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Mathematical Modeling for Atmospheric Dispersion of Radioactive Cloud Passing Over Jeddah

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Abstract: Atmospheric dispersion has been performed for a hypothetical accidental airborne radionuclide release from any nuclear installation such as power reactor, research reactor or any facility which uses radioisotopes as its tools. Estimate of release for various radionuclides are based on U.S Nuclear Regulatory Commission (NRC 1.183). The normalized concentration distribution (NCD) of pollutants is calculated as a function of downwind horizontal distance up to 10 km from the release point. These estimates have been performed for Jeddah city (Kingdom of Saudi Arabia) using Gaussian Plume Model (GPM). The calculations have been evaluated for the atmospheric thermal stability class , B , (moderately unstable), which is, meteorologically, and according to Pasquill classification, the dominant stability category for Jeddah city. The computer program "Mathmatica" is used for this purpose.

Also, the effect of radioactive decay on The NCD of pollutants has been investigated. The relevant meteorological data, namely, atmospheric thermal stability class, mean wind speed and direction and their frequency of occurrence for Jeddah city have been analyzed and presented .

The results indicate that the NCD is significantly affected by the radioactive decay factor, particularly, in cases of short- lived isotopes, where It reduces the concentration of cloud by different ratios depending on the half- life time of a radionuclide.

Keywords: Atmospheric dispersion, radioactive cloud, pollutant.

Introduction

Atmospheric dispersion modeling for the release of radioactive gases and volatiles is an important contribution for various stages in the nuclear technology safety criteria. These stages are: Licensing requirements for the selection of nuclear reactor site, normal operating conditions stage, and finally, accidental release in case of reactor accident[1].

Under normal operating conditions, nuclear reactor, especially research reactor, do not release significant quantity of radioactive material to the atmosphere. However, under accidental conditions with severe core damage, a significant fraction of the radionuclide inventory in the core may be released to the atmosphere. An earlier document, WASH-1400[2] used release fraction of 0.9, 0.7, 0.4 and 0.05 for noble gases, halogens, alkali metals, tellurium and the Ba-Sr group, respectively.

An IAEA document on research reactors used 100%, 50% and 1% release fractions for noble gases, halogens and particulates, respectively[3].

The potential damage from a nuclear power reactor (or even research reactor) is initiated in case of accident occurring, and the radioactive cloud diffuse and transport in the atmosphere and finally, the dramatic exposure of public to radiation. The area - on the ground surface or in the atmosphere - which is affected by the radioactive release is determined by various factors[4]: amount of radiation released (source strength), wind direction and speed, weather conditions (particularly, atmospheric thermal stability states) and the physical characteristics of radioactive material released (half-life time and its deposition velocity).

In fact, the formulation of emergency plans and controlling of air quality are based on the possible scenarios of pollution concentrations both in air and on ground surface, which require some tools able to predict and foresee the consequences of the nuclear accident on the environment. These tools are the mathematical models of atmospheric dispersion. Thus, only with the mathematical modeling, it is possible to forecast and simulate concentration fields of contaminants in accidents in accordance with action plans ensuring safety to the population. In this concern, we can say that, models are instruments for control strategies and pollutants emissions.

In this frame, Gaussian Plume Model (GPM) is one of the most important and widespread atmospheric dispersion model in nuclear accident assessments to predict the radiological consequences to the public[5].

In this work, we have applied GPM to calculate the diffusion and transport of the radioactive cloud during its path from its point of emission up to its final fate. Some modifications have been performed in GPM in order to investigate the effect of the most important physical phenomena's, radioactive decay.

Also this study include meteorological and climatological characteristics and condition for the region on which plume disperse , Jeddah city . The most important meteorological concepts (that were used in the GPM), namely, atmospheric thermal stability classes for Jeddah city [6] have been calculated and presented.

The main objectives of this work are the pollutants concentration calculations all - over- the distance from the source (assumed position) to the receptor and studying the effect of variation of atmospheric thermal stability classes on the plume rise and ground level concentration values at different positions.

Meteorological Data

The study area chosen is Jeddah city which is located on the east coast of Kingdom of Saudi Arabia at 21.7°N and 39.2°E. Since the atmospheric conditions are a driving force in the dispersion and transport of pollutant plumes, the meteorological data for the city, required for this modeling were obtained from National Meteorology and Environment Center for one year (2008) [7]. Table1 shows the average meteorological and climatological data per month that used to determine the atmospheric stability classes for Jeddah city .

Atmospheric Stability

Pasquill's stability classification method [8] is used to determine atmospheric stability classes. This method defines six stability classes ranging from A (extremely unstable) to F(moderately stable) on the basis of wind speed at 10 m level, amount of incoming solar radiation during the day and cloud cover at night (Table 1). Analysis of one typical year of the meteorological and climatological characteristics show that the atmospheric thermal stability class of the region is the class B (moderately unstable) . Table 2 shows the repetition of stability classes in one year depending on Pasquill's stability classification method and their percentage. It is clear that; class B is the dominant stability class for Jeddah city most of the year.

Table 1. The average meteorological and climatological data for Jeddah city per month.

Month	Temperature (deg.c)	Mean wind speed at elevation: 10 m	Pre. Direction.	Sky cover oktes mean
January	23	2.8	NNE	3.3
February	24.4	3.2	N	1.1
March	26.8	2.4	SW	0.95
April	29.2	2.8	N	2.4
May	30	2.8	N	2.45
June	31.7	2.4	W	1.15
July	33.4	2.4	N	1.25
August	32.9	2.8	NNW	1.25
September	32.3	2.4	NNW	2.35
October	29.9	2.4	N	0.65
November	27.6	2.4	N	1.7
December	25.8	2.8	ENE	1.2

Table 2. Thermal stability classes for Jeddah city for 2008.

Stability class	Repetition	Percentage
A	29	16.47
B	67	38.07
C	38	21.6
D	15	8.52
E	15	8.52
F	12	6.82
sum	176	100

Wind Speed

Analysis of wind data indicates that the predominant wind direction is North (N) and the mean wind speed at 10 m is 2.4 m/s.

Dispersion Model

Analytical solution of diffusion equation was the first and remains the easiest way for modeling air pollution . The Gaussian Plume Model (GPM) is the most widely used dispersion model, it is recognized to be a simple analytic approximation to a complex solution of the non-linear equation of turbulent motion.

The concentration distribution of a pollutant released from a continuous single point source having emission rates *Q*, is expressed in the following formula[5]:

$$\chi(x,y,z)=\frac{Q}{2\pi \vec{u}\,\sigma_y\sigma_z}\times \exp\left[\frac{-y^2}{2\sigma_y^2}\right]\left[\exp\left[-\frac{(Z-H)^2}{2\sigma_z^2}\right]+\exp\left[-\frac{(Z+H)^2}{2\sigma_z^2}\right]\right] \quad (1)$$

where;

χ = the concentration of pollutants in ($Bq.s^{-3}$).

Q = the emission rate in (*Bq*),

H = the effective stack height in (*m*),

u = the mean wind speed (*m/s*), and

σ_y, σ_z = the dispersion parameters in (*m*),

The ground level concentration (glc) below the centerline of the plume is obtained by setting *y=z=0* in Eq.(1), then we have:

$$\chi(x,0,0)=\frac{Q}{\pi u\sigma_y\sigma_z}\exp\left[\frac{-H^2}{2\sigma_z^2}\right] \quad (2)$$

The normalized concentration is defined as:

$$\chi_n = \frac{\chi}{Q} \quad (3)$$

in our treatment, we deal with the general case where plume rise Δh is varying with downwind distance *x*, and consequently *H*[9].

$$H = h_s + \Delta h$$

Dispersion parameters of Gaussian model σ_y, σ_z could be expressed as function of downwind distance *x* and atmospheric stability[9];

$$\sigma_y = a\,x^b \qquad and \qquad \sigma_z = c\,x^d \quad (4)$$

where the coefficients *a, b, c,* and *d* depend on the atmospheric stability.

Radioactive Decay Factor

In case of short lived radionuclides, the corrected concentration can be obtained by multiplying the initial source strength *Q*, by the following depletion factor [5]:

$$F\left(\frac{x}{u}\right) = \exp(-\lambda t) = \exp\left(-\lambda \frac{x}{u}\right) \quad (5)$$

where λ is the radioactive decay constant of the radionuclide, and t is the time of travel of the cloud in (*s*)

Source Term and Accident Scenario

It was assumed that the radioactive plume passing over Jeddah city has been emitted in accidental conditions from a nuclear power plant with the following source and release characteristics:

a) The reactor is assumed to operate on continuous basis at its full power of 10 MW to achieve an average burn - up of 21% at the time of accident [10]. This assumption led to maximum possible fission products inventory in the core, which was 3.17×10^{17} Bq.

b) The release scenario is assumed to occur at a stack height of 61m and the external stack diameter was 3m . The radionuclides released from the core are assumed to be mixed within the containment free volume and escaped from the building through the ventilation system at an air exhaust rate of 25000 m^3/h [11].

c) The radionuclide activity released to the atmosphere is immediately picked up by the wind and transported downwind according to the receptor site (which is Jeddah city) meteorology.

Meteorological data of Jeddah city have been mentioned above and listed as:

- The wind is blowing with a mean speed of *4.95 m/s* at *61*m height and *2.4m/s* at *10m* height.
- The predominant wind direction is the North (N) direction.
- The dominant stability class through the data collected for one year duration the class B (moderately unstable) (Table 2). The dispersion parameters (standard deviations coefficients) relevant to class B have been used for dispersion calculation.

Results and Conclusions

Calculation of dispersion parameters as a function of downwind distance was illustrated in Fig. 1.2 by using Eq. (4). The normalized concentration distribution of pollutant from a single release was calculated by using Eq. (3) as a function of downwind distance up to 10 km for atmospheric stability class (Pasquill B) by using Mathematica 5.1. The pollutant would be received by a person at ground level who remained within the plume for the entire duration of cloud passage. As the release occurs at 61m stack height, the plume first increases with distance, reaches a maximum values and then decrease as shown in Fig. 3. Concentration values for any pollutant depend on, thermal stability class of the site under consideration and on the type of the radioactive pollutant and it's life-time.

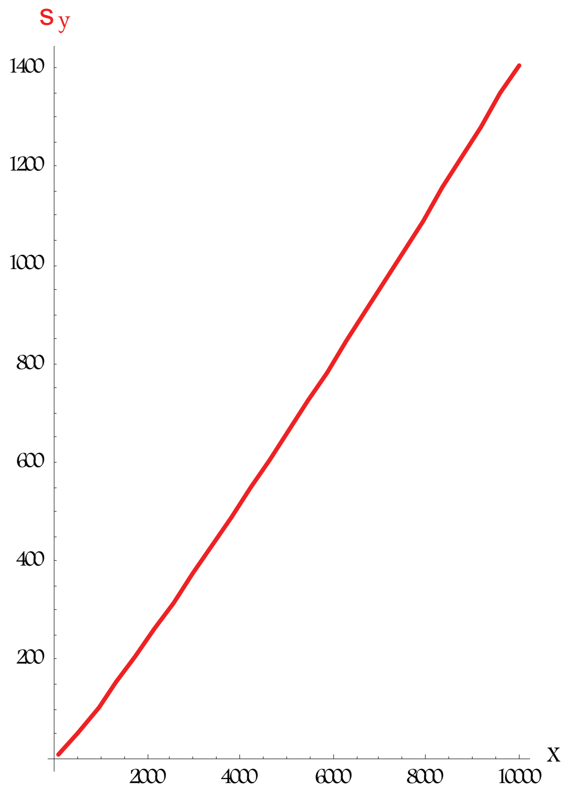

Fig. 1. Horizontal dispersion parameter as a function of downwind distance from the source.

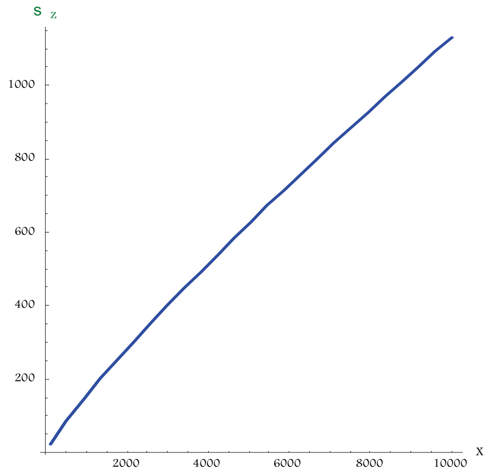

Fig.2. Vertical dispersion parameter as a function of downwind distance from the source.

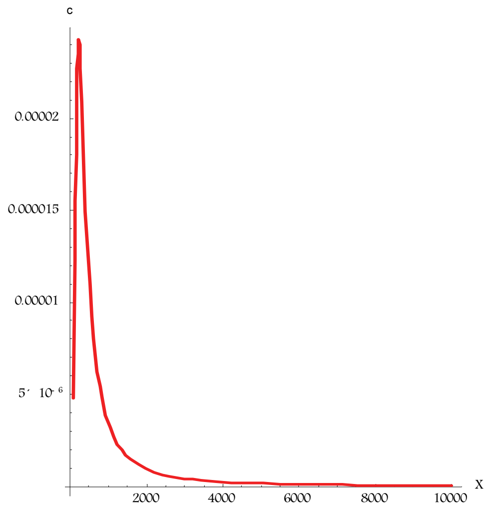

Fig. 3. The normalized concentration pollutant χ as a function of downwind distance x.

The effect of radioactive decay on the normalized concentration distribution of pollutant from a single release has been calculated by multiplying the glc by Eq. (5) . Also the factor of the life-time of the released radioactive nuclides has been investigated by calculating the dispersion of 12 different radioactive isotopes (Table.3). These predictions are performed in the downwind direction up to 10 Km with 100 m step for vary life- time isotopes.

Table 3. Half - life for different radionuclides released to the environment.

Radionuclide	Half-life
Rb-88	18 min
I-134	52.5 min
Kr-85m	4.5 h
Xe-135	9.1 h
Te-131	30 h
Xe-133	5.2 d
Ba-140	12.8 d
Sr-89	50 d
Ce-144	285 d
Cs-134	754 d
Kr-85	10.7 yr
Sr- 90	29 yr

A comparison of the normalized concentration distribution of a radioactive pollutant from a single release – we choose 5 different life-time radionuclides – is made, with that computed from a standard GPM, we found that radioactive decay effect is clear in cases of short lived isotopes. It reduces the concentrations of the cloud as shown in Figs. 4-8. Also, it is clear from Table 4 that the concentration was reduce by 75% in Rb-88 radionuclide, 50% in I-134 and by 25% in Kr-85m, while it was reduced by 0.01% in Sr-89 and 0.00001 in Kr-85. This indicates that, corrections of depletion of the plume through radioactive decay are very important to be accounted for when dealing with short-lived isotopes.

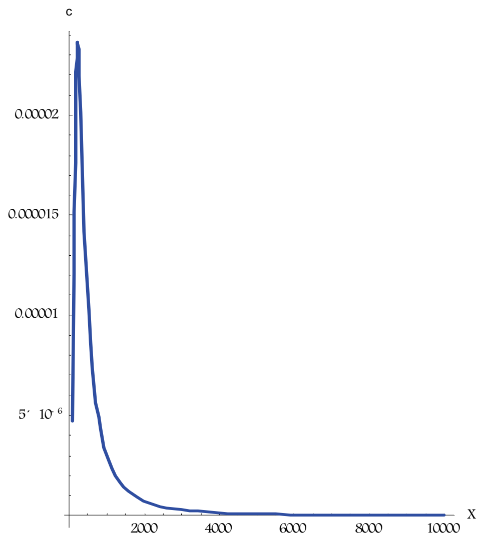

Fig. 4. Radioactive decay effect on the normalized concentration χ for (Rb-88) nuclide.

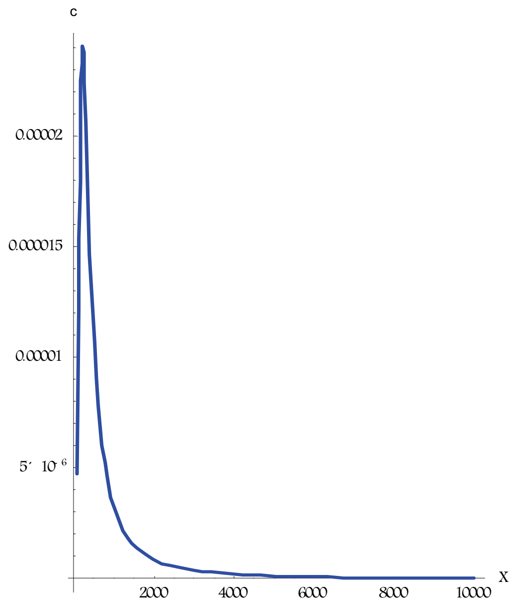

Fig. 5. . Radioactive decay effect on the normalized concentration χ for (I-134) nuclide.

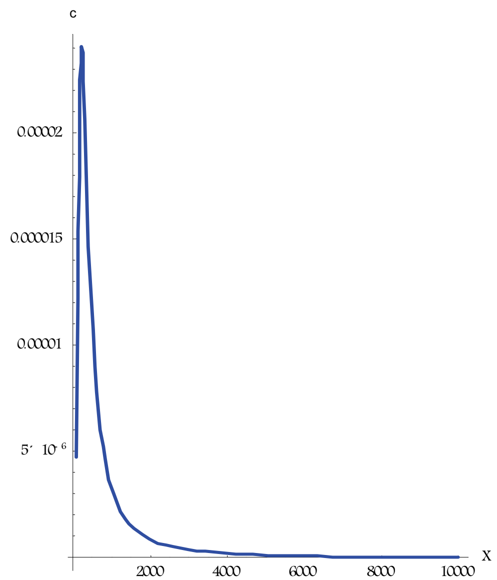

Fig. 6. Radioactive decay effect on the normalized concentration χ for (Kr-85m) nuclide.

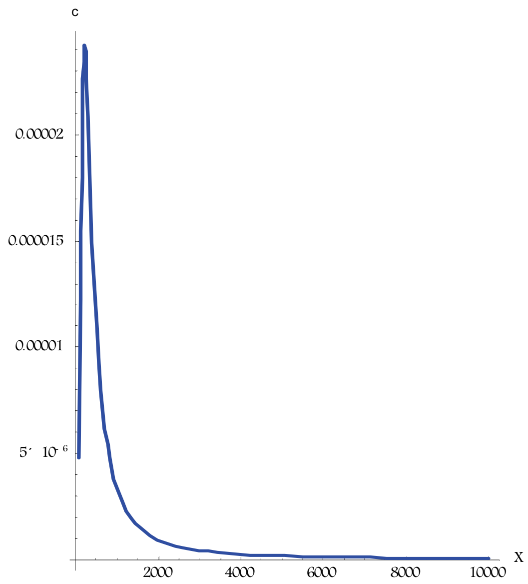

Fig. 7. Radioactive decay effect on the normalized concentration χ for (Sr-98) nuclide.

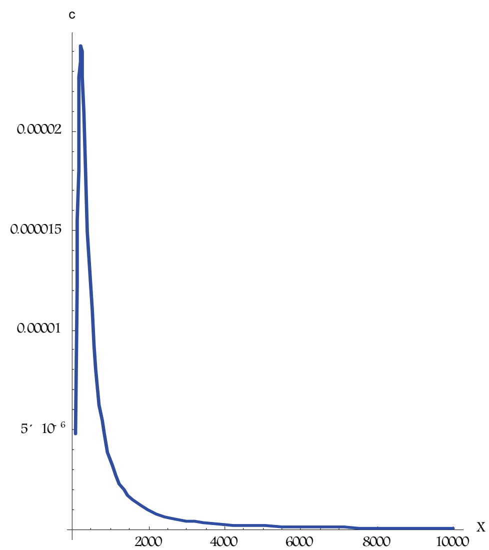

Fig. 8. Radioactive decay effect on the normalized concentration χ for (Kr-85) nuclide.

Table 4. Normalized concentration distribution (NCD) calculations before and after inserting decay factor for different radionuclides.

Distance (km)	NCD (before decay)	NCD (Rb-88) (18 min)	NCD (I -134) (52.5 min)	NCD (Kr-85m) (4.5h)	NCD (Sr-89) (50 d)	NCD (Kr-85) (10.7y)
1	3.41145×10^{-6}	2.99594×10^{-6}	3.2622×10^{-6}	3.38204×10^{-6}	3.41134×10^{-6}	3.41145×10^{-6}
2	9.27778×10^{-7}	7.15538×10^{-7}	8.48371×10^{-7}	9.11851×10^{-7}	9.27717×10^{-7}	9.27777×10^{-7}
3	4.24299×10^{-7}	2.87379×10^{-7}	3.7101×10^{-7}	4.1342×10^{-7}	4.24258×10^{-7}	4.24298×10^{-7}
4	2.42588×10^{-7}	1.44294×10^{-7}	2.0284×10^{-7}	2.34331×10^{-7}	2.42556×10^{-7}	2.42588×10^{-7}
5	1.57022×10^{-7}	8.20223×10^{-8}	1.25549×10^{-7}	1.50369×10^{-7}	1.56996×10^{-7}	1.57021×10^{-7}
6	1.09992×10^{-7}	5.04576×10^{-8}	8.4098×10^{-8}	1.04424×10^{-7}	1.0997×10^{-7}	1.09991×10^{-7}
7	8.13804×10^{-8}	3.27855×10^{-8}	5.95×10^{-8}	7.65948×10^{-8}	8.13619×10^{-8}	8.13802×10^{-8}
8	6.26773×10^{-8}	2.21751×10^{-8}	4.38206×10^{-8}	5.8483×10^{-8}	6.2661×10^{-8}	6.26771×10^{-8}
9	4.97773×10^{-8}	1.54661×10^{-8}	3.32791×10^{-8}	4.60459×10^{-8}	4.97628×10^{-8}	4.97772×10^{-8}
10	4.05024×10^{-8}	1.10516×10^{-8}	2.58935×10^{-8}	3.71432×10^{-8}	4.04892×10^{-8}	4.05022×10^{-8}

* The highlighted cells shows the decreases in concentration due to decay factor.

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References

[1] **IAEA,** Information to be submitted in support of licensing application for nuclear power plants, A safety guide, technical report series No. 50-SG-G2, Vienna, (1979).

[2] **Nuclear Regulatory Commission (NRC),** Reactor safety study: An assessment of accident risk in US commercial nuclear power plants, WASH-1400, NUREG-75/014, (1975).

[3] **IAEA,** Research reactor core conversion guide book, IAEA-TECDOC-643, Vienna, (1992).

[4] **Davidson Moreira, M., Tiziano Tirabassi, Marco Vilhena, T., Jonas Carvalho, C.,** A semi- analytical model for the tritium dispersion simulation in the PBL from the Angra I nuclear power plant, *Ecological Modeling,* **189**: (2005).

[5] **Denis Quelo, Bruno Sportisse,** and **Olivier Isnard,** Data assimilation for short range atmospheric dispersion: a case study of second-order sensitivity. *Journal of Environmental Radioactivity,* **84**: (2005).

[6] **Zheng, D.Q.; Leung, J.K.C.; Lee, B.Y.** and **Lam, H.Y.,** Data assimilation in the atmospheric dispersion model for nuclear accident assessment, *Atmospheric Environment,* **41**: 2438 (2007).

[7] **Surface Monthly Climatological Report,** National Meteorology and Environment Center, Presidency of meteorology and environment protection, (2008).

[8] **Pasquill, F.,** Atmospheric Diffusion, Van Nostrand, New York, London (1962).

[9] **Apismon, H.M.** and **Goddard, A.J.H.,** Atmospheric transport of radioisotopes and the assessment of population doses on European scale, CEC Luxembourg EUR-9128 (1984).

[10] **Srinivas, C.V.** and **Venkatesan, R.,** A simulation study of dispersion of air borne radionuclides from a nuclear power plant under a hypothetical accidental scenario at a tropical coastal site, *Atmospheric Environment,* **39**: 1497 (2005).

[11] **Shoaib Raza, S.** and **Iqbal, M.**, Atmospheric dispersion modeling for an accidental release from the Pakistan research reactor-1(PARR-1), Annals of nuclear energy, **32**: 1157 (2005).

نمذجة رياضية لانتشار الملوثات المشعة الناتجة عن مرور سحابة إشعاعية في أجواء مدينة جدة

نجلاء دخيل الله الحربي

كلية العلوم للبنات – جامعة الملك عبدالعزيز – المملكة العربية السعودية

المستخلص: هذه الدراسة تندرج تحت مفهوم التلوث الإشعاعي الناشئ عن وقوع حادث إشعاعي أو انطلاق سحابة مشعة ناشئة عن العمل الروتيني لأي منشأة تعمل إما بالطاقة النووية أو تستخدم المواد المشعة كأحد أدوات عملها.

في هذه الدراسة قمنا باستخدام أحد النماذج الرياضية الشهيرة واسعة الاستخدام على مستوى عالمي وذلك لحساب تشتت وانتشار وانتقال السحابة المشعة من موضع انطلاقها وحتى مصيرها الأخير. هذا النموذج هو: " نموذج جاوس للسحابة ". وقمنا بتعديل في بعض صيغه الرياضية لكي يتضمن أهم العمليات الفيزيائية التي تواجهها السحابة المشعة أثناء حركتها ونعني عملية التحلل الإشعاعي.

تتضمن هذه الدراسة الخصائص الأرصادية والمناخية للمنطقة التي تنتقل وتمر في أجوائها السحابة الإشعاعية قيد الدراسة، وهي هنا مدينة جدة. وتم حساب أهم الخصائص الأرصادية المطلوبة لاستكمال البيانات اللازمة لتطبيق نموذج جاوس حيث تم حساب درجات الاستقرار الحراري الجوي لمدينة جدة المتوقع مرور السحابة المشعة في أجوائها.

في هذه الدراسة تم حساب تركيز الملوث المشع في الهواء الجوي وعلى سطح الأرض بدءاً من موضع انطلاق السحابة وحتى وصولها للمتلقي مع الأخذ في الاعتبار تأثير درجات الاستقرار

الحراري الجوي المختلفة على مدار العام على كل من تصاعد السحابة وقيم التركيز كدالة في الموضع. أيضا تم دراسة تأثير معامل الاضمحلال الإشعاعي على تركيز الملوثات المشعة حيث أظهرت الدراسة أن تركيز الملوثات المشعة انخفض بنسب مختلفة تبعا لفترة نصف العمر للأنوية ويظهر هذا جلياً في الملوثات المشعة ذات فترات نصف عمر قصيرة.