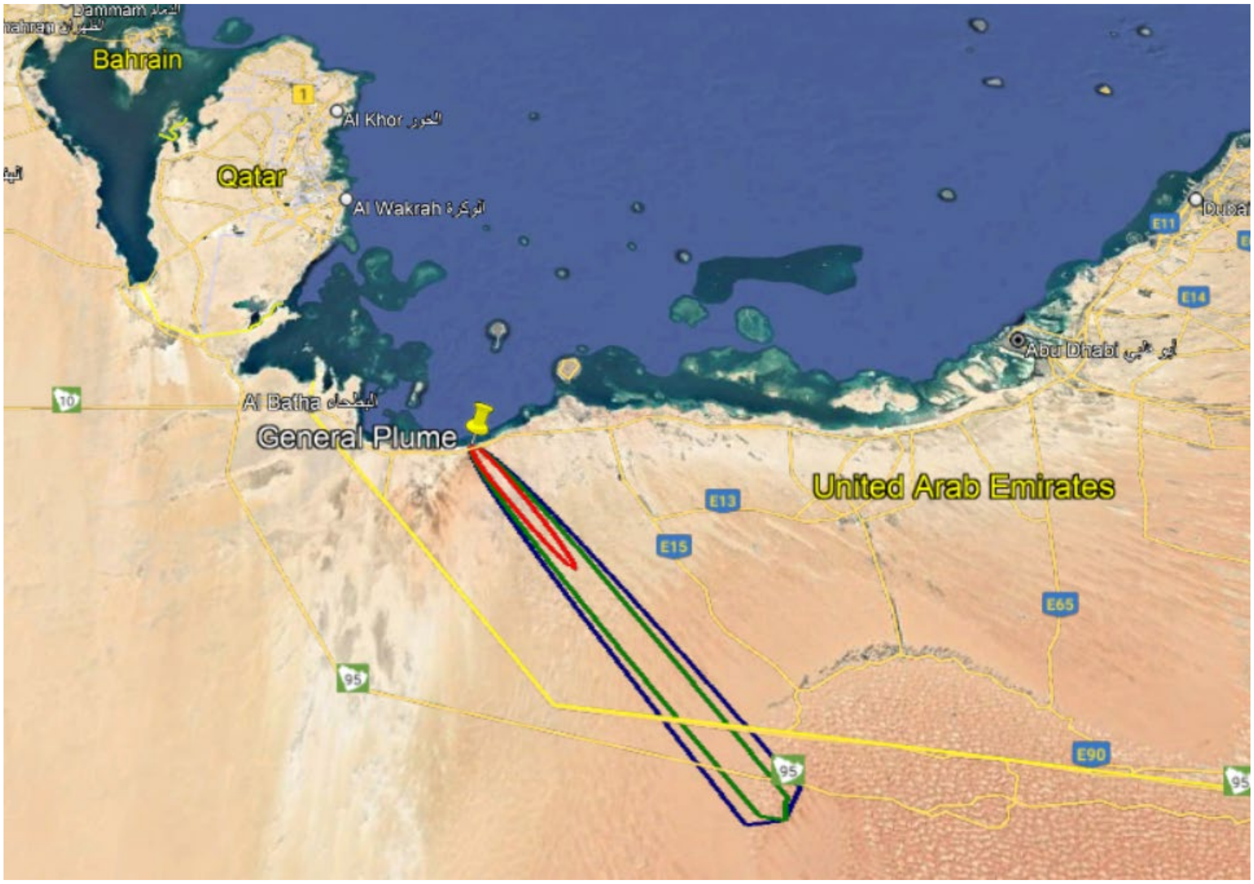

Fig 13. Plume dispersion for 10% source term activity released before cooling (fuel burnup step 32) for most probable scenario with atmospheric stability class, C.

The most stable part of the day is thought to be the night (atmospheric stability class D). Compared to the other two situations, the TED values are much higher in this instance. The nighttime Plume dispersion and the TED contours are shown in Fig. 14. Comparing this situation to earlier ones, we saw a remarkable amount of steadiness in the plume from not dispersing in the atmosphere.

Fig 14. Plume dispersion for 10% source term activity released before cooling (fuel burnup step 32) for most probable scenario with atmospheric stability class, D.

6.1.1.2 Plume dispersion analysis for activity released after one year of cooling (Fuel burnup step 35)

Analysis was done for three distinct atmospheric stability classes, A, C, D, like the discussion in section 6.1.1.1. The TED values drop below 10 mSv at around 5 km, but it takes over 15 km to decrease below 1 mSv, for atmospheric stability class, A as illustrated in Fig. 15.

Fig 15. Plume dispersion for 10% source term activity released after one year cooling (Fuel burnup step 35) for most probable scenario with atmospheric stability class, A.

For atmospheric stability class, C fig. 16 shows how the plume disperses. For this case the TED values drop below 10 mSv at around 12 km, but it takes over 60 km to decrease below 1 mSv, as illustrated in fig. 16.

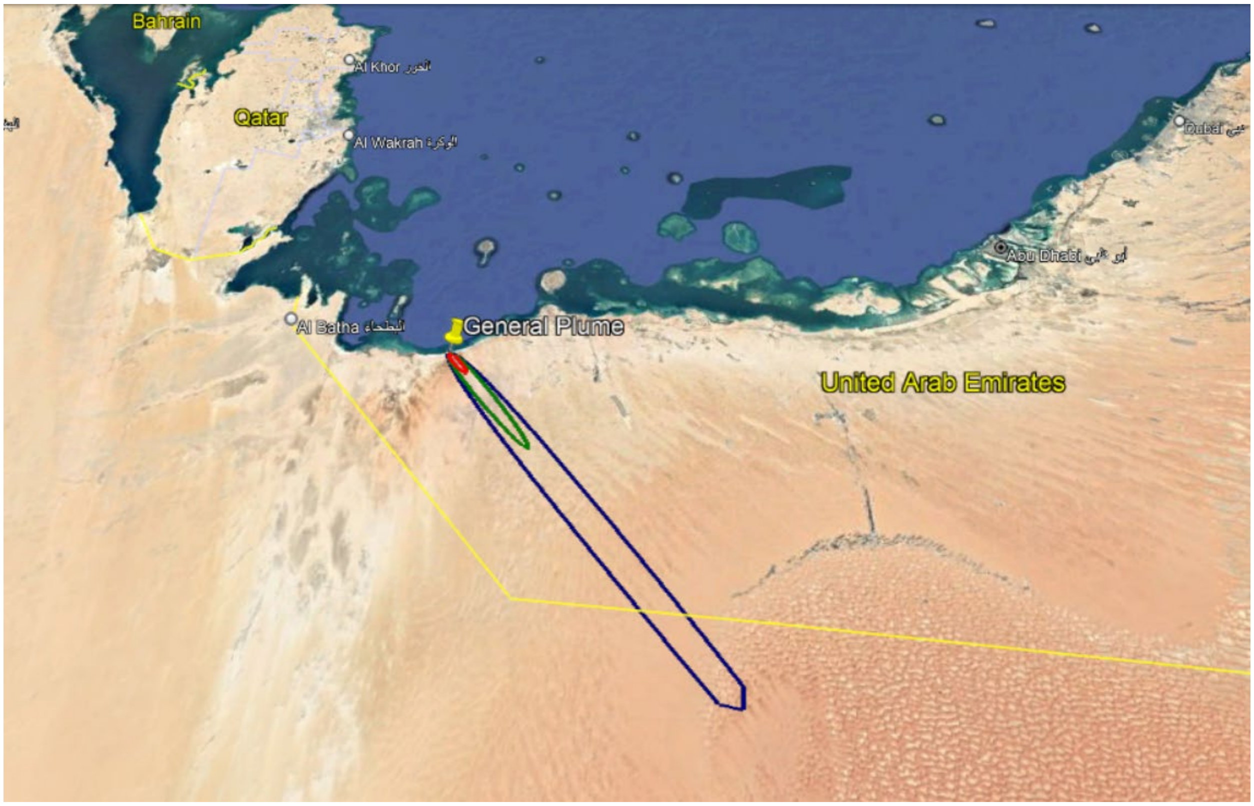

Fig 16. Plume dispersion for 10% source term activity released after one year cooling (Fuel burnup step 35) for most probable scenario with atmospheric stability class, C.

In the evening, when conditions are the steadiest of the day, as previously indicated (atmospheric stability D). Compared to the other two situations, TED is much higher in this instance. The nighttime Plume dispersion TED is shown in Fig. 17. For TED to be less than 10 mSv, 50 km are expected.

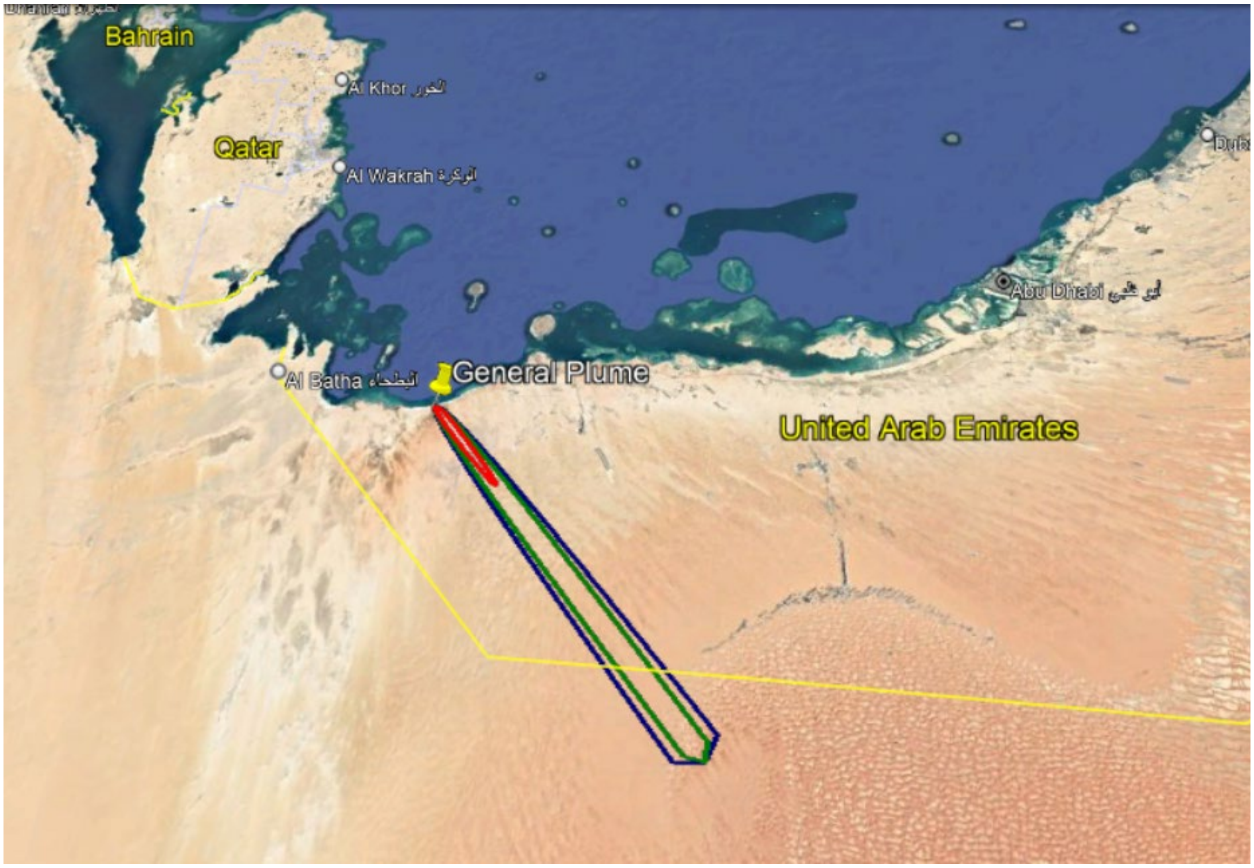

Fig 17. Plume dispersion for 10% source term activity released after one year cooling (Fuel burnup step 35) for most probable scenario with atmospheric stability class, D.

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6.1.2 Plume dispersion of 1% of source term activity released

6.1.2.1 Plume dispersion analysis for activity released from a fully operational core (Fuel burnup Step 32 with no cooling)

Like the study reported in section 6.1.1, study was conducted for three distinct atmospheric stability classes to understand the plume dispersion and the variation in TED values. Sun high in the sky is the first example under investigation (atmospheric stability A). The plume dispersion and the TED contours are shown in Fig. 18, the TED value drops to below 10 mSv in around 3 km, but it takes a little over 9 kilometers to fall below 1 mSv.

Fig 18. Plume dispersion for 1% source term activity released before cooling (Fuel burnup step 32) for most probable scenario with atmospheric stability class, A.

Figure 19 displays how the plume disperses when the sun is low in the sky, or it is overcast (Atmospheric stability C). Both the red and blue contour levels rose from the prior scenario because of variations in stability. As seen in Fig. 19, the TED decreases to Under 10 mSv at around 6 km, but it takes 27km to drop below 1 mSv.

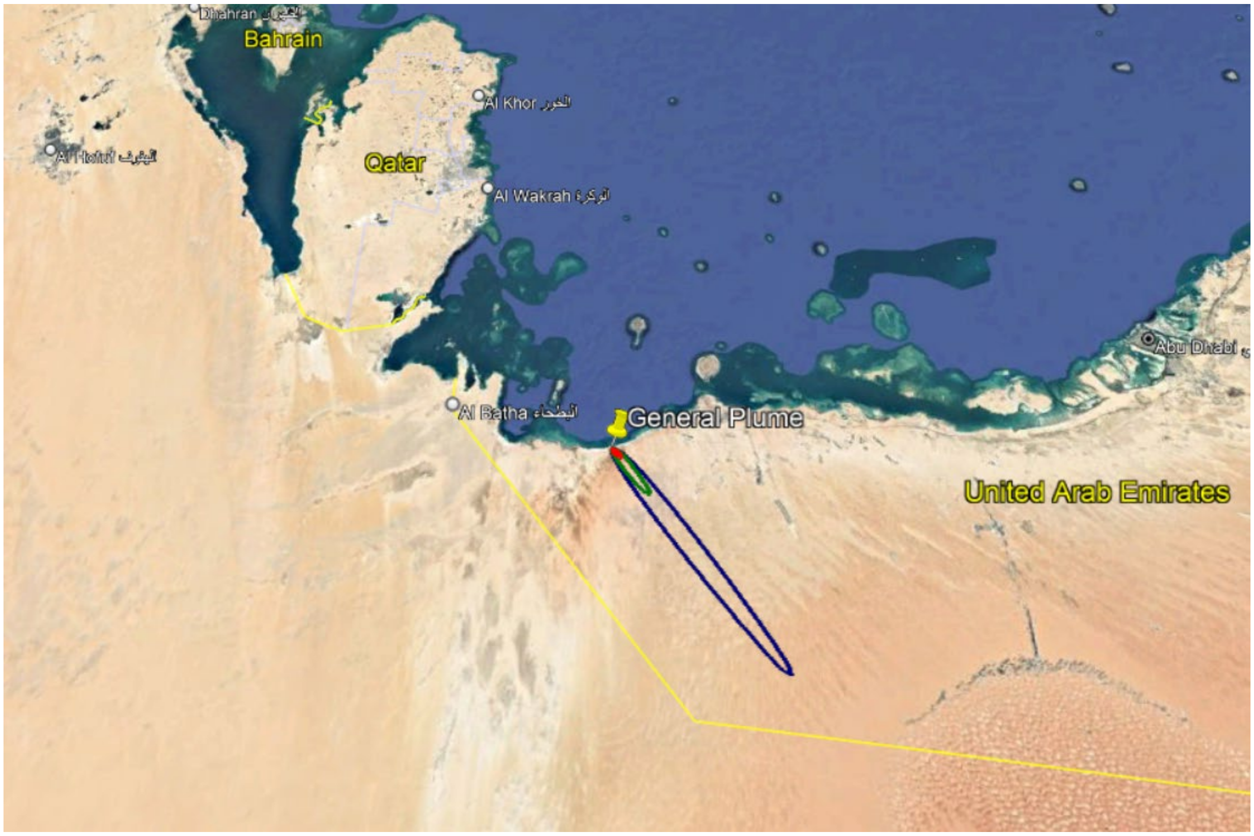

Fig 19. Plume dispersion for 1% source term activity released before cooling (Fuel burnup step 32) for most probable scenario with atmospheric stability class, C.

For atmospheric stability class, D the TED values are much higher than the other two stability classes. The nighttime plume dispersion and the TED contours are shown in Fig. 20. For TED to be less than 10 mSv, 16 km is the expected distance from the source and for 1 mSv it is 131 km.

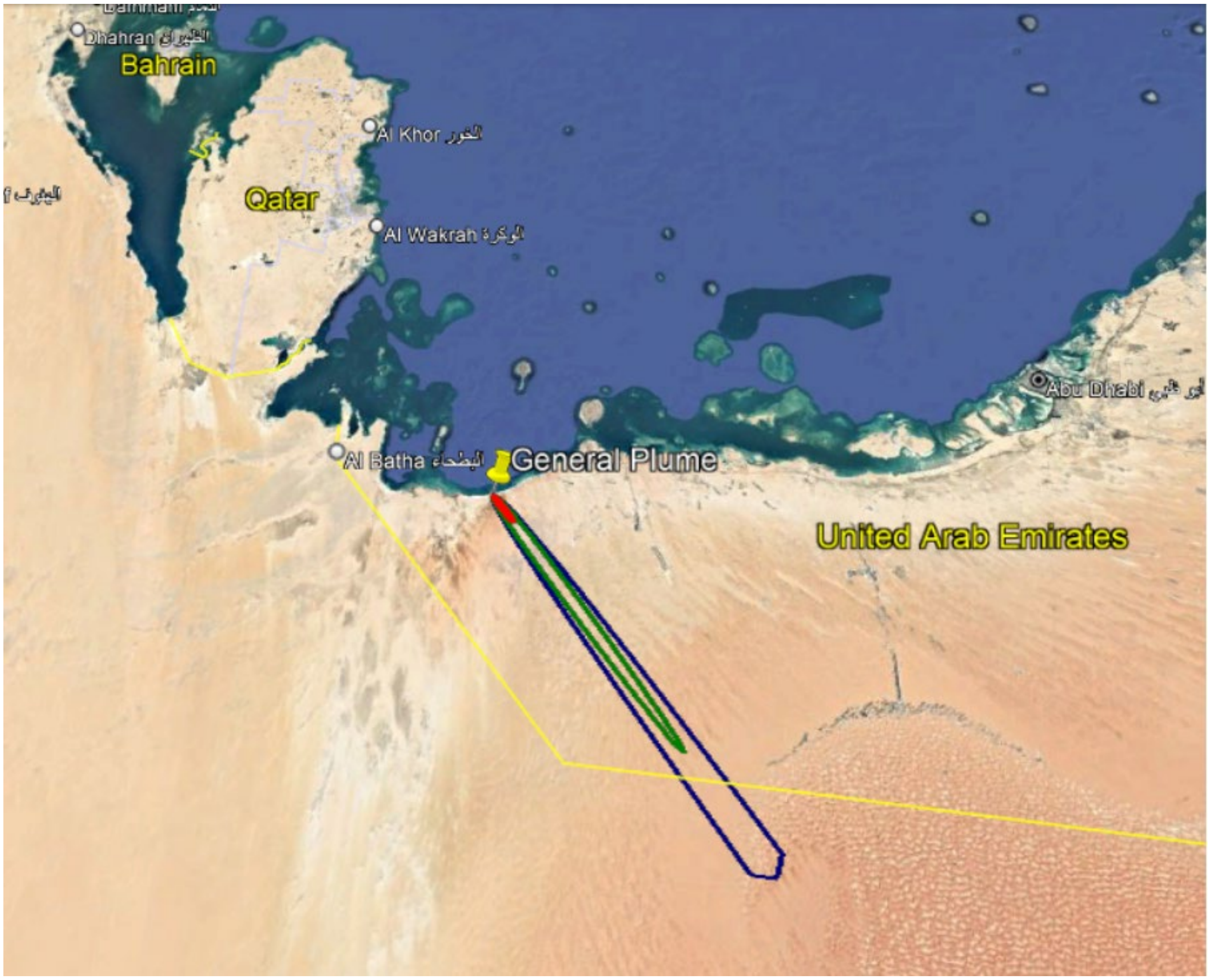

Fig 20. Plume dispersion for 1% source term activity released before cooling (Fuel burnup step 32) for most probable scenario with atmospheric stability class, D.

6.1.2.2 Plume dispersion analysis for activity released after one year of cooling (Fuel burnup step 35)

In this section the analysis was carried out for three different atmospheric stability classes, A, C, and D. to understand the plume dispersion for 1% source term activity release. For stability class A, it can be seen that at 1.85 km the TED values dropped below 10 mSv while it took more than 5.5 km to be dropped below 1 mSv as shown Fig. 21.

Fig 21. Plume dispersion for 1% source term activity released after one year cooling (Fuel burnup step 35) for most probable scenario with atmospheric stability class, A.

Figure 22 displays how the plume disperses when the sun is low in the sky, or it is overcast (Atmospheric stability class, C). Both the red and blue contour levels rose from the prior scenario because of variations in stability. As seen in Fig. 22, the TED values decrease to less than 10 mSv at around 3.3 km, but it takes about 14 km to drop below 1 mSv.

Fig 22. Plume dispersion for 1% source term activity released after one year cooling (Fuel burnup step 35) for most probable scenario with atmospheric stability class, C.

In the evening, when conditions are the steadiest of the day, as previously indicated (atmospheric stability class, D), TED values are much higher as shown in Fig. 23. For TED values to be less than 10 mSv, 7 km distance is expected and for 1 mSv it is about 48 km.

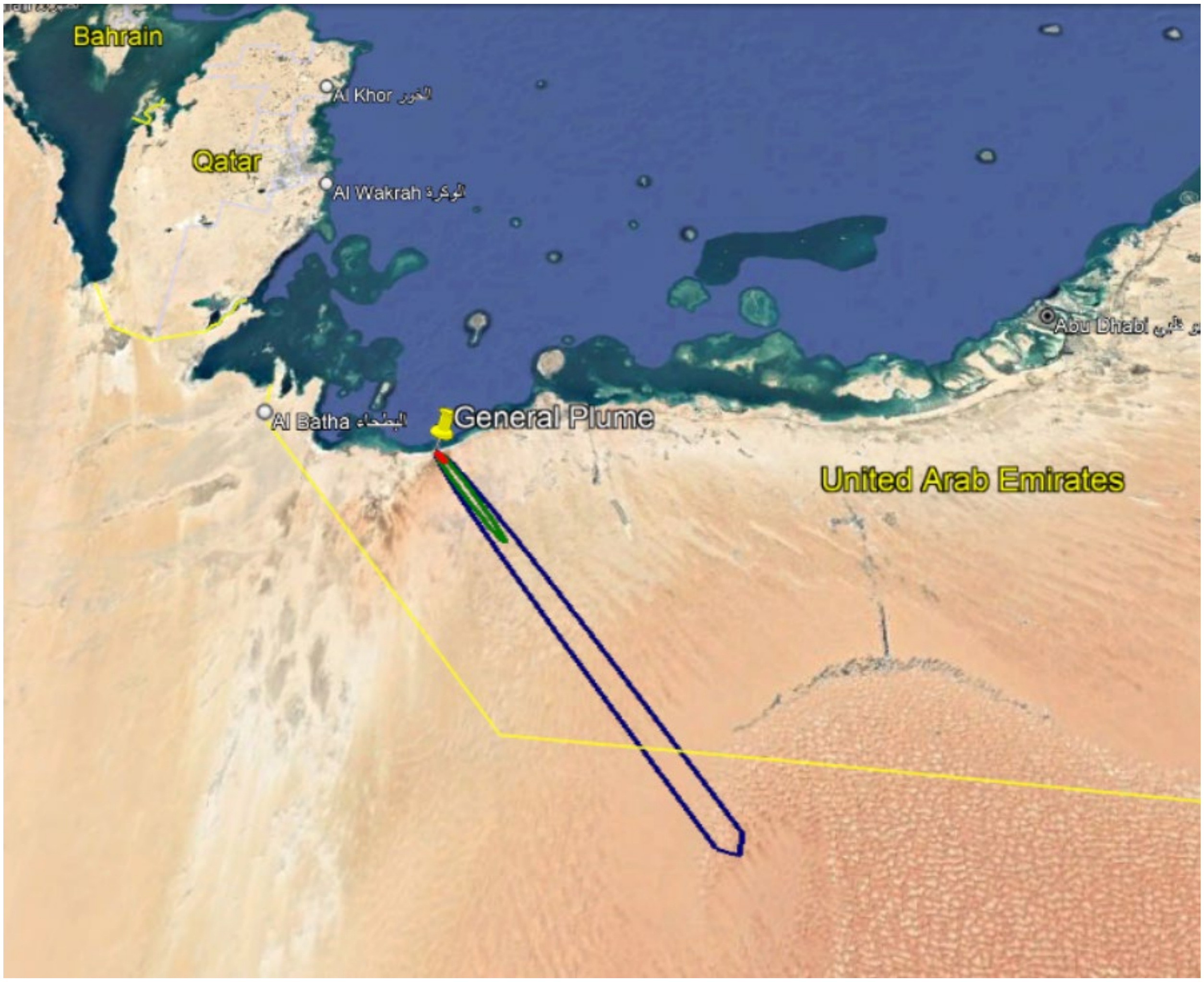

Fig 23. Plume dispersion for 1% source term activity released after one year cooling (Fuel burnup step 35) for most probable scenario with atmospheric stability class, D.

6.2 Worst-case Scenario

The worst-case scenario for the Barakah region, as described in chapter 5, is when the wind speed is 3 m/s simultaneously with the presence of atmospheric stability class, F. The plume is more cohesive in this instance, and TED values are expected to be high for this scenario. The Barakah NPP is about 300 kilometers away from Manama, the capital of the Kingdom of Bahrain; hence, TED values at distances of 100, 200, and 300 km have been estimated.

As a function of distance from the activity release point and based on atmospheric stability classes A, C, and D, up to 322 km, released activity is shown in Table 8. Two scenarios where, the reactor core is completely functional (fuel burnup step 32), and after the fuel components have been cooled for a year (fuel burnup step 35) are included in this study with release fraction variations of 10% and 1% of the source term.

The wind speed estimate for this segment is that it will remain at 3 m/s during the whole plume dispersion period. Additionally, the assumption of static atmospheric stability class, F is maintained throughout the plume dispersion process.

6.2.1 Plume dispersion analysis for activity released at 10% source term activity release

Figure 24 represents the TED contours in Sv for the worst-case scenario before the fuel in the core is cooled. In this case, it can be noticed that at 100 km that the TED is 130 mSv, while at 200 km the TED is 63 mSv and finally at 300 km the TED is 41 mSv.

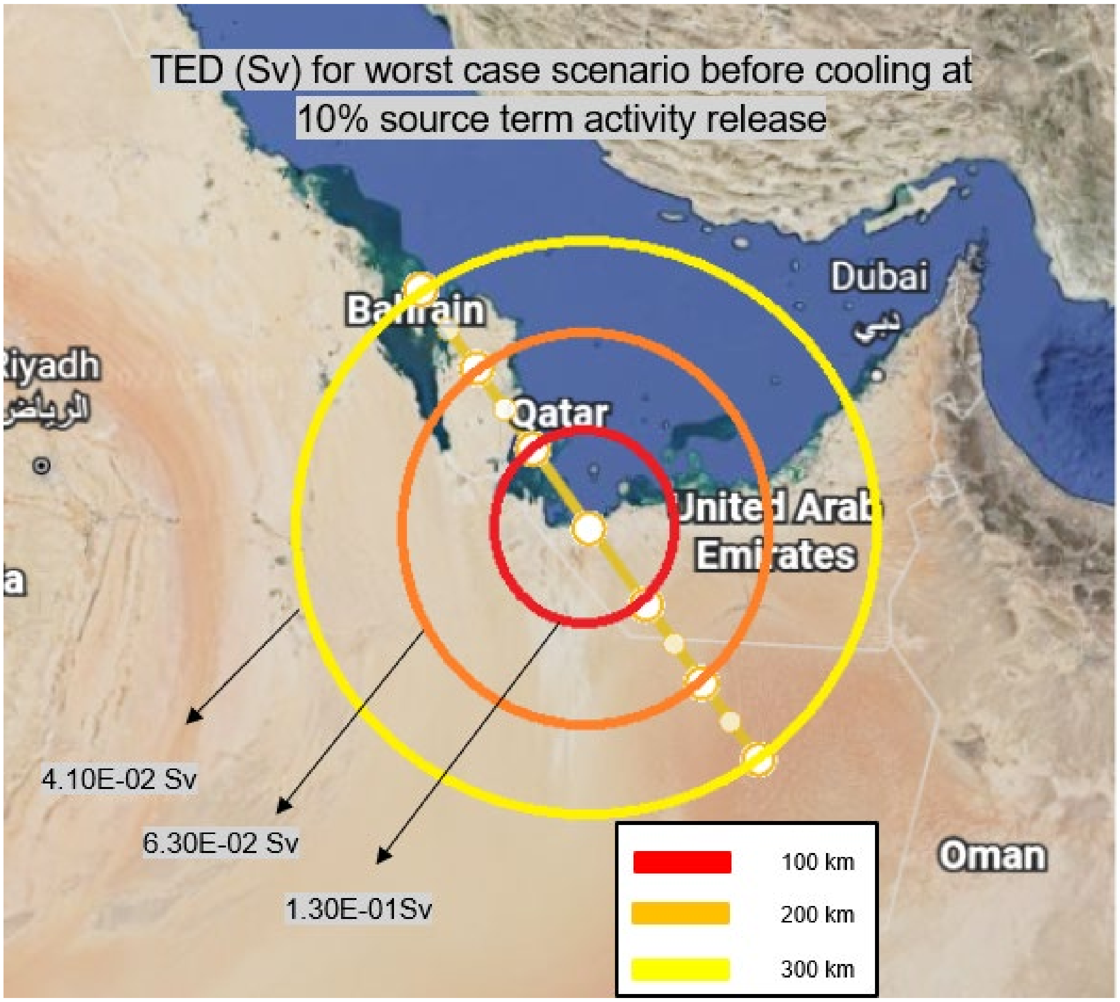

Fig. 24 Total Effective Dose (TED) in Sv for the worst-case scenario before the fuel is cooled in the core and for 10% source term activity release.

Figure 25 represents TED in Sv for the worst-case scenario after one year of cooling. In this case, at 100 km distance that the TED is 46 mSv, while at 200 km the TED is 23 mSv and finally at 300 km the TED is 15 mSv.

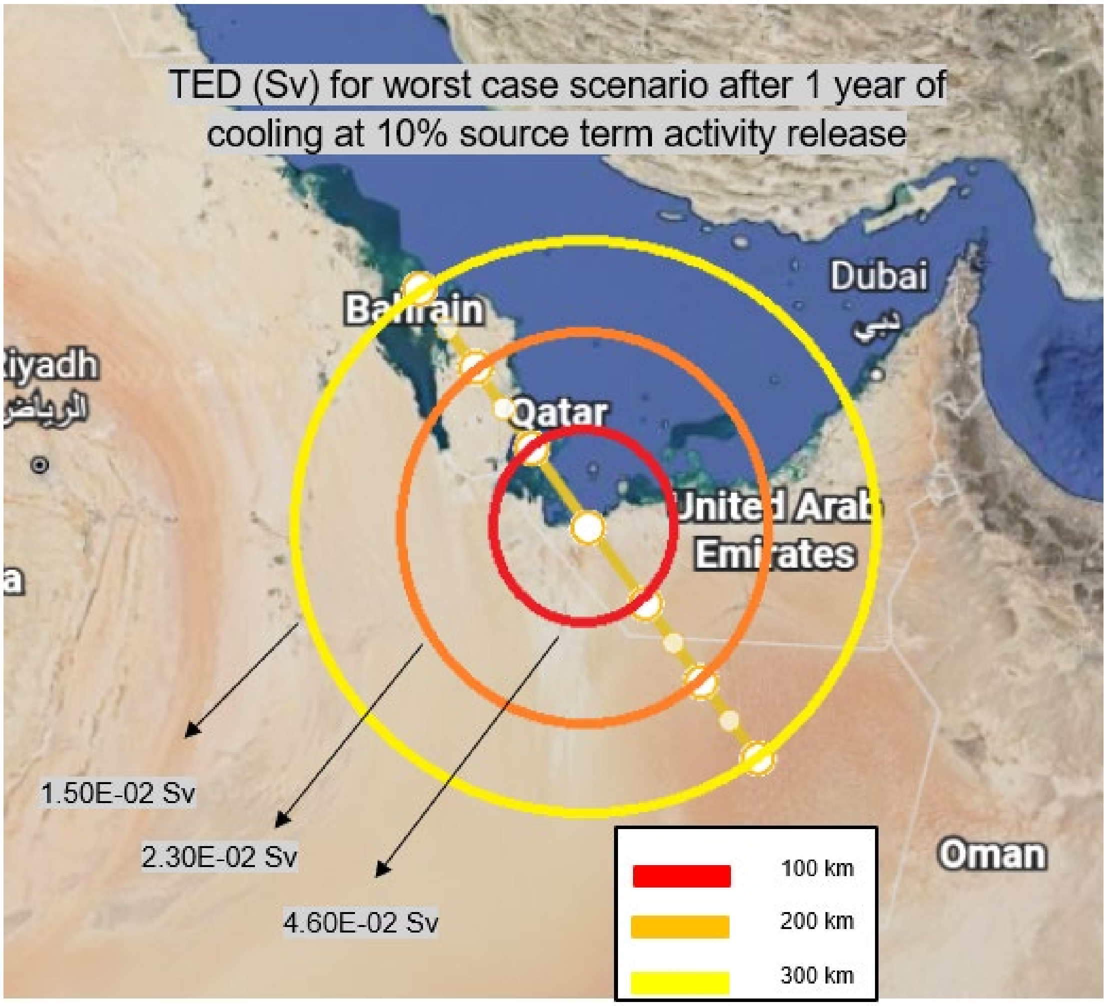

Fig. 25 Total Effective Dose (TED) in Sv for the worst-case scenario after the fuel is cooled for one year in the core and for 10% source term activity release.

6.2.2 Plume dispersion analysis for activity released at 1% source term activity release

Figure 26 represents the TED in Sv for the worst-case scenario before the fuel in the core is cooled. In this case, one can note that at 100 km distance that the TED is 13 mSv, while at 200 km the TED is 6.3 mSv and finally at 300 km the TED is 4.1 mSv.

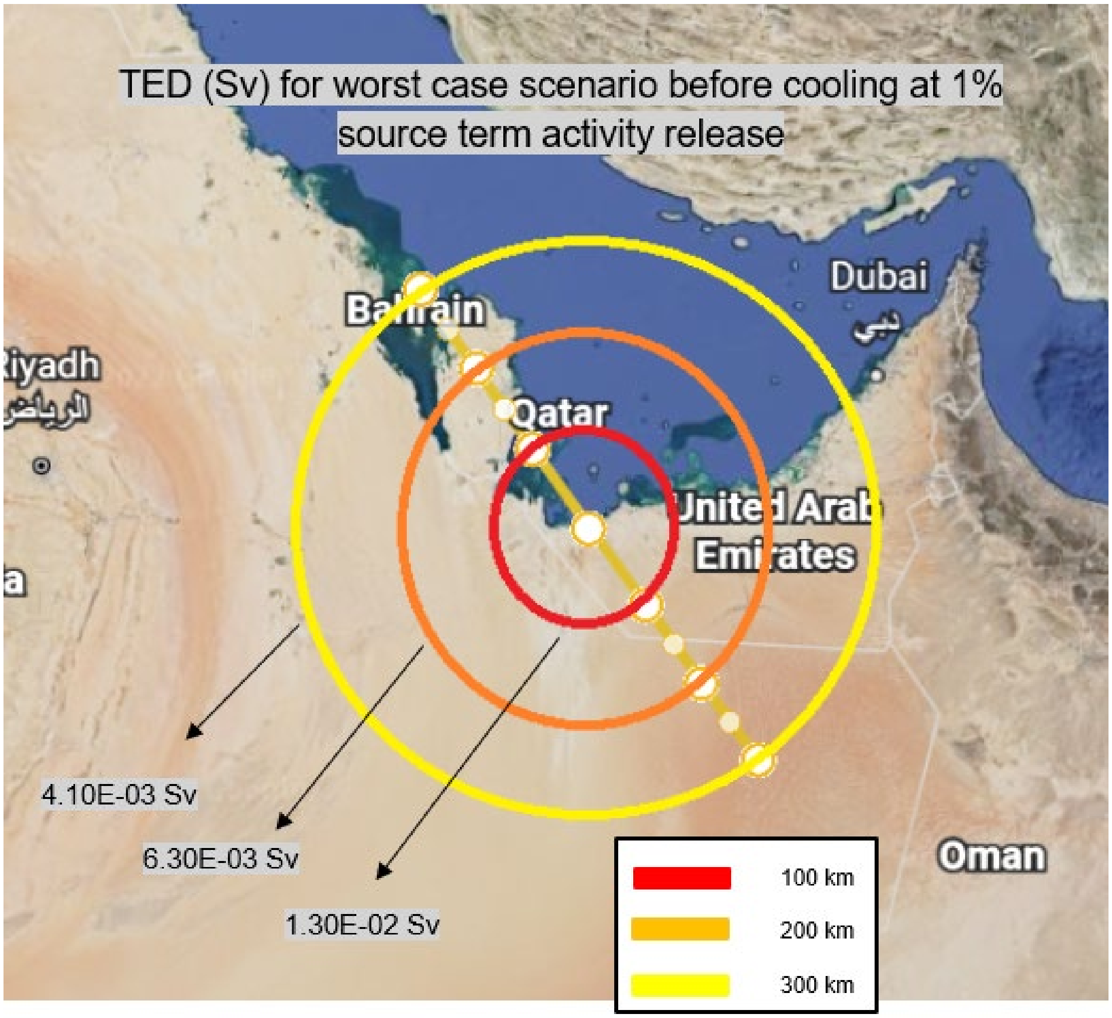

Fig. 26 Total Effective Dose (TED) in Sv for the worst-case scenario before the fuel is cooled in the core and for 1% source term activity release.

Figure 27 represents the TED in Sv for the worst-case scenario after one year of fuel cooling. In this case, it can be noticed that at 100 km distance that the TED is 4.6 mSv, while at 200 km the TED is 2.3 mSv and finally at 300 km the TED is 1.5 mSv.

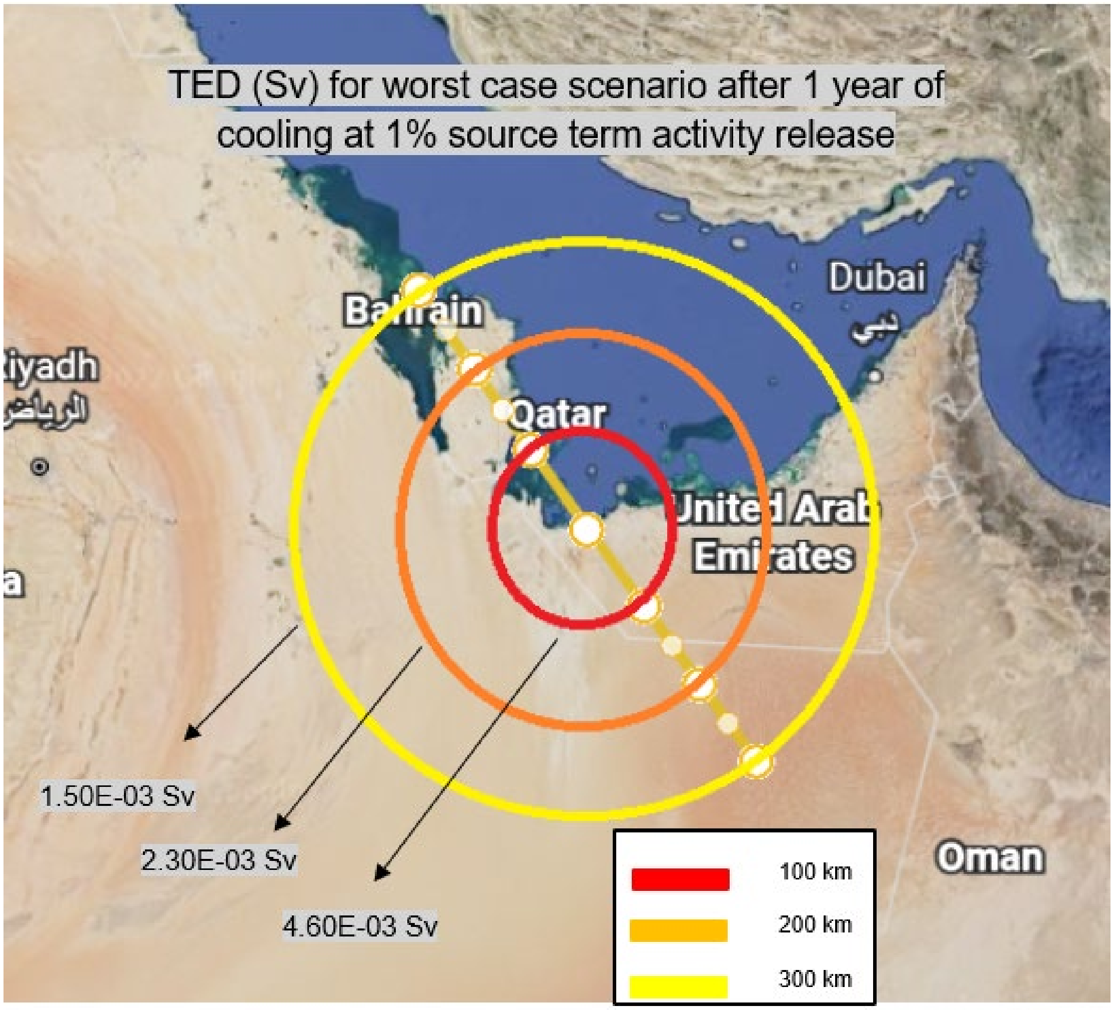

Fig. 27 Total Effective Dose (TED) in Sv for the worst-case scenario after the fuel is cooled for one year in the core and for 1% source term activity release.

7. SUMMARY AND CONCLUSIONS

7.1 Summary

The procedures used in this study to estimate TED due to hypothetical accidental release of radioactive materials from a nuclear reactor is illustrated in Fig. 28. First step was to estimate the radioactive source term of APR-1400 by performing fuel burnup simulation using MCNP code. Fractions at the level of 10% and 1% were released in multiple scenarios to estimate TED by performing radioactive material dispersion through the plume using the HOTSPOT code. Parameters such as meteorological and atmospheric conditions, land topography, and receptor locations were used in the HOTSPOT plume dispersion simulation.

The plume dispersion analysis in this study was divided into two categories: the most probable scenario and the worst-case scenario. This thesis covered both 10% and 1% of the source term released. Three atmospheric stability classes, A, C, and D have been studied for each scenario of radioactive activity release. Fuel burnup step 32 (fuel element irradiation without any cooling afterwards) and 35 (fuel element irradiated and one-year of cooling) have been covered for each atmospheric stability, as shown in fig. 29.

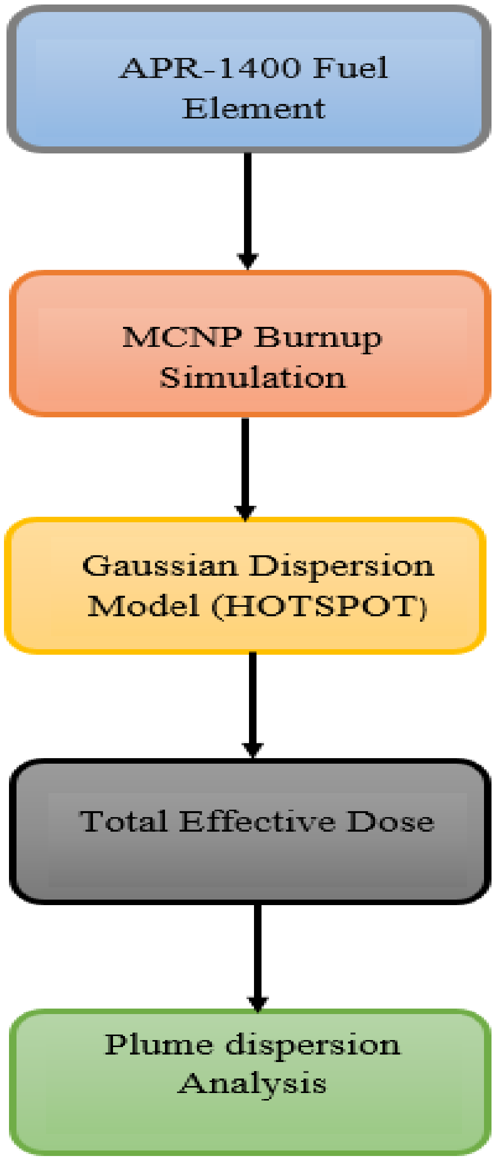

Fig. 28. Thesis procedures summary.

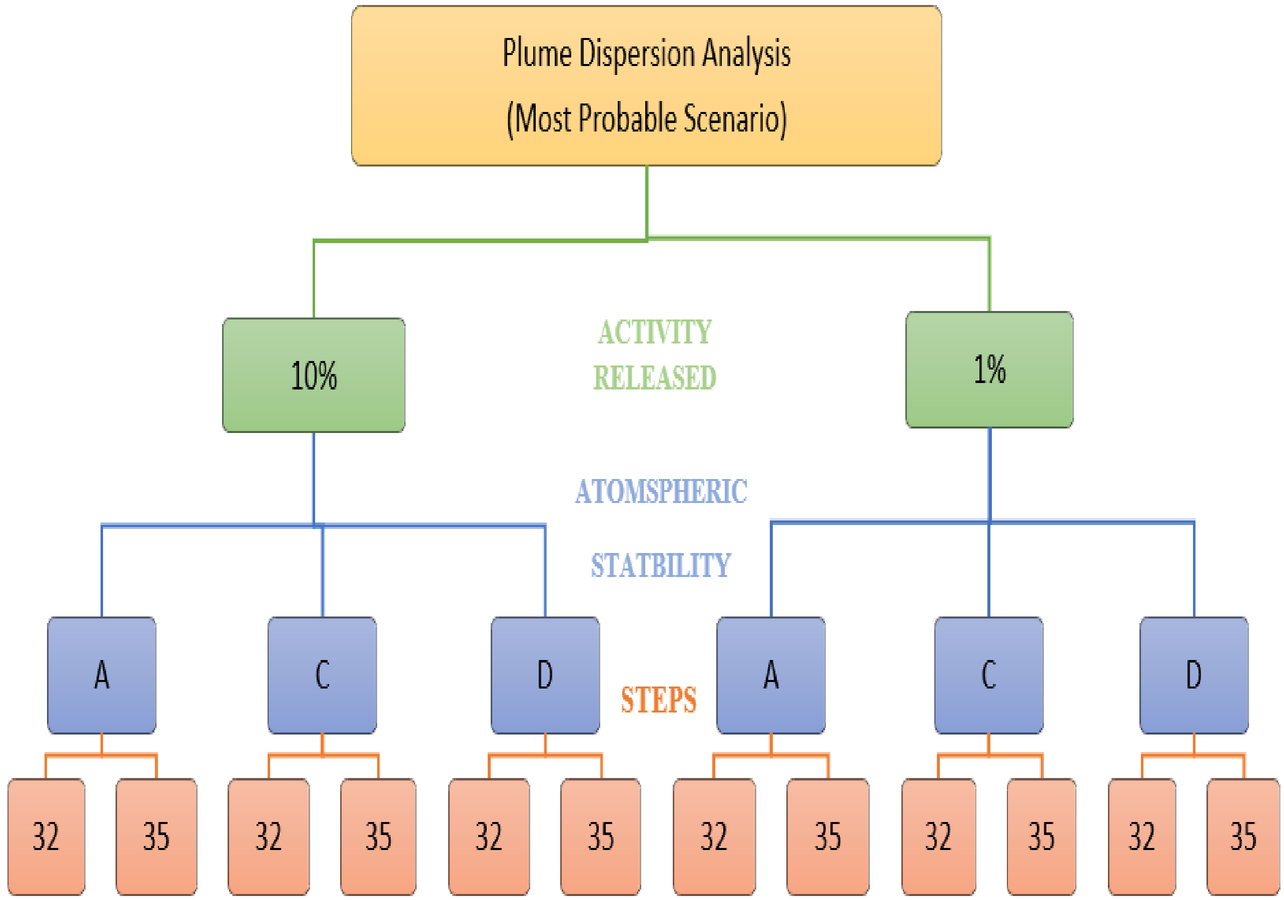

Fig. 29. Plume analysis summary flowchart (most probable scenario)

For the worst-case scenario also, this thesis covered both 10% and 1% source term released like the most probable scenario for comparison purposes. For each scenario of activity release, three atmospheric stability classes A, C and D has been analyzed. Both fuel burnup steps 32 (before cooling) and 35 (after one-year of cooling) were considered for each atmospheric stability class as shown in fig. 30.

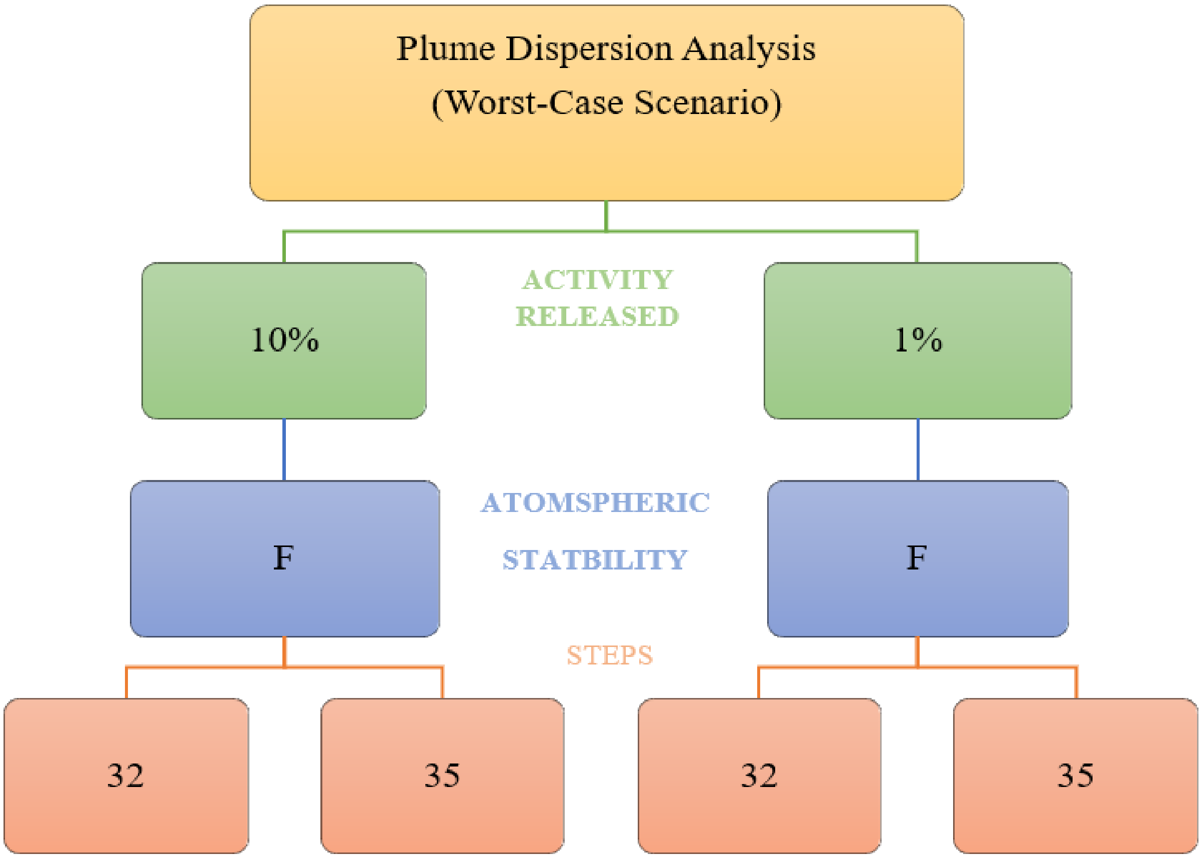

Fig. 30. Plume analysis summary flowchart (worst-case scenario)

Table 14 illustrates the estimated TED in the capital of the Kingdom of Bahrain. For both cases of 10% and 1% source term activity release, TED results for the most probable and worst-case scenarios for all covered atmospheric stabilities (A, C, D, and F) are shown. For both steps 32 and 35, we observed that the estimated TED at 1% source term activity release is one-tenth of the estimated TED at 10% source term activity release. This corresponds to the linear relationship between source activity and estimated TED.

Table 14 TED at Manama in Kingdom of Bahrain (300 km).

Percentage of source term activity released	Burnup Steps	TED at Manama in Kingdom of Bahrain (300 km) Sv			
		Most probable Scenario			Worst case Scenario
		Atmospheric Stability			
		A	C	D	F
10%	Step 32 (No cooling)	8.50E-06	2.50E-04	4.30E-03	4.10E-02
	Step 35 (1 year cooling)	3.10E-06	8.90E-05	1.60E-03	1.50E-02
1%	Step 32 (No cooling)	8.50E-07	2.50E-05	4.30E-04	4.10E-03
	Step 35 (1 year cooling)	3.10E-07	8.90E-06	1.60E-04	1.50E-03

7.2 conclusion

The main objective of this thesis research is to perform radiation dose assessments for the Kingdom of Bahrain and the countries of the Arabian Gulf region for the case of a large radioactive material release due to a hypothetical accident in a regional nuclear power plant. A radioactive release fraction of 10% and 1% of the nuclear reactor term were considered in the study to assess the radiation dose to members of the public in the Kingdom of Bahrain. The changes in wind speed, wind direction, and atmospheric stability are crucial in determining the coherence, length, and dispersion of the plume. It was seen in the study that the meteorological conditions are one of the most important factors, if not the most important.

Additionally, utilizing the HOSTPOT software, this study showed a linear relationship between source-term activity and TED. By knowing the proportion of source term leakage in the space for the same fuel element, it is possible to estimate the plume dispersion in this case without having to do separate research for each situation.

For the most probable scenario with a 10% of the nuclear source term activity released, for atmospheric stability classes from A, C, and D the radiation dose rates to the members of the public were calculated. The higher the letter, the more stable the situation. Before the fuel elements were cooled, the estimated TED ranged from 0.0085 mSv to 4.30 mSv. The maximum TED in this case is more than four times the permissible dose limit for public exposure, which is 1 mSv per year.

The highest estimated TED in the Kingdom of Bahrain was 41 mSv/year at 10% source term activity released when atmospheric stability was at its peak (Stability F), (see table 14). That is 41 times higher than the permissible dose limit for public exposure of 1 mSv/year, and nearly double the permissible dose limit for radiation workers per year, 20 mSv averaged over five years for a total of 100 mSv. An annual dose of 1000 mSv (1 Sv) may cause radiation sickness symptoms such as nausea and vomiting. A dose of 7000-10000 mSv (7-10 Sv), on the other hand, may result in death.

To obtain 41 mSv/year, I used a very conservative approach in the calculations in which all fuel pins are at maximum irradiation time, but in reality, the source term is predicted to be approximately 66% at any point in time, implying about 27 mSv/year, which is still higher than the public dose limit for a year (1 mSv). However, to bring this dose rate value to perspective, if 10000 members of the public received this amount of dose one in that group may develop cancer according to the radiation risk studies found in literature.

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APPENDIX

1. MCNP input file

```
Geometry: Fuel Pin Cell with Reflective Boundary (3.5% UO2)
C Cell Cards:
C Cell Number; Material Number; Material Density; Surface Pnemonic; Importance
10 1 -10.339  -100 201 -202              imp:n=1 vol=178.4758 $UO2 fuel
11 0          100 -101 201 -202          imp:n=1 $air gap
12 2 -6.3902   101 -102 201 -202         imp:n=1 $clad
30 3 -0.66163  102 201 -202 301 -302 401 -402 imp:n=1 $borated water
99 0          -201:202:-301:302:-401:402      imp:n=0 $outside pin cell

C Surface Cards:
c fuel pin
100 cz 0.39398
101 cz 0.40226
102 cz 0.45972
c
```

```
c pin cell, 366x1.26678x1.26678 cm3 (infinitely repeated structure)

201 pz -183

202 pz  183

*301 px -0.63339

*302 px  0.63339

*401 py -0.63339

*402 py  0.63339


C Data Cards:

C Physics information, Source information, Materials, Tallies

c Physics information

mode n

mphys

C KCODE    NPS/history | Initial keff Guess | #Cycles to Skip | Total #Cycles

  kcode      5000            1                  50            550

C KSRC (x1, y1, z1)  (x2, y2, z2)  ...  (xn, yn zn) -- neutron source points (in fissile material)

  ksrc  0 0  175  0 0  125

        0 0   75  0 0   25
```

```
    0 0  -25  0 0  -75
    0 0 -125  0 0 -175 $where to start neutron events
c KSRC points must occur in a cell with fissile content
c for continuations: comment out KSCR and use SRCTPE file ("read file=srctpe")
BURN TIME=0.3,0.3,0.4,1.0,3.0,25.0,40,40,40,40,40,40,40,
     40,40,40,40,40,40,40,40,40,40,40,40,40,40,40,
     40,40,40,40,1,29,335
    PFRAC=1.0,1.0,1.0,1.0,1.0,1.0,1.0,1.0,1.0,1.0,
       1.0,1.0,1.0,1.0,1.0,1.0,1.0,1.0,1.0,1.0,
       1.0,1.0,1.0,1.0,1.0,1.0,1.0,1.0,1.0,1.0,
       1.0,1.0,0.0,0.0,0.0
    POWER=0.06722
    MAT=1
    MATVOL=178.4758
    AFMIN=1E-10 1E-10
    BOPT=1.0 -24 1.0
c Materials:
c Fuel: 3.5 w/o U-235 UO2 (weight fractions)
```

```
m1    8016 -0.1185365983 $ 15.999 u
     92234 -0.0003468019 $ 234.040950 u,  0.04 w/o of Uranium
     92235 -0.0304752100 $ 235.043928 u,  3.50 w/o of Uranium
     92238 -0.8506413899 $ 238.050790 u, 96.46 w/o of Uranium
c
c Zircaloy (atom fractions)
m2   40090 5.01944E-01 40091 1.09462E-01
     40092 1.67315E-01
     40094 1.69558E-01 40096 2.73167E-02
     50112 1.18836E-04 50114 7.96322E-05 50115 4.41040E-05
     50116 1.78008E-03 50117 9.40884E-04 50118 2.96722E-03
     50119 1.05114E-03 50120 3.99263E-03 50122 5.67226E-04
     50123 7.09339E-04
     26054 2.16063E-04 26056 3.35887E-03 26057 7.69039E-05
     26058 1.02539E-05
     24050 9.49456E-05 24052 1.83095E-03 24053 2.07591E-04
     24054 5.16793E-05
      8016 5.39867E-03 6000 9.08126E-04
```

c Borated Water (weight fractions)

m3   1001 -0.111759

     5010 -2.56379E-04

     5011 -1.13465E-03

     8016 -0.886850

mt3 LWTR.01t $ S(a,B) treatment for molecular water and thermal neutrons