

ISTANBUL TECHNICAL UNIVERSITY ★ ENERGY INSTITUTE

**ATMOSPHERIC DISPERSION AND CORRESPONDING DOSE AND RISK
CALCULATIONS FOR A HYPOTHETICAL ACCIDENT IN
ITU TRIGA MARK II RESEARCH REACTOR**



M.Sc. THESIS

Sefa BEKTAŞ

Energy Science and Technology Division

Energy Science and Technology Programme

JUNE 2020

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ ENERJİ ENSTİTÜSÜ

**İTÜ TRIGA MARK II ARAŞTIRMA REAKTÖRÜNDEKİ
HİPOTETİK BİR KAZA İÇİN ATMOSFERİK DAĞILIM VE
İLİNTİLİ DOZ VE RİSK HESAPLAMALARI**

YÜKSEK LİSANS TEZİ

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To my Family and COVID-19 pandemic fighters,



FOREWORD

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ABBREVIATIONS

ABL	: Atmospheric Boundary Layer
ARL	: Air Research Laboratory
ASOS	: Automated Surface Observing System
BWR	: Boiling Water Reactor
CAC	: Codex Alimentarius Commission
CAPTEX	: Cross-Appalachian Tracer Experiment
CODEX	: Codex Alimentarius International Food Standards
DBA	: Design Basis Accident
DCAL	: Dose and Risk Calculation Software
DCF	: Dose Conversion Factor
DOE	: U.S. Department of Energy
ECMWF	: European Centre for Medium-Range Weather Forecasts
FGR	: Federal Guidance Report
FSAR	: Final Safety Analysis Report
FTP	: File Transfer Protocol
GAR	: Safety Analysis Report
GUI	: Graphical User Interface
HTTP	: Hyper-Text Transfer Protocol
HYSPLIT	: Hybrid Single Particle Lagrangian Integrated Trajectory
IAEA	: International Atomic Energy Agency
INES	: International Nuclear and Radiological Event Scale
KJRR	: Ki-Jang research reactor
MCNP	: Monte Carlo Code
NetCDF	: Network Common Data Form
NOAA	: National Oceanic and Atmospheric Administration
NPP	: Nuclear Power Plant
NRA JAPAN	: Japan Nuclear Regulation Authority
NRC	: United States Nuclear Regulatory Commission
PWR	: Pressurized Water Reactor
RH	: Relative Humidity
TIBL	: Thermal Internal Boundary Layer
TRIGA	: Training, Research, Isotopes, General Atomics
TSV	: Total Spatial Variance
STE	: Stratosphere-Troposphere Exchange
USEPA	: U.S. Environmental Protection Agency
USEPR	: U.S. European Pressurized Reactor



SYMBOLS

A	: Pasquill stability class
$\alpha_{p,i}$	: Activity concentration in tap water, Bq/L
α_x	: Dispersivity in x-direction, m
α_y	: Dispersivity in y-direction, m
α_z	: Dispersivity in z-direction, m
B	: Pasquill stability class
Bq	: Becquerel, disintegration/second
b	: Aquifer thickness, m
β	: The converted mass fraction
β_{decay}	: Decay time constant, s ⁻¹
β_{dry}	: Time constant for dry deposition, s ⁻¹
β_{rad}	: Decay constant, s ⁻¹
β_{wet}	: Time constant for wet deposition, s ⁻¹
C	: Pasquill stability class
C_{avg}	: Activity concentration, Bq m ³
C_d	: Risk coefficient of daughter radionuclide
C_p	: Risk coefficient of parent radionuclide
c	: Concentration of pollutant as a function of x, y, z, and t, kg/(m ³ t)
c'	: Fluctuation of pollutant concentration as a function of x, y, z, and t kg/(m ³ t)
D	: Molecular diffusivity constant, m ² /s and Pasquill stability class
D_L	: Dilution
D_{total}	: Total deposition
$d\mu$	: Random velocity frequency between time interval lag Δt
E	: Pasquill stability class, powers of ten
η	: Surface that calculation is starting from there
F	: Soil to plant transfer factor
F_v	: Pasquill stability class
$f_{p \rightarrow d}$	: Fraction yield of daughter nuclide
G	: Pasquill stability class
H	: Mixing height, m and Pasquill stability class
h_L	: Top of the ABL, m
h_p	: Effective emission height of effluent, m
K	: (3x3) turbulent diffusivity tensor and mean hydraulic conductivity, cm s ⁻¹
K_d	: Distribution coefficient, mL g ⁻¹
K_x	: Diffusivity in x-direction, m ² /s
K_y	: Diffusivity in y-direction, m ² /s
K_z	: Diffusivity in z-direction, m ² /s
k	: Outflow or loss rate
k_{eff}	: Effective loss, s ⁻¹
k_p	: Physical loss, s ⁻¹

k_w	: Weathering loss, s^{-1}
χ	: Concentration of pollutant as a function of x, y, z , and t , $kg/(m^3 \cdot t)$
L	: Length of the box, m
λ	: Decay constant, s^{-1}
M_1	: Original mass
M_r	: Removal mass
m	: A variable that varies with atmospheric stability and the surface roughness
n_e	: Effective porosity
Q	: Total amount of pollutants released, kg/m^3 and flow rate, $m^3 s^{-1}$
Q'	: Pollutants releasing rate, $kg/(m^3 \cdot t)$
q	: Tracer amount
P	: Initial position, m
p	: Probability function
P_a	: expression allowing for chemical change of the pollutant, a , through possible interaction with other pollutants and the solar radiation field (in the case of photochemical smog), kg/t
P_{final}	: Adjusted position, m
P_{mean}	: Position comes from advection and the horizontal turbulent velocity component, m
ϕ	: Characterization factor
π	: Pi number
R	: Autocorrelation vector or Conversion rate, s^{-1} and inflow rate and daily intake rate, $m^3 L^{-1}$
R_d	: Retardation coefficient
ρ_b	: Bulk density, $g cm^{-3}$
rem	: Roentgen Equivalent Man
S	: Source field for the pollutant, (x, y, z, t) , $kg/(m^3 \cdot t)$
S_a	: Source field for the pollutant, a , as a function of (x, y, z, t) , kg/t
σ	: Standard deviation of the Gaussian distribution
σ_x	: Standard deviation of the Gaussian distribution in x-direction
σ_y	: Standard deviation of the Gaussian distribution in y-direction
σ_z	: Standard deviation of the Gaussian distribution in z-direction
σ_r	: Standard deviation of the Gaussian distribution both in radial x- and y-direction
Sv	: Sievert
T	: Temperature, K
t	: Time, s
T_L	: Lagrangian time scale
T_{Li}	: Lagrangian time scale
u	: Wind speed at height z , m/s
u_e	: Pseudo velocity, m/s
U	: Pore velocity, m/s
U_{max}	: Maximum transport velocity, m/s
u_1	: Wind speed at reference height z_1 , m/s
$\bar{u}$	: Stable component of the velocity, m/s
U'	: Previous turbulent velocity component, m/s
u'	: Remaining unstable component of the velocity, m/s
u''	: Purely stochastic term of velocity components, m/s
U''	: Computer-generated random component of velocity, m/s

x	: Cartesian coordinate, m
V	: Volume of the elemental “box”, m^3
V_d	: Dry deposition velocity, m/s
V_T	: Source volume, m^3
W	: Width of the box L length of the box, m; Watt, $kg.m^2/s^3$
w	: Vertical turbulent velocity, m/s
w_d	: Deterministic velocity, m/s
w_s	: Stochastic velocity, m/s
$w\eta$	: Computed velocity, m/s
Z_{scf}	: Surface layer, m
z	: Height and Cartesian coordinate, m
z_1	: Reference height, m
y	: Cartesian coordinate, m
∇^2	: Laplacian operator
∇	: Gradient operator.
$\langle \rangle$	: Theoretical group mean



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ATMOSPHERIC DISPERSION AND CORRESPONDING DOSE AND RISK CALCULATIONS FOR A HYPOTHETICAL ACCIDENT IN ITU TRIGA MARK II RESEARCH REACTOR

SUMMARY

A radioactive release can be a result of different incidents in different facilities harvesting radionuclides. If such an incident occurs, it is important to predict where the radionuclides are going, when they will arrive at a particular location, and how much of them is in the air or on the ground at that location. The atmospheric dispersion calculations can answer these questions.

The radionuclide concentration in the air after a release will result in external exposure to the public as well as internal exposure due to deposition on vegetation, soil, and water. The effect of radiation on human health is assessed with dose. In practice, dose assessments would be based on measurements of air concentration, ground deposition or radiation fields resulting from the release. However, this is not always possible. Instead, mathematical models are used to estimate the impact of radionuclide release.

In order to perform atmospheric release calculations, the number of radionuclides together with their activities and forms must be known. All this information is called the source term. In addition, meteorological conditions at the time of release and geological conditions at the release site and its surrounding terrain must be taken into consideration.

In this thesis, the dispersion calculations due to a hypothetical accident at ITU TRIGA Mark II research reactor were performed by the HYSPLIT4 code built up by NOAA Air Resources Laboratory to estimate accidental releases and their consequences.

HYSPLIT4 implements Gaussian, top-hat horizontal distribution within a puff, and fixed number particle dispersal. Its libraries consist of a particular arrangement of sub-modular directories for each calculation mode (trajectory or concentration calculations). The meteorological data must be gridded as a latitude-longitude grid format or one of three conformal (Polar, Lambert, Mercator) map projections within arranged time intervals. The sub-grid data are created by interpolating from a given data file. This process reduces computational time efforts and shows the grid flexibility to obtain fine resolution.

In the first phase of the thesis, the average wind direction estimation for the reactor site was performed. The results of the analysis showed that the average wind direction altered from NE direction to NE-NNE over time when compared with the ITU TRIGA Mark II safety analysis report (SAR) from 1979. On the contrary, average wind speed approximately stayed the same since the value is 4.7 m/s in SAR and 4.6 m/s in this study. These outcomes were supported by the measured meteorological data information from Istanbul/Ataturk ASOS and processed global

reanalysis meteorological data. This step is vital for all calculations coming afterwards.

ITU TRIGA Mark II research reactor which is operational since 1979 is a tank type research reactor with inherent safety feature. The core inventory of the 40-years operation was calculated by using MCNP (version 6.2) code that implements the Monte Carlo method. In order to do that the generic, verified MCNP input of the reactor produced by Dr. Senem Şentürk Lüle was modified for burnup simulation. The source term then created by taking into account the failure of all fuel elements at the same time after 55 days continuous operation at full power. It should be noted that in SAR, the failure of one fuel element producing the highest power among all fuel elements after 4 years of operation was investigated. On the contrary, in this study, the failure of all 69 fuel elements was analyzed. This assumption is the basis of the hypothetical accident.

The atmospheric dispersion simulations were performed with the source term and wind properties achieved in this study to investigate the effect of external exposure and internal exposure (ingestion of contaminated tap water and food) due to the hypothetical accident in ITU reactor. The relationship between these exposure mechanisms and mortality and morbidity was also investigated.

The atmospheric dispersion models were classified into three groups as 3D-Particle, Gaussian-Horizontal particle-vertical (Gh-Pv), and Top-Hat-Horizontal particle-vertical (THh-Pv) in HYSPLIT4 code. In the grid cell that had the maximum concentration, 3D particle model concentration was 2.0 and 2.2 times greater than Gh-Pv and THh-Pv models, respectively, under stable air condition with high grid resolution (0.002 degree) and 4.6 m/s average wind speed in the NE-NNE direction. In addition, simulations showed that under unstable condition particles tend to spend more time before leaving the grid cell in certain time intervals compared to a stable condition if grid resolution is low. With high grid resolution (0.002 degree), half-hour average activity concentration for the stable condition is 31.5 % higher than unstable condition concentrations. Therefore, 3D-Particle and stable condition were selected to perform conservative investigation.

For external exposure, the maximum total cloudshine and groundshine as a result of exposure of half-hour and annually were found as 1.37 μrem and 0.206 mrem, respectively, at ITU Ayazağa Campus (near the Chemical and Metallurgical Engineering Faculty building). These values are below the limit for the public (5.59 $\mu\text{rem}/0.5\text{h}$ or 0.1 rem/yr). It should be noted that the radioactive cloud leaves the area in half-hour. It was observed that non-settled noble gas radionuclides Kr-85, Xe-133, and Xe-135 contributed to exposure only for a given period whereas deposited ones' contribution was long-lasting. This study showed that for inhalation, Ba-140 radioisotope has the maximum risk of mortality and morbidity among other radionuclides owing to its decay progeny and the high-risk coefficient for inhalation.

For ingestion as drinking tap water, it is known that when radionuclides transported in the groundwater, because of dilution, they mostly lose their significance for the ingestion of contaminated tap water compared with the ingestion of contaminated food. It was found that lifetime ingestion of some radionuclides such as Sr-89, Sr-90, Y-91, Ru-106, Sb-125, I-131, Cs-134, and Cs-137 from contaminated tap water could carry a risk, since they have relatively low retardation by soil, short travel times to reach well, low dilution, high concentration in pollutant, progenies, and high-risk coefficient, even though some of them have a relatively short half-life e.g.

Sr-89, Y-91, Ru-106, I-131, Sb-125, and Cs-134, but for other radionuclides, there is no considerable risk.

For the ingestion of contaminated food, the uptake and loss mechanisms of foliar and root uptake are different but they directly depend on chemical characteristics of radionuclides, weather conditions, soil types, and plant types. Radionuclides are intercepted by leaves of vegetables before settling to the ground surface. The accumulation of the radionuclides on the vegetable surfaces is due to radionuclides in air and continues until that pollutant leaves the place of interest. It should be noted that weathering loss from the leaf of vegetables could still cause soil contamination. The calculations showed that although many plants were affected from contamination, the calculated concentrations in plants are well below the limits, especially for important radionuclides such as Sr-90 ($2.56\text{E-}02$ Bq/kg), I-131 ($2.16\text{E-}02$ Bq/kg), and Cs-137 ($2.24\text{E-}02$ Bq/kg). Even though Sr-90 maintains its importance in terms of mortality ($5.03\text{E-}07$) and morbidity ($6.43\text{E-}07$) among the other radionuclides, risks are rather low considering the survival rates.

The results of this thesis which adopt conservative methodology showed that even for a very conservative hypothetical accident scenario at ITU TRIGA Mark II research reactor, the dose levels and risks are below international limits. In addition, different models and atmospheric conditions play an important role in the dispersion calculations. Furthermore, corresponding intake ways either inhalation or ingestion appear to take a key role in mortality and morbidity.



İTÜ TRIGA MARK II ARAŞTIRMA REAKTÖRÜNDEKİ HİPOTETİK BİR KAZA İÇİN ATMOSFERİK DAĞILIM VE İLİNTİLİ DOZ VE RİSK HESAPLAMALARI

ÖZET

Radyonüklidleri kullanan farklı tesislerde meydana gelebilecek kazalar sonucu radyoaktif bir salım gerçekleşebilir. Böyle bir olay meydana geldiğinde, radyonüklidlerin nereye gittiğini, belirli bir yere ne zaman varacaklarını ve bunların ne kadarının havada veya yerde olacağını tahmin edebilmek önem arz etmektedir. Atmosferik dağılım hesaplamaları bu soruları cevaplayabilecek bir araçtır.

Bir salımdan sonra havadaki radyonüklid konsantrasyonu halkı dış ışınlanmaya ve havanın solunması, bitki örtüsü, toprak ve su içinde biriken radyonüklidlerin vücuda alınmasıyla iç ışınlamaya maruz bırakacaktır. Radyasyonun insan sağlığı üzerindeki etkileri doz ile değerlendirilir. Uygulamada, doz değerlendirmeleri salımdan kaynaklanan hava konsantrasyonunun, birikim miktarının veya radyasyon alanlarının gerçek ölçümlerine dayandırılmaktadır. Ancak, bu her zaman mümkün değildir. Bunun yerine, radyonüklid salınımlarının etkilerini tahmin etmek için matematiksel modeller kullanılır.

Atmosferik salım hesaplamaları yapabilmek için, radyonüklidlerin miktarı ile birlikte aktiviteleri ve formları da bilinmelidir. Tüm bu bilgilere kaynak terimi adı verilir. Ayrıca, salım anındaki meteorolojik koşullar ile salım alanındaki jeolojik koşullar ve çevresindeki arazi dikkate alınmalıdır.

Bu tez çalışmasında, İTÜ TRIGA Mark II araştırma reaktöründe gerçekleşen hipotetik bir kaza için atmosferik dağılım hesaplamaları, NOAA Air Resources Laboratory tarafından kazara salınımları ve bunların sonuçlarını tahmin etmek için geliştirilen HYSPLIT4 kodu ile yapılmıştır.

HYSPLIT4 bir puf içinde Gaussian ve Top-Hat yatay dağılımını ve 3D parçacık dağılımını içerir. Kodun kütüphaneleri, her hesaplama modu (yörünge veya konsantrasyon hesaplamaları) için belirli alt-modül dizinlerden oluşur. Meteorolojik veriler, enlem-boylam örgü biçimi veya düzenlenmiş zaman aralıklarıyla örgüsel yapıda üç konformal (Polar, Lambert, Mercator) harita projeksiyonundan biri şeklinde düzenlenmelidir. Alt örgü verileri, belirli bir veri dosyasından enterpolasyon uygulanarak oluşturulur. Bu süreç hesaplama zamanını azaltır ve hassas çözünürlük elde etmek için örgü esnekliğini gösterir.

Çalışmanın ilk aşamasında, reaktör bölgesi için ortalama rüzgâr yönü tahmini yapılmıştır. Analiz sonuçları, ortalama rüzgâr yönünün 1979 tarihli İTÜ TRIGA Mark II güvenlik analiz raporuna (GAR) kıyasla NE yönünden NE-NNE yönüne değiştiğini göstermiştir. Bunun aksine, ortalama rüzgâr hızı güvenlik analizi raporunda verilen 4,7 m/s değeriyle hemen hemen aynı kalmıştır (çalışma sonucu bulunan değer 4,6 m/s'dir). Bu sonuçlar İstanbul/Atatürk ASOS ile ölçülen

meteorolojik veriler ve işlenmiş küresel meteorolojik veriler ile desteklenmiştir. Bu adım, daha sonra gelen tüm hesaplamalar için hayati önem taşımaktadır.

İTÜ TRIGA Mark II araştırma reaktörü 1979 yılından beri faaliyet gösteren kendiliğinden güvenli tank tipi bir araştırma reaktörüdür. 40 yıllık reaktör operasyonu sonucu oluşan kalp envanteri Monte Carlo yöntemini kullanarak çalışan MCNP (sürüm 6.2) kodu ile çıkarılmıştır. Bunu yapabilmek için reaktörün Dr. Senem Şentürk Lüle tarafından hazırlanan doğrulanmış baz MCNP modeli yanma hesapları için yeniden düzenlenmiştir. Daha sonra kaynak terimi 55 gün tam güçte çalışan reaktördeki tüm yakıt elemanlarının aynı anda radyonüklid sızdırmaya başlaması dikkate alınarak hesaplanmıştır. Burada şunu belirtmek gerekir ki İTÜ GAR'da 4 yıl sürekli çalışma sonucu kalpte en yüksek gücü üreten yakıt elemanının radyonüklid sızdırması kazası incelenmiştir. Bunun aksine, bu tez çalışmasında 69 yakıt elemanının tamamında sızma meydana geldiği varsayılmıştır. Bu varsayım hipotetik kazanın temelini oluşturmaktadır.

Atmosferik dağılım simülasyonları, İTÜ reaktöründeki hipotetik kazaya bağlı dış ve iç ışınlama (kontamine su ve yiyeceklerin yutulması) etkisini araştırmak için bu çalışmada elde edilen kaynak terimi ve rüzgâr özellikleri ile gerçekleştirilmiştir. Bunun yanında iç ışınlama mekanizmaları ile mortalite ve morbidite arasındaki ilişki de araştırılmıştır.

Atmosferik dağılım modelleri HYSPLIT4 kodunda 3D parçacık, Gauss-yatay parçacık-dikey (Gh-Pv) ve Top-Hat-yatay parçacık-dikey (THh-Pv) olarak üç gruba ayrılır. Maksimum konsantrasyona sahip örgü hücresinde, 3D parçacık modeli konsantrasyon sonucu, yüksek örgü çözünürlüğü (0.002 derece) ve NE-NNE yönünde 4.6 m/s ortalama rüzgâr hızı ile kararlı hava koşullarında sırasıyla Gh-Pv ve THh-Pv modellerinin sonuçlarından 2.0 ve 2.2 kat daha büyük çıkmıştır. Ek olarak, simülasyonlar, kararsız koşullar altında parçacıkların, örgü çözünürlüğü düşükse, kararlı bir koşulla karşılaştırıldığında, belirli bir zaman aralığında örgü hücresini terk etmeden önce örgü hücresinde daha fazla zaman harcama eğiliminde olduğunu göstermiştir. Yüksek örgü çözünürlüğü (0.002 derece) ile kararlı durum için yarım saatlik ortalama aktivite konsantrasyonu, kararsız durum konsantrasyonlarından %31,5 daha yüksek bulunmuştur. Bu nedenlerle, daha tutucu bir yaklaşım sergileyerek ışınlama hesaplarını yapmak adına 3D parçacık ve kararlı hava koşulları seçilmiştir.

Dış ışınlama durumunda, radyoaktif bulut ve yerde biriken radyonüklidlerden gelen yarım saatlik ve yıllık maksimum dış ışınlama İTÜ Ayazağa Kampüsü'nde sırasıyla 1.37 μ rem ve 0.206 mrem bulunmuştur. Bu değer halk için belirlenen doz sınırın (0.1 rem/yıl ya da 5.59 μ rem/0.5saat) altındadır. Burada radyoaktif bulutun yarım saat içinde alanı terk ettiği belirtilmelidir. Kr-85, Xe-133 ve Xe-135 gibi zeminde birikmeyen asal gaz radyonüklidleri belirli bir süre dış ışınlamaya katkıda bulunurken, biriken radyonüklidlerin katkısı uzun sürelidir. Bu çalışma göstermiştir ki radyoaktif havanın solunması durumunda, Ba-140 radyoizotopu, bozunma ürünleri ve soluma için yüksek risk katsayısı nedeniyle maksimum mortalite ve morbidite riskine sahiptir.

Kontamine içme suyu tüketimi dikkate alındığında, radyonüklidlerin yeraltı suyuna taşınması esnasında seyrilmeleri nedeniyle musluk suyunun ve yiyeceklerin tüketimi karşılaştırıldığında önemlerini kaybederler. Çalışma sonuçları Sr-89, Sr-90, Y-91, Ru-106, Sb-125, I-131, Cs-134 ve Cs-137 gibi bazı radyonüklidlerin bazıları çok kısa yarı ömre sahip olmalarına rağmen (Sr-89, Y-91, Ru-106, Sb-125, I-131 ve Cs-134)

ömür boyunca kontamine musluk suyu vasıtasıyla tüketilmesinin toprak tarafından geciktirilmelerinin az olması, su kaynağına ulaşmalarının kısa sürmesi, düşük oranda seyrelmeleri, radyonüklidler arasında yüksek konsantrasyona sahip olmaları, bozunma ürünleri ve yüksek risk katsayısına sahip olmaları nedeniyle risk taşıyabileceğini göstermiştir. Ancak diğer radyonüklidler için bir risk gözükmemektedir.

Kontamine yiyeceklerin tüketilmesi durumunda, bitkinin yaprağı ve kökü vasıtasıyla bünyesine aldığı radyonüklidlerin alım ve kayıp mekanizmaları farklıdır. Ancak bunlar doğrudan radyonüklidlerin kimyasal özelliklerine, hava koşullarına, toprak tipine ve bitki türüne bağlıdır. Radyonüklidler zemin yüzeyine yerleşmeden önce bitki yaprakları tarafından tutulur. Radyonüklidlerin bitki yüzeylerinde birikmesi, havadaki radyonüklidlerden kaynaklanır ve kirletici bulut ilgilenilen yerden ayrılana kadar devam eder. Bitkilerin yaprağından hava etkisiyle ayrışma kaybının hala toprak kontaminasyonuna neden olabileceği unutulmamalıdır. Tezde elde edilen sonuçlara göre, her ne kadar birçok bitki kontaminasyondan etkilenmiş olsa da, bitkilerde hesaplanan konsantrasyonlar, özellikle Sr-90 ($2.56E-02$ Bq/kg), I-131 ($2.16E-02$ Bq/kg) ve Cs-137 ($2.24E-02$ Bq/kg) için, sınırların çok altındadır. Sr-90, radyonüklidler arasında mortalite ($5.03E-07$) ve morbidite ($6.43E-07$) açısından önemini korumasına rağmen, sağkalım oranları göz önüne alındığında riskler oldukça düşüktür.

Tutucu analiz metodolojisinin benimsendiği bu tez çalışmasının sonuçları İTÜ TRIGA Mark II araştırma reaktöründeki çok tutucu hipotetik bir kaza senaryosunda bile doz değerlerinin ve risklerin uluslararası limitlerin çok altında olduğunu göstermiştir. Çalışma ayrıca atmosferik dağılım incelenirken farklı dağılım modellerinin ve atmosferik koşulların önemini göstermesinin yanı sıra, solunum veya sindirime karşılık gelen alım yollarının mortalite ve morbidite için önemli bir rol oynadığına işaret etmektedir.



1. INTRODUCTION

The radionuclides can be released to the atmosphere from nuclear facilities as a result of unintentional events. In addition, it is also possible to have such release because of radiological incidents at other facilities involving radiation usage or as a result of accidents during radioactive material transportation. The knowledge of where the radionuclides are going, when they will arrive at a particular location, and how much of them is in the air or on the ground at that location is important to reduce the effects of these radionuclides.

The atmospheric dispersion calculation combines a very wide range of topics such as source term that defines the amount therefore activity of radioactive materials to be released, meteorological conditions that decide the pathway of radioactive materials, geological conditions that affect concentration distribution on ground and vegetation, numerical methods without them it is not possible to perform any simulation, and so on.

This thesis addresses the comprehensive explanations on concentration distribution at a certain place and time, the aftermath of a hypothetical accidents, and comparison between methods.

In order to achieve the aim of the thesis, ITU TRIGA Mark II research reactor was selected to provide a hypothetical accident scenario. The core inventory which is the basis of the source term in dispersion calculations was calculated by using the Monte Carlo method.

Ideally, dose assessments would be based on measurements of air concentration, ground concentration or radiation fields resulting from the release. However, this is not always possible. Instead, mathematical models must be used to estimate the impact of radionuclide release [1].

At first, distinctive methods to select effectively atmospheric dispersion, transportation, and deposition models were discussed. After introducing the fundamentals of meteorology and standards, modeling approaches associated with

meteorological parameters were covered to understand whether they can be used within models or not. Beside fundamental principles, comprehensive and appropriate methods were also given because sometimes applications need the synthesis to deal with complicated problems and to get more accurate results.

Then, atmospheric dispersion assessment was described. It is known that atmospheric dispersion calculation cannot be restricted to a certain period of time because it points out the past, present, and future. A number of studies from literature to provide an insight into the sequence of developing steps and key points of the calculation process were summarized. At least three different meteorological dataset references that have free access on the internet for different time periods were mentioned.

After the theoretical backgrounds for dispersion, transportation, and deposition modeling were given, how to specify key parameters for different types of calculation methods were analyzed. Despite similarities, it is necessary to perceive the difference between calculation methods.

In this thesis, HYSPLIT atmospheric dispersion and transportation code was used. Therefore, the calculation methodology of the code together with a test case examples that are verified with CAPTEX release data was introduced before starting calculations for this study. In addition, the ways of radionuclides from the release to deposit on surface vegetation and soils were discussed. This is important since, after deposition, radionuclides may transfer to plants or lost from the plants by weathering, leaching, and abrasion.

The method used in this thesis was verified with performing I-131 dispersion calculation and comparing the results with the results presented in the safety analysis report of ITU TRIGA. The specifications of wind were determined for the hypothetical scenario for the reactor site in Ayazağa Campus. By using the 2019 core inventory of the reactor, the source term was prepared. The external exposure together with mortality and morbidity due to inhalation of radioactive air, tap water intake contaminated due to fallout, and ingestion of contaminated food were calculated for the hypothetical accident scenario. The results were compared with international environmental protection policy and recommendations.

2. LITERATURE REVIEW

The air composition surrounding the earth has undergone a number of changes because of anthropogenic activities, especially using coal as the primary energy source [2]. Sulfur, nitrogen, carbon, and halogen compounds count the primary gaseous emissions of air pollutants as well as radioactivity originated from both natural and anthropogenic sources [3]. Then, meteorological models were developed to explain local, regional, and global meteorological phenomena and they were made available for air dispersion models [4]. Meteorological models are divided into two groups: Physical and mathematical. Physical models were playing a key role to pave the way for providing data to validate mathematical models [5]. The mathematical models, are investigated under two main topics: analytical models and numerical models. The numerical meteorological methods further separated into two groups, the diagnostic models (no time tendency) and the prognostic models (full time-dependent equations) [6]. The prognostic models later lead up stochastic models [7].

In the grand scheme of radioactivity, the radiological assessment began with the experiments performed to find out the path of radioactive pollutants after the testing of nuclear weapons [8]. Until the late 1970s, there was no detailed analysis and large scale testing [9]. After the Three Mile Island (TMI) nuclear power plant (NPP) severe accident in 1979, the U.S. Department of Energy (DOE) tracked and measured the activity in plume by using helicopters [10]. A few years after the TMI accident, the Chernobyl disaster occurred in Ukraine in 1986. The Chernobyl 4 reactor was destroyed by steam explosions and fire. At least 5% of radioactive reactor core content was ejected from the reactor into the atmosphere and spread by wind over Europe mainly Belarus, Ukraine, and Russia [11]. The radioactive pollutant transported over the entire northern hemisphere and deposited substantial amounts of radioactive material over large areas of the former Soviet Union and some other countries [12]. Turkey was another country that suffered from radionuclides transport and deposition after the Chernobyl accident. The simulations have been carried out over the Anatolian Peninsula with HYSPLIT code in [13] but

the ingestion of tap water and food was not considered in that study to estimate the environmental effects of accidents.

More recently on 11 March 2011, approximately 15-meters tsunami wave hit the east coastline of Japan as a result of the earthquake of magnitude 9.0. This wave caused station blackout and the cooling of three Fukushima Daiichi reactors could not be provided and this resulted in a nuclear accident [14]. The accident was rated 7 (like the Chernobyl accident) according to the International Nuclear and Radiological Event Scale (INES) rating descriptions [15]. Although estimations of atmospheric source term vary organization to organization around the world, the estimated releases over days 4 to 6 were accepted 940×10^{15} Bq (I-131 eq.) [16]. Measurement results close to the accident region posted by Japan nuclear regulation authority were compared with calculated values by HYSPLIT [17]. The results were fairly similar to official data. The radioactivity monitoring systems after the Fukushima Daiichi accident detected several radionuclides that are produced in nuclear reactors artificially and then scientists managed to find out the location of release by simulating HYSPLIT with backward mode [18], [19], [20], [21].

The TRIGA is a type of research reactor and its' concept first displayed in August 1955 Geneva Switzerland at an international conference [22]. ITU TRIGA Mark II research reactor was commissioned as 54th TRIGA reactor in the world and became critical in 1979. The atmospheric dispersion assessment is a part of safety analysis of research reactors in order to estimate the consequences of releases in case of accidents. There are a few numbers of studies in the field of atmospheric dispersion and transportation for TRIGA reactors all around the world. For example, the core inventory analysis of the PUSPATI TRIGA was performed to determine the source term for the atmospheric release of radionuclides [23]. The source term was found critical to calculate potential release, and then the results had been simulated by using Gaussian Plume Model. Only cloud shine exposure was addressed that 300 m away from reactor annual effective dose rate exceeded the standard [24]. Besides, the environmental radiological impact has been carried out by PAVAN and CALLPUFF models for the Ki-Jang research reactor (KJRR), and it was concluded that Gaussian dispersion models (PAVAN) resulted in more conservative dose values that might lead to redundant installation cost [25]. Another study on atmospheric release from the research reactor has been carried out for 5 MW research reactor in the south of

Iran by HYSPLIT code but severe accident scenarios, deposition, and food-chain contamination were ignored in this study [26].





3. MODELING OF ATMOSPHERIC DISPERSION AND TRANSPORTATION

The radionuclides can be released to the atmosphere during routine operation or in consequence of unintentional events. Thus, habitats that live around the releasing location could be exposed to radiation via various pathways. These different pathways can be expressed as external exposure from radionuclides, internal exposure by inhalation of radionuclides in the air, and ingestion of essential nutrients that might be contaminated by radioactive materials.

The magnitude of the exposure depends on atmospheric transport, diffusion, and deposition processes that indicate three important results: *where* the pollutants are going, *when* they will arrive at a particular location, and *how much* of the pollutant concentration is in the air and on the ground at that location. Ideally, dose assessments would be based on measurements of air concentration, ground concentration, or radiation fields resulting from these releases. However, this is not always possible. Instead, mathematical models must be used to estimate the impact of radionuclide releases [1].

This chapter presents distinctive methods to select atmospheric dispersion, transportation, and deposition models effectively. After introducing the fundamentals of meteorology and standards, modeling approaches associated with meteorological parameters are discussed whether they can be used within models or not. Beside fundamental principles, comprehensive and appropriate methods are given because sometimes applications need the synthesis to deal with complicated problems and to get more accurate results.

3.1 The Atmosphere

The atmosphere is a protective filter that surrounds the earth and is a mixture of gases and water vapor. The composition of the mixture significantly affects the destiny of pollutants. The atmosphere can preserve them for hundreds of kilometers

by effects of earth's gravity, wind direction, specific humidity as well as other specific properties.

3.1.1 Composition of the atmosphere

The atmosphere is mainly composed of two gases: Oxygen (21%) and Nitrogen (78%). The remainder part of the atmosphere consists of some tracer gases each of which has a percentage of much less than 1%. Water vapor and Carbon Dioxide are two of those substantial ingredients that constitute the tracer gases. Even though the percentages of the Oxygen and Nitrogen remain relatively constant throughout the atmospheric boundary layer (ABL), others can greatly vary location to location. These varieties and condensation of water vapor cloud or precipitation demonstrate how important it is to conserve energy balance over the globe.

3.1.2 Vertical extend importance for release

Most of the solar radiation reaching the earth's surface is absorbed and then radiated back into the atmosphere. One result of the complex interactions between the incoming solar energy, the surface of the earth, and the atmosphere is that, on average, the atmosphere develops a distinct vertical temperature structure. A thermometer rising above the surface at mid-latitudes would indicate that the temperature of the atmosphere decreases up to a height of about 12 km [27]. After this heights (the tropopause), the temperature begins to increase with height. The tropopause is at its highest level in the tropics ($\sim 20^{\circ}\text{N}$ - 20°S). It descends sharply in altitude from ~ 16 km at the equator to 12 km at ~ 30 - 40° latitude and as low as about 9 km at the poles. The tropopause separates the lowest layer of the atmosphere, the troposphere, from the next layer the stratosphere [28]. Stratosphere-troposphere exchange (STE) occurs across the tropopause. The stratosphere and troposphere are two adjoining regions of distinctive characteristics observed just above the tropopause. These characteristics are mainly due to the rapid increase in ozone mixing ratio and the sudden decrease in water vapor mixing ratio with altitude [29]. Figure 3.1 shows layers of the earth's atmosphere.

Although almost all weather phenomena and consequences of the surface-air activities occur in the troposphere, consequences of highly energetic radionuclide releases such as nuclear weapon explosion might arrive to the stratosphere. The bottom of the troposphere includes an interface extending upward from the surface of

the earth to the “free atmosphere.” This interface is called the atmospheric boundary layer (ABL).

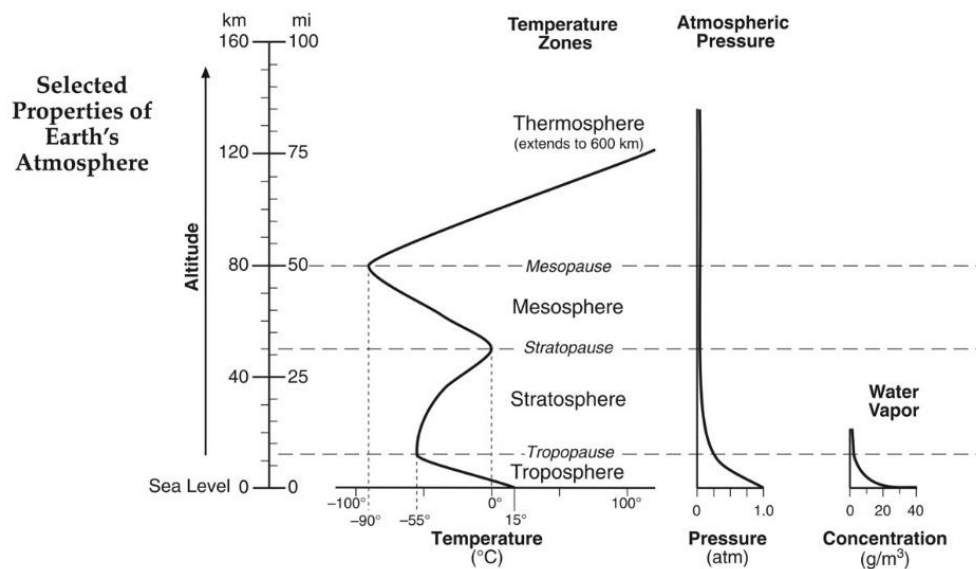


Figure 3.1 : The layers of the earth with selected properties [30].

The height of the ABL varies spatially and temporally but it generally ranges between a few meters to 2,000 m depending on the time of day and many other factors [31]. The ABL is the layer of air directly above the earth’s surface in which the effects of the surface (friction, heating, and cooling) are felt directly on time scales less than a day. It has significant fluxes of momentum, heat or matter that are carried by turbulent motions on a scale on the order of the depth of the boundary layer or less. The exact characteristic of the ABL greatly influences the dispersion of radionuclides and the subsequent exposure to people [32]. The diurnal intermittency of the ABL caused by the sun shining during the day and absence of the sun at night plays a significant role in ABL as a function of time and space.

3.1.3 The scale of motion

The atmospheric transportation and diffusion calculation include many crucial parameters. The most important of them is the wind which has direction and speed so it can answer questions *where* and *why*. Its basic property, the density of gases, even answers the question *how much*.

The wind has a variety of scales of motion. At large, it is called the macro or synoptic- scale (1,000-2,000 km). The weather fronts, mid-latitude cyclones, hurricanes, low and high-pressure region, and rotation of earth are the examples of

synoptic weather patterns and events. These features specify the wind speed and direction. As the motion in the synoptic-scale is around the world, the wind direction and speed changes after three to seven days period at the specific location. The radionuclides released during the Chernobyl accident reaching the United States and the long-term effects of the Fukushima Daiichi Accident are examples of the macro-scale motion of radioactive pollutants.

The next scale is defined as a mesoscale at a distance of about 100 km. The mesoscale weather events mostly caused by differential heating of the earth's surface such as sea breezes, gravity winds, local convective activity, and thunderstorms. The periodicity of these kinds of weather events is one day. Besides, it determines the speed and direction of winds over the mesoscale. Sea breezes are associated with the coastal atmospheric environment. When cool (stable) air going from the offshore towards the onshore and warm (unstable) air rising from the land surface interacts, a thermal internal boundary layer (TIBL) is created. Pollutants produced into the TIBL are confined within the layer but if they are emitted above the TIBL, they tend to remain aloft until coinciding with TIBL. Then, downward diffusion motion begins abruptly which proves the reason for higher pollutant concentration near the upper surface and at the ground surface. This downward diffusion is shown in Figure 3.2.

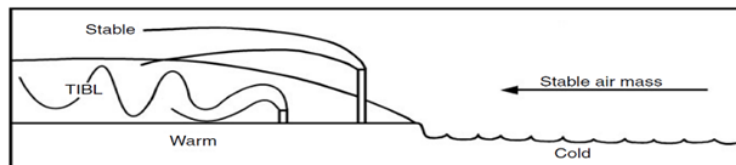


Figure 3.2 : Pollutant behavior for emissions within and above the thermal internal boundary layer [33].

The weather system that has average diameter between less than a meter to 1 km is called the microscale. The wind dynamics over the microscale is caused by surface roughness, buildings, forest to grass transition, and valleys that all are mainly important in the case of frictional forces. These weather phenomena typically occur in a short time, from two seconds to minutes [34]. The wind direction and speed changes with varying height under all conditions.

Generally, the wind speed begins to increase with height above the ground while its direction shifts or veers in the ABL because of the turbulence of the air. The thermal

structure of the atmosphere affects the rate of change of wind with height. The relation between them is given as a function of horizontal wind speed in further chapters. The existence of buildings, forests, and other places where the surface roughness is great, the flow of air might be disordered over the surface. Figure 3.3 shows the airflow distribution around a simple building. Three major zones around it are the upwind displacement zone where the approaching air is deflected around the body, the cavity zone that is isolated comparing with others and on the sheltered side of the body, and the highly unstable wake zone which is greater distance downwind of the body [35].

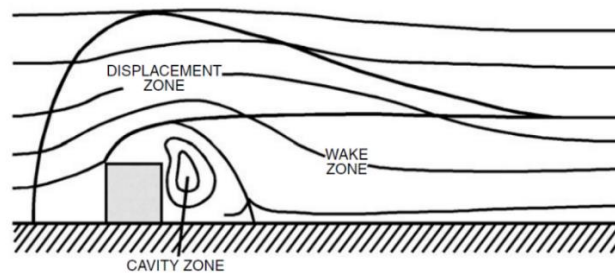


Figure 3.3 : Flow characters of air around the body [36].

When the transport and diffusion calculations are performed for different scales, average wind and turbulence velocity values are used since calculations rely on the resolution of the input data and the size of the pollutant cloud. The wind stirs the pollutant clouds entirely with turbulence. Even smaller eddies diffuse to edges in the cloud, while larger eddies force the cloud to move. The effects of different size eddies on the motion are shown in Figure 3.4.

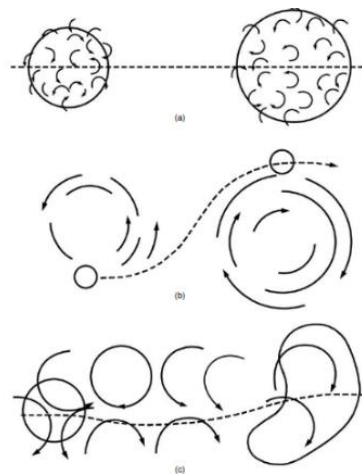


Figure 3.4 : Idealized dispersion patterns. (a) A large cloud in a uniform field of small eddies. (b) A small cloud in a uniform field of large eddies. (c) A cloud in a field of eddies of the same size as the cloud [37].

3.2 The Input Data

It is essential to identify several different atmospheric data before the examination of atmospheric diffusion and transportation calculations. The data play an important part in terms of both quantity and quality to get results with good accuracy.

3.2.1 The source term

The source term refers to amount and characteristics of radionuclides that are released into the atmosphere after accident, incident, or discharging. The following information can be accepted as a guide to dig out all aspects of a calculation in terms of source specification:

- The physical features of a place or location connected with the earth's surface, population, divisions, etc.
- A typical feature or quality of released material (size and weight, radioactivity, chemical stability, etc.)
- A particular period that released material lasts or continues in.
- A particular distance above the ground where material is released.
- The exit velocity of radionuclides from source or stack to the atmosphere.
- Thermal properties of released materials.
- The location of the nearest buildings.

3.2.2 The wind

The wind compels the radioactive pollutants to move in a line. Therefore, inhabitants living in wind direction may be exposed to radioactivity. The determination of the wind direction is generally difficult since the wind direction can change easily and several parameters have a great effect on it. The location of the facility may give an idea about the wind direction and speed over a certain period. Also, it depends on the atmospheric data measurement near the release points. Figure 3.5 shows the wind direction hourly over a day for the Three Mile Island Nuclear Facility site on March 28, 1979.

Aforementioned earlier, the wind speed is likely to increase with upward movement in the ABL. As a rule of thumb, the diversity of height produces a change in release point wind velocity, especially, in case of the atmospheric stability and surface

roughness. Sutton [38] has started to explain the natural process of speed change with the Equation 3.1.

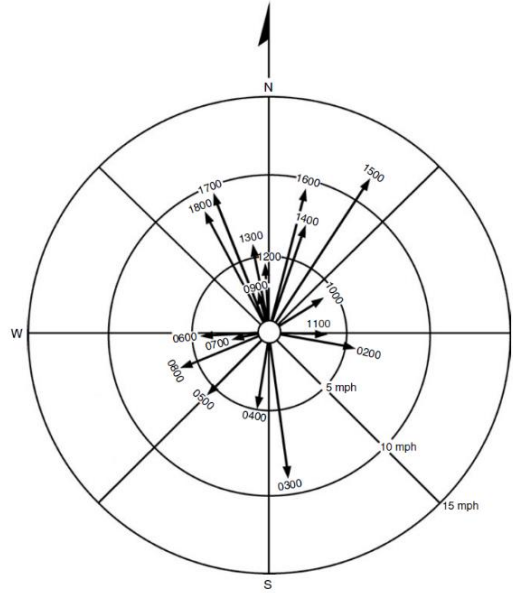


Figure 3.5 : The wind direction as a function of time and velocity at the Three Mile Island Nuclear Facility site on March 28, 1979 [39].

$$u = u_1 \left(\frac{z}{z_1} \right)^m \quad (3.1)$$

where u is the wind speed at height z , u_1 is the wind speed at the reference height z_1 , and m is a variable that varies with atmospheric stability and the surface roughness as seen in Table 3.1.

Table 3.1 : m values as a function of atmospheric stability and surface roughness [38].

Surface Roughness	Atmospheric stability			
	Thermally Unstable	Near Neutral	Stable	Very stable
Rural	0.07	0.14	0.35	0.55
Urban	0.15	0.23	0.40	0.60

3.2.3 Turbulence and stability

The direction change in the air that happens suddenly and violently is called turbulence and it carries vital importance for pollutants in the ABL. It is logical to

split the turbulence into two different parts: the mechanical turbulence that is created by the tendency of moving air against the rough earth's surface and the thermal turbulence which is generated by incoming solar radiation and the buoyant effect of floating bubbles in the air. The strength of thermal turbulence in the ABL relies heavily on the stability of the atmosphere, while the stability of the atmosphere in the ABL is relevant to the rate of change in temperature. If a parcel of dry air moves upward adiabatically, its temperature decreases $0.98\text{ }^{\circ}\text{C}$ with elevation for every 100 m of rising. This is known as the dry adiabatic lapse rate. If the lapse rate of the atmosphere in which this parcel is rising is less than the dry adiabatic lapse rate, the displaced parcel will be warmer than its surroundings and buoyant forces will tend to keep the parcel rising vertically. When it occurs, the atmosphere is unstable. If the lapse rate of the atmosphere is greater than the dry adiabatic lapse rate, the parcel will be cooler than its surroundings and tends to return to its original position. Under these conditions, the atmosphere is stable. One of the most stable atmospheric conditions happens when the lapse rate of the atmosphere is positive. When the lapse rate of the atmosphere is equal to the dry adiabatic lapse rate, the atmosphere is neutral [40]. Figure 3.6 shows the mechanism of positive, neutral, and negative lapse rate.

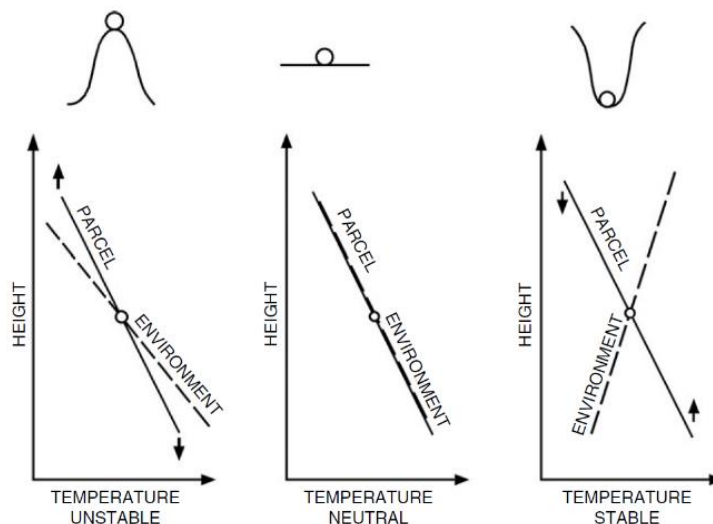


Figure 3.6 : Explanation of lapse rate relationship between dry adiabatic parcel and environment under the different stability conditions.

Although there are few stability categories, the Pasquill-Gifford stability category is one of the most commonly used one to specify turbulence. Pasquill categorized the turbulence stability into six classes that are marked from most unstable to most stable

respectively as A, B, C, D, E, and F in 1967 [41]. He used surface wind speed and incoming solar radiation to describe classes as listed in Table 3.2.

Table 3.2 : Pasquill stability classes related to meteorological conditions.

Surface wind speed (m/s)	Atmospheric stability			Nighttime cloud cover	
	Strong ⁱ	Moderate ⁱ	Slight ⁱ	> 3/8 cloudiness	< 3/8 cloudiness
< 2	A	A-B	B	E	F
2-3	A-B	B	C	E	F
3-5	B	B-C	C	D	E
5-6	C	C-D	D	D	D
>6	C	D	D	D	D

(i) Incoming solar radiation is based on the following: strong ($> 700 \text{ W m}^{-2}$), moderate ($350\text{-}700 \text{ W m}^{-2}$), and slight ($< 350 \text{ W m}^{-2}$) [42].

3.3 The Modeling

Mathematical models play an important role to estimate potential or actual impact of radionuclides released into the atmosphere. A diffusion model aims to estimate the future of the released materials. Thus, a model should answer the following questions:

- Where do released materials move and when do they reach a specific location?
- What is the dilution rate while traveling?
- What is the removal mechanism from the atmosphere?
- What kind of chemical reaction features they have?

Generally, answering these questions is difficult because the meteorological properties of the atmosphere depend on each other. A practical way to solve complicated problems is to ignore some of these questions that have less importance compared with others.

3.3.1 The Gaussian diffusion model

The Gaussian diffusion model resembles the three-dimensional conduction equation because their analytical solutions are similar. This model requires an assumption, for example, taking diffusivity constant like constant conductivity in the conduction equation. If an elemental cube is imagined, the time rate of change of the

concentration in the cube is equal to the change in content. Equation 3.2 expresses it mathematically as follow [43].

$$\frac{\partial \chi}{\partial t} = \frac{\partial}{\partial x} \left[K_x \left(\frac{\partial \chi}{\partial x} \right) \right] + \frac{\partial}{\partial y} \left[K_y \left(\frac{\partial \chi}{\partial y} \right) \right] + \frac{\partial}{\partial z} \left[K_z \left(\frac{\partial \chi}{\partial z} \right) \right] \quad (3.2)$$

where, x , y , and z represent the downwind, cross-wind, and vertical wind direction, respectively. K_x , K_y , K_z are diffusivity in x -, y -, and z -directions and χ is the concentration of pollutants as a function of x , y , z , and t .

Gaussian diffusion model gives results quickly and generates tolerable results with measured data although it has limitations. Different scenarios require distinctive initial and boundary conditions to solve Equation 3.2. Most of these scenarios will be discussed in the subsequent section.

If a pollutant is instantaneously produced in the free atmosphere by a point source, the solution is described in Equation 3.3.

$$\chi = \frac{Q}{8(\pi t)^{3/2} (K_x K_y K_z)^{1/2}} \exp \left[-\frac{1}{4} t \left(\frac{x^2}{K_x} + \frac{y^2}{K_y} + \frac{z^2}{K_z} \right) \right] \quad (3.3)$$

where Q is the total amount of pollutants released. The diffusivity constant of each direction relates to the standard deviation of the Gaussian distribution σ . This relation presented in Equation 3.4.

$$\sigma^2 = 2Kt \quad (3.4)$$

The cartesian coordinate system can be altered with a spherical system. In order to do that all parameters should be changed to define a new equation (Equation 3.5) in spherical coordinates.

$$\chi = \frac{Q}{(2\pi)^{3/2} (\sigma_r)^3} \exp \left[-\frac{1}{2} \left(\frac{r^2}{\sigma_r^2} \right) \right] \quad (3.5)$$

where σ_x , σ_y , and σ_z is formed as σ_r in the Gaussian distribution.

If a point source located far away from any boundary emits pollutant at a constant rate Q' per unit time and mean wind speed (u) blows in the x -direction, the concentration χ is not a function of time [44]. Furthermore, it is experimentally proved that the movement of pollutants is mostly caused by the downwind. Therefore, the diffusivity of x -direction K_x can be ignored and Equation 3.3 is rearranged as Equation 3.6.

$$\chi = \frac{Q'}{2\pi u \sigma_y \sigma_z} \exp \left[-\frac{1}{2} \left(\frac{y^2}{\sigma_y^2} + \frac{z^2}{\sigma_z^2} \right) \right] \quad (3.6)$$

For the line source that lies along the y -direction, the source term is calculated by integrating the line source along the y -direction. When the same assumptions above are applied for K_y diffusivity of y -direction, Equation 3.6 reduces to Equation 3.7.

$$\chi = \frac{Q''}{(2\pi)^{1/2} u \sigma_z} \exp \left[-\frac{1}{2} \left(\frac{z^2}{\sigma_z^2} \right) \right] \quad (3.7)$$

where Q'' is released amount per unit time per unit length.

The effluent either can be emitted from the ground or an elevated source for example a stack. A very convenient approach is that if materials release from an elevated source, they will move downwind direction until encountering the ground. The ground behaves like a mirror and it reflects them into the atmosphere. This mechanism is illustrated in Figure 3.7 and defined in Equation 3.8 by Gifford (1968) [45].

$$\chi = \frac{Q'}{2\pi u \sigma_y \sigma_z} \exp \left[-\frac{1}{2} \left(\frac{y^2}{\sigma_y^2} + \frac{(z - h_p)^2}{\sigma_z^2} \right) \right] \quad (3.8)$$

where h_p is an effective emission height of effluent.

If Equation 3.8 is modified for imaginary source placed at a distance h_p from the ground surface, Equation 3.8 takes the form shown in Equation 3.9.

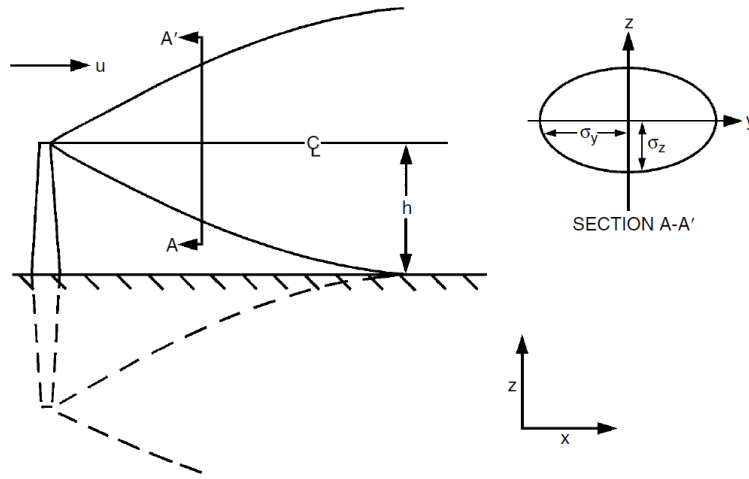


Figure 3.7 : Schematic representation of elevated source release in vertical and cross-wind direction [46].

$$\chi = \frac{Q'}{2\pi u \sigma_y \sigma_z} \exp \left[-\frac{1}{2} \left(\frac{y^2}{\sigma_y^2} + \frac{(z - h_p)^2}{\sigma_z^2} \right) \right] + \frac{Q'}{2\pi u \sigma_y \sigma_z} \exp \left[-\frac{1}{2} \left(\frac{y^2}{\sigma_y^2} + \frac{(z + h_p)^2}{\sigma_z^2} \right) \right] \quad (3.9)$$

The atmospheric stability categories are classified earlier in Table 3.2. These categories are used in the Gaussian dispersion model. According to the categories, σ_y and σ_z parameters are determined as a function of distance from the source. These parameters are illustrated in Appendix A. They were calculated experimentally for six different atmospheric classes. There is another stability category G which is not given above and is known as the extremely stable condition and is approximately calculated with the following equation.

$$\sigma_z(G) = \frac{3}{5} \sigma_z(F), \quad \sigma_y(G) = \frac{2}{3} \sigma_y(F) \quad (3.10)$$

3.3.2 The Puff-transport and diffusion model

It is vital to make an appropriate selection of whether a particular release is a puff or a plume by utilizing statistics before starting the calculation since their statics are different from each other. If the emission time of pollutants is short compared to the travel time of interest, the release can be distinguished as a puff model rather than the plume model [35]. The puff model also carries out similarities with the Lagrangian

dispersion model. These similarities are due to the scale such that when they move above the puff size, they are treated as Lagrangian trajectory model, and for sub-puff size, they behave like the Gaussian plume model [47]. Therefore, puff models contain the effect of turbulence more than one particular way: for large-scale application, a stochastic random walk; for sub-puff-scale application, through the deviation of a normal distribution inside each puff [48].

Specifying a puff trajectory relies on the wind field over the simulation domain. The velocity usually depends on time. It is interpolated from a grid point to grid point where wind data are available, used in the simulation, and weighted with $1/r^2$ where r is the radial distance from grid point to point. The puff trajectory model is more useful beyond 10 km. Furthermore, this model can be applied to a synoptic (500-5000 km) scale as well [49]. Varying condition in the atmosphere brings limitation to Gaussian plume model as mentioned earlier. The sequential Gaussian puff trajectory model helps to overcome this limitation. It provides a continuous plume that is divided into a series of puffs emitted sequentially. This phenomenon is shown in Figure 3.8.

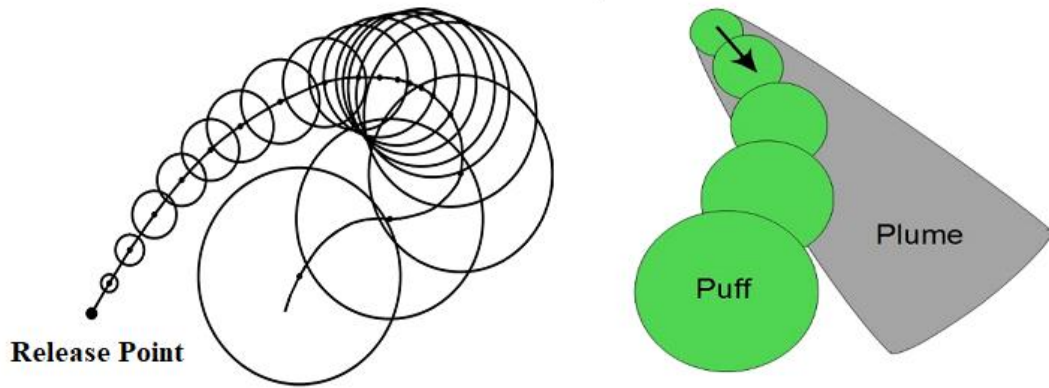


Figure 3.8 : Simulation of plume consisting of a series of puff emitted at equal time intervals [46].

If each puff is symmetric in the horizontal plane, σ_r is used to determine the distribution in both cross-wind (y) and downwind (x) direction. The radial distance is defined between the center of the puff and the requested location. It is assumed that total reflection of the bottom of the puff (the ground) to up (the top of the ABL h_L) and the concentration are functions of location x , y , and z and time t . The i^{th} puff concentration is found by using Equation 3.11 [50].

$$\chi_i(r, z, t) = \frac{Q(t)}{(2\pi)^{3/2} \sigma_r^2 \sigma_z} \left\{ \exp \left[-\frac{1}{2} \left(\frac{r^2}{\sigma_r^2} \right) \right] \right\} G(z) \quad (3.11)$$

where $Q(t)$ indicates material in the puff at time t , r is the distance between the center of puff and any location which will be calculated, and $G(z)$ is a reflection term that is defined by Equation 3.12.

$$G(z) = 2 \sum_{m=-\infty}^{\infty} \exp \left\{ -\frac{1}{2} \left[\frac{(2mh_L - h_p)^2}{\sigma_z^2} \right] \right\} \quad (3.12)$$

where m is the number of reflection from both the ground and the top of the ABL, h_L is the ABL height, and h_p is the effective height of the plume.

The Pasquill-Gifford curves are generally used for both microscale and mesoscale distance to specify the puff variance (σ) values. However, other ways are also possible to use and estimate it such as similarity theories. The similarity theories are composed of assumptions that at very long distance (order of 1000 km) effluent cloud becomes equal to the size of the largest eddy of the atmosphere. The K values in the horizontal direction would be independent of time and changing them relies on directions of smaller size eddy characteristics. The vertical diffusivity K_z is parametrized with respect to horizontal eddy diffusivities.

3.3.3 The box model

The box model is utilized to model the regional chemical releases as the governing equation includes an expression that allows the estimation of the chemical change rate of pollutants. The box model has simple algorithms. The air-filled box is defined to tackle air pollutants inside the box. The mass conservation equation is represented in Equation 3.13 [51].

$$\begin{aligned} \frac{\delta \chi}{\delta t} + u \frac{\delta \chi}{\delta x} + v \frac{\delta \chi}{\delta y} + w \frac{\delta \chi}{\delta z} &= \frac{\delta}{\delta x} \left(K_x \frac{\delta \chi}{\delta x} \right) + \frac{\delta}{\delta y} \left(K_y \frac{\delta \chi}{\delta y} \right) \\ &+ \frac{\delta}{\delta z} \left(K_z \frac{\delta \chi}{\delta z} \right) + \frac{S_a}{V} + \frac{P_a}{V} \end{aligned} \quad (3.13)$$

where, χ is pollutant concentration as a function of (x, y, z, t) for each pollutant a (subscript “ a ” left off for clarity) of interest, u , v , and w are wind velocity components in the x -, y -, and z -direction, respectively, S_a is source field for the pollutant a as a function of (x, y, z, t) , P_a is expression allowing for chemical change of the pollutant a through possible interaction with other pollutants and the solar radiation field (in the case of photochemical smog), and V is the volume of the elemental “box”.

Some assumptions must be made to solve this equation since it is nonlinear and it cannot be solved analytically. If the vertical flux is ignored, diffusion terms are uniform, and the box has homogeneous concentration, therefore Equation 3.13 can be rewritten as Equation 3.14 [52].

$$\frac{dCV}{dt} = QA + uC_{in}WH - uCWH \quad (3.14)$$

where Q is pollutant emission rate per unit area, C is homogeneous species concentration within the box, V is volume described by box, C_{in} is species concentration entering the box, A is horizontal area of the box $L \times W$, L is length of the box, W is width of the box, u is wind speed normal to the box, and H is mixing height.

Although the box model is practical and useful to evaluate average regional pollutant concentration as mentioned before, it has limitations such as turbulent eddy diffusivities in the horizontal plane. In reality, the box model is an application of the Eulerian box model that is discussed in the next section.

3.3.4 The Eulerian model

The Eulerian model was developed from the conservation of mass. The concentration $c(x, y, z, t)$ of the pollutant can be written as,

$$\frac{\partial c}{\partial t} = -V \cdot \nabla c + D \nabla^2 c + S \quad (3.15)$$

which is similar to Equation 3.13 but has an additional molecular diffusion term $D \nabla^2 c$ where D is molecular diffusivity, ∇^2 is the Laplacian operator, and ∇ is the gradient operator.

An appropriate assumption is to take the velocity V as the summation of two components (average and fluctuation) as shown in Equation 3.16.

$$V = \bar{u} + u' \quad (3.16)$$

where $\bar{u}$ means the stable component of the velocity and u' is a remaining unstable component. Another assumption for concentration c is

$$c = \langle c \rangle + c' \quad (3.17)$$

where $\langle \rangle$ represents the theoretical group mean. These assumptions then put into Equation 3.15 to find the group average.

$$\frac{\partial \langle c \rangle}{\partial t} = -\bar{u} \cdot \nabla \langle c \rangle - \nabla \cdot \langle c' u' \rangle + D \nabla^2 \langle c \rangle + \langle S \rangle \quad (3.18)$$

In this equation, according to the ergodic hypothesis, it is supposed that $\langle \bar{u} \rangle = \bar{u}$ and $\langle u' \rangle = 0$. The Eulerian model has a large unstable portion u' that is generally at the same order of magnitude as $\bar{u}$. Besides, the value of $\langle c' u' \rangle$ term is relatively large. It involves most of the turbulent atmospheric diffusion eddies and their diffusion effects which are orders of magnitudes larger than the molecular diffusion.

The unstable component of the velocity u' may be minimized but never eliminated because it plays an important role for ensemble averaging. It is demonstrated in Figure 3.9 as a member of infinite u' function [53].

Each potential member of u' the function produces a new concentration group average $\langle c \rangle$. In reality, if u' could be measured everywhere, c would be calculated correctly. Having not enough information, all theoretical values of u' are accepted more likely to occur. It is a very useful assumption. Therefore, even if monitoring data could be used for evaluation of $\langle c \rangle$ in the place of actual c , model outputs differ from measurements because it still carries the intrinsic uncertainty due to instability of the velocity component. On the other hand, the term $\nabla \cdot \langle c' u' \rangle$ in Equation 3.18 presents new unknowns. Thus, additional requirements are needed

relating to the ensemble mean concentration $\langle c \rangle$ to solve Equation 3.18. This relation is called K -theory or gradient-transport theory.

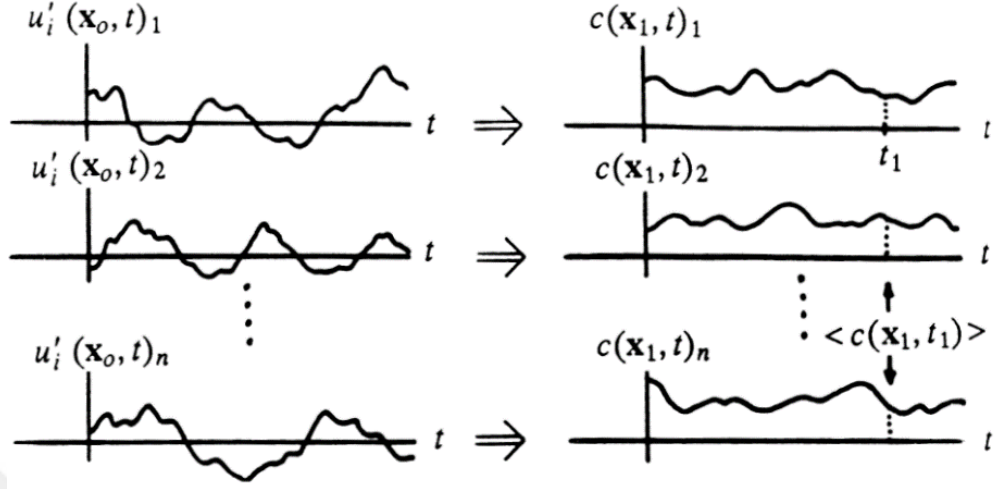


Figure 3.9 : Time change of the infinite family of velocity functions u'_i and the corresponding family of concentration distributions at fixed points x_o and x_1 [53].

It is assumed that

$$\langle c' u' \rangle = -K \nabla \langle c \rangle \quad (3.19)$$

where K is a (3x3) turbulent diffusivity tensor. Its elements come from meteorological measurements or assigned from other models. The turbulent eddy diffusivity tensor elements are all zero except diagonal elements as seen below.

$$\begin{bmatrix} K_{xx} & 0 & 0 \\ 0 & K_{yy} & 0 \\ 0 & 0 & K_{zz} \end{bmatrix} \quad (3.20)$$

where cross vector diffusivities are ignored. When Equation 3.18 is altered for the turbulent diffusivity tensor being diagonal, the molecular diffusivity being negligible, $\langle c \rangle$ represents average concentration, and chemically stable assumptions, the new equation is written as in Equation 3.21.

$$\frac{\partial \langle c \rangle}{\partial t} = -\bar{u} \cdot \nabla \langle c \rangle + \nabla \cdot K \nabla \langle c \rangle + S \quad (3.21)$$

3.3.5 The Lagrangian model

Lagrangian models allow simulating atmospheric dispersion in two ways. First one, an old approach, separates the Lagrangian box from the Eulerian box by using a changeable reference frame with an average wind trajectory described in Figure 3.10.

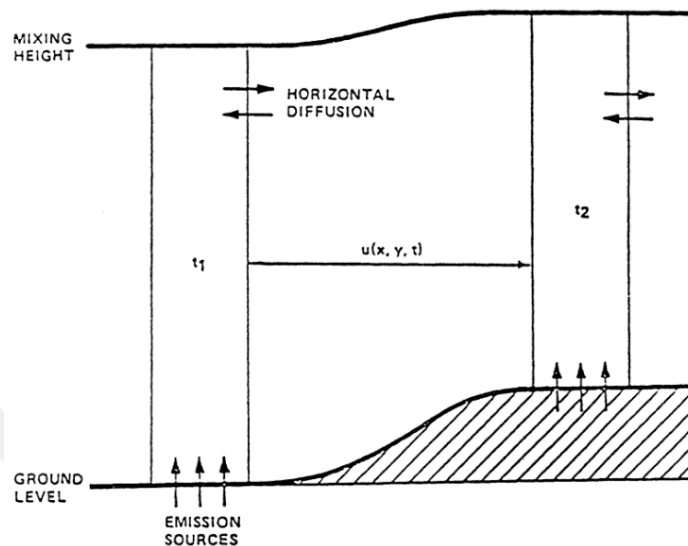


Figure 3.10 : Horizontal cross-section of Lagrangian box dynamics [54].

The difference between Lagrangian and Eulerian models is based on the reference grid system. Eulerian reference grid system stays the same while the Lagrangian reference grid acts in the average atmospheric motion as illustrated in Figure 3.11. Although the Lagrangian box model provides many advantages especially for photochemical simulations, it is easy to recognize some defects such as constant wind speed and direction through the AB and almost the same results with fixed Eulerian box model.

The second one, the Lagrangian particle model, is a more effective numerical method than the Lagrangian box model and has numerous application fields [56]. Particle dispersion techniques use transport terms with their numerical properties which require effort to calculate with the Eulerian grid models. Since particles follow the main flow, they are accepted in the Lagrangian universe and marked as the Lagrangian particles. The particle moving process may include both deterministic velocities and semi-random pseudo velocities produced by Monte Carlo methods. Monte Carlo methods are likely to give any group of solution for pathways of a single particle. If the system has enough particles, the mean particle ensemble is not affected by random pseudo velocities.

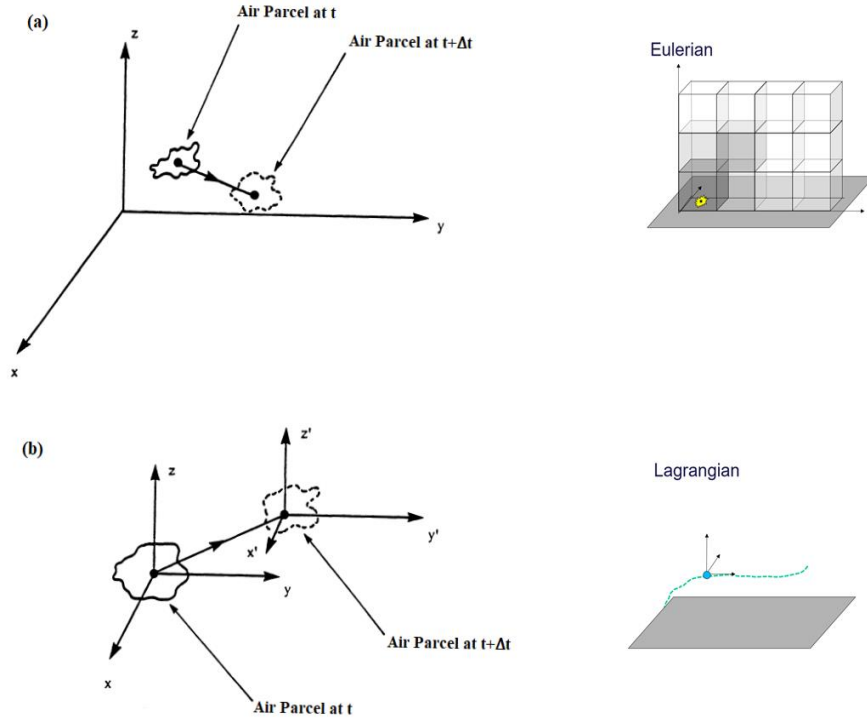


Figure 3.11 : (a) Eulerian reference system, (b) Lagrangian reference system [55].

The Lagrangian atmospheric dispersion equation of pollutant can be defined as,

$$\langle c(r, t) \rangle = \int_{-\infty}^t \int p(r, t | r', t') S(r', t') dr' dt' \quad (3.22)$$

where the system is integrated over all domain, $\langle c(r, t) \rangle$ represents the average group concentration at r at time t , $S(r', t')$ is the source term, $p(r, t | r', t')$ is probability function that air domain moves from r' at time t' to r at time t .

The probability density function plays a key role when deriving the Gaussian plume and puff model from the Lagrangian equation [57]. In the application of the Lagrangian particle method, released materials identified by a group of particles and each particle moves under the effect of pseudo velocities. Then the main three components of dispersion were determined: transport because of the mean bulk velocity, turbulent fluctuations of wind components, and the molecular diffusion (it is negligible). The vertical turbulent velocity is determined by designating each particle a stochastic term [58], [59], [60].

$$w = w_d + w_s \quad (3.23)$$

where w_d is deterministic velocity and w_s is stochastic velocity due to fluctuation [61]. In air dispersion calculation, the Langevin stochastic differential equation is used [62], [63], [64].

$$dw = -\left(\frac{w}{T_L}\right)dt + d\mu \quad (3.24)$$

where w is a vertical component of the Lagrangian particle velocity, T_L is the Lagrangian time scale, and $d\mu$ is random velocity frequency which depends on a random number generator. The more detailed explanation of this process could be found in [65].

If Equation 3.22 is redefined with the simplification of the function of p , it can be reduced to the Gaussian dispersion and puff model but more complex functions of p require numerical solutions.

In the application of the model, the particles are considered as moving with a velocity u_e which represents “pseudo velocity” at each time step. The velocity u_e is defined to avoid the calculation of each molecule in the atmospheric turbulent flow. The displacement is corrected after the calculation of the group average velocity. If a particle is placed on $x(t_1)$ location at the time t_1 , then its position at the time t_2 should be,

$$x(t_2) = x(t_1) + \int_{t_1}^{t_2} u[x(t), t] dt \quad (3.25)$$

where u is the wind vector at each location $x(t)$ of the particle pathway between time step t_1 and t_2 .

Atmospheric turbulent eddies prevent having information about the exact value of u . Because of the turbulent eddies, finding the velocity vector is not only improbable but also impossible. The solution is to specify equivalent wind vector component u_e as seen in Equation 3.26. Equation 3.26 explains that particles change position directly from $x(t_1)$ to $x(t_2)$ in the time interval (t_1, t_2) . u_e can be estimated from

Eulerian measurements of u but care should be given that the integral term of u_e in Equation 3.26 has to resemble a particle group aspect.

$$u_e = \int_{t_1}^{t_2} u[x(t), t] dt / (t_2 - t_1) \quad (3.26)$$

For instance, equivalent wind vector component can be described as,

$$u_e = \bar{u} + u' \quad (3.27)$$

To develop $\bar{u}$ from the average Eulerian wind vector at a particular location in Figure 3.12 is the most suitable way to represent the deterministic aspect of the average transport process.

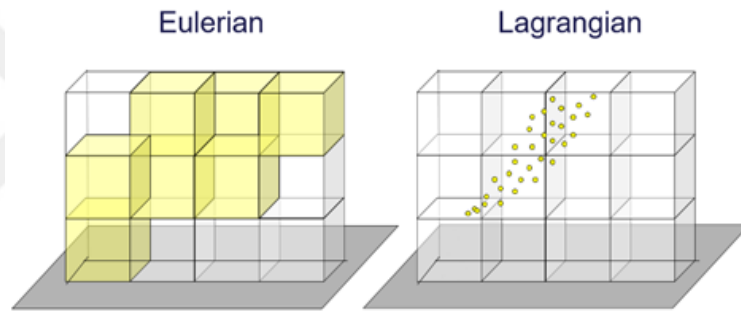


Figure 3.12 : Particle movement in the Eulerian and Lagrangian grid cells.

The $\bar{u}$ is generated from meteorological data statistics, while u' -the diffusivity velocity caused by turbulence- is generated from numerical perturbation artificially. The diffusivity velocity is mainly associated with turbulent characteristics and eddy profile. The key problem then is how u' values will be computed for the Lagrangian model. Fundamental approaches to compute u' are deterministic and stochastic approaches. In the deterministic approach, the diffusion theory is modified to get the Equation 3.28 [66], [67]. Computational domain must be separated into cells for solution.

$$u' = \left(-\frac{K}{c} \right) \nabla c \quad (3.28)$$

where K represents the eddy diffusion coefficient and c is the concentration.

Another method is the stochastic method which has a different basis and uses a randomness model (Monte Carlo types model). By the stochastic approach, u' is computed by modifying computer-generated random numbers. To execute this process, statistical information about u' is supplied by the Eulerian measurement of u . With this assumption, first order the auto-regression process called the Markov process provides a simple description for both Lagrangian wind vector fluctuations [68]. This process is defined as

$$u'(t_2) = R(\Delta t) u'(t_1) + u''(t_2) \quad (3.29)$$

where $R(\Delta t)$ is the autocorrelation vector between time interval $lag \Delta t = t_2 - t_1$ of u' components, u'' is a purely stochastic term. Equation 3.29 specifies that the output variable depends linearly on its previous value (u') and on stochastic term (u'') that is generated randomly. This phenomenon is performed for all particles individually as shown Figure 3.13.

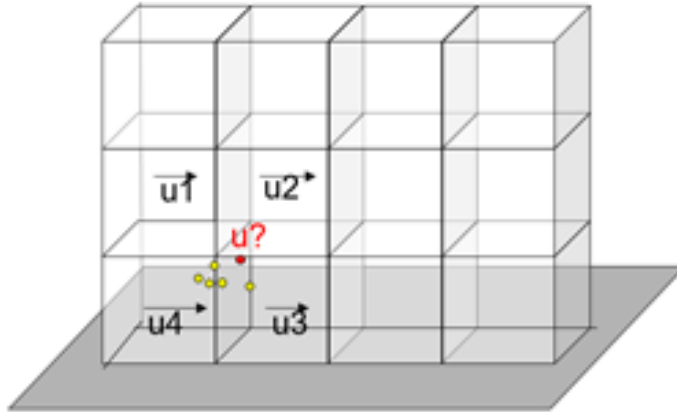


Figure 3.13 : New location after interpolation of deterministic velocity and generation of random fluctuation velocity.

If the Equation 3.29 is explained more comprehensively, it can be said that two or more particles might be at the same place at t_1 simultaneously even if their past history would be precisely the same but they follow different trajectories because of random generation of numbers. Their final positions or displacements are independent of each other. The increase in the particle history number mainly helps to obtain accurate results. According to particle history number, every possible pathway is satisfied to follow. Nevertheless, this phenomenon relies on situations and varies from case to case.

3.3.6 Pollutant transformation and deposition

The pollutant transformation indicates the mass M_r removed from original pollutant mass M_1 . The transformation depends on conversion rate R and time step Δt . The converted mass fraction β is calculated for each time step as follows [69].

$$\beta = R\Delta t \quad (3.30)$$

Then, the mass M_r is removed from pollutant M_1 as

$$M_r = \beta M_1 \quad (3.31)$$

The term deposition is described as a reduction of pollutant mass when it interacts ground surface due to the wind velocity or precipitate presence of rainfall. The dry deposition is calculated when the particle intersects with the surface layer Z_{sfc} which is the top of the second meteorological data layer with dry deposition velocity V_d that depends on species characteristics. The time constant for dry deposition is defined as [70]

$$\beta_{dry} = V_d \Delta Z_{sfc}^{-1} \quad (3.32)$$

The wet deposition is relevant to relative humidity (RH) of the cloud layers at all levels. The removal occurs when the RH first reaches 80% at the bottom of the cloud and drops below 60% at the top of the cloud [71]. The total deposition process can be described by using time constants as in Equation 3.33.

$$D_{total} = m(1 - \exp(-\Delta t(\beta_{dry} + \beta_{wet} + \beta_{decay} + \beta_{...}))) \quad (3.33)$$

where m is the particle mass.

The wet deposition process differs for particles and gases. Besides, noble gases are not affected by any deposition process.



4. CALCULATION METHODOLOGY OF HYSPLIT AND UPTAKE MECHANISMS

The HYSPLIT4 (Hybrid Single-Particle Lagrangian Integrated Trajectory) is a unique system code, which computes complex trajectory dispersion and deposition simulations [72]. Calculations can be performed with several models for different purposes with HYSPLIT4. The HYSPLIT4 uses puff and particle trajectory approaches. Its libraries consist of a particular arrangement of sub-modular directories for each calculation mode (trajectory or concentration calculations).

The meteorological data must be gridded as a latitude-longitude grid format or one of three conformal (Polar, Lambert, Mercator) map projections within arranged time intervals. The sub-grid data are created by interpolating from a given data file. This process reduces computational time efforts and shows the grid flexibility to obtain fine resolution [73].

Air concentration calculation requires the definition of the pollutant's emissions and physical characteristics (in case of deposition). Multiple pollutant releases could be simulated with several species involved in a single puff or each specie could be released as a puff.

The dispersion calculations performed by HYSPLIT4 are simply Gaussian, top-hat horizontal distribution within a puff, and fixed number particle dispersal [72]. A single released puff will grow until it becomes greater than the meteorological grid cell spacing and then it will be divided into several puffs.

HYSPLIT4 code is built up by NOAA Air Resources Laboratory. HYSPLIT4 allows users to estimate accidental releases and their consequences [74]. It also provides several hybrid models such as a vertical trajectory with a horizontal puff model to users [75]. On the other hand, HYSPLIT4 can find the origin of pollutants and locations where they are released from by using a back trajectory calculation. Although it is difficult to determine the origin from any arbitrary location where

pollutants reached, HYSPLIT4 set an excellent relation between the source and the receptor [76].

4.1 The Meteorological Data Files

In this section, the meteorological data files used in the HYSPLIT4 are reviewed and extra meteorological files are presented for the customized concentration simulations. All meteorological data files involve the data such as u and v components of wind velocity, temperature, and several other variables within a systematic grid at multiple levels and periods. These files are either already been in a format that can be read by HYSPLIT4 or they can be modified from other formats to be used by HYSPLIT4. There are several conversion programs available under the meteorology section in the HYSPLIT4 but it is not recommended because of the importance of data selection for HYSPLIT4 calculations [77].

Although meteorological data files are accessible from many sources, the majority of them have not been formatted. They have to be formatted to be used in the HYSPLIT4. The best way to access and convert the meteorological data is the graphical user interface (GUI) application in the HYSPLIT4. The “Convert to ARL” section under the Meteorology menu in the GUI application provides few alternatives to reformat data into HYSPLIT4 format. The format type may be presented as a Gridded Binary Format, Network Common Data Form (NetCDF) or customized binary format. The HYSPLIT4 data conversion is obligatory when each data format includes different variable names like data organization, horizontal grid projection or vertical coordinate system since HYSPLIT4 uses an even space grid (latitude-longitude or conformal projection) at multiple heights and periods throughout the simulation [78]. There are several sub-menus under the “Convert to ARL” menu to make the conversion from various sources. The European Centre for Medium-Range Weather Forecasts (ECMWF –ERA 40) [79] is one of them but to be able to use it in HYSPLIT4 at least following data are required: 3D (geop, temp, uvel, vvel, wvel, and rh); 2D (wm temp, and 10 UVel). These data are assigned as three different data files to ARL converter program. However, the formatted meteorological data files in ARL (Air Research Laboratory) format exist and can be obtained easily from different file transfer protocol (FTP) servers. If the administrator of a system restricts access to the FTP client because of security concerns, HTTP protocol which is using

“www” comment is also available [80]. The meteorological data servers that can be accessed to get data already been formatted compatible with HYSPLIT4 without any restrictions are [81].

- ARL server forecast data
- NCEP server forecast data
- ARL server archive data

HYSPLIT4 also provides an option to create user-entered input data files manually. This file is generated a spatially homogeneous custom meteorological file at 10 km resolution covering 250 by 250 km domain [82].

4.2 The Trajectory Calculation

In this section, the trajectory calculation model is discussed in more detail. The movement of a particle or a puff is described by the mean of three-dimensional velocity vectors at the initial-position $P(t)$ at time t and the first-estimate position $P'(t + \Delta t)$ at the time $(t + \Delta t)$. The velocity vector is linearly interpolated in both space and time at a time interval $(t, t + \Delta t)$ [83]. The first estimate position is

$$P'(t + \Delta t) = P(t) + V(P, t)\Delta t \quad (4.1)$$

and final position is

$$P(t + \Delta t) = P(t) + 0.5[V(P, t) + V(P', t + \Delta t)]\Delta t \quad (4.2)$$

In order to maintain stability, the advection distance per time step has to be less than the grid spacing U_{max} . The stability conditions ensure the following equation.

$$U_{max} (grid - units.min^{-1}) \Delta t(min) < 0.75(grid - units) \quad (4.3)$$

The trajectories are terminated if particles move out of the meteorological data grid. However, advection continues along the surface if particles come across to the ground surface [83].

The computational trajectory error is investigated by comparing the forward and the backward trajectory results. In this approach, the forward trajectory is computed first. Then the backward trajectory is computed. The backward trajectory endpoint is

compared with the original starting point of the forward trajectory calculation. The difference must be small for acceptable results. The ground surface must be discarded because of intersection complications [84]. On the other hand, the meteorological error is not playing a key role in computational error. The real problem is that the gridded meteorological data used represents a snapshot of the continuous meteorological data. If winds are uniform and do not change in time, it does not matter what resolution meteorological data have because all grid points will give the same value. If the wind field is varying quickly in space and time, the data resolution needs to be sufficiently dense to get good accuracy. It is called trajectory uncertainty [85]. The meteorological grid ensemble method is a useful tool to find the meteorological grid uncertainty. If backward simulation results are inconsistent with the forward trajectories, it shows the uncertainty of the meteorological grid. To find absolute trajectory error, the CAPTEX experiment provides aircraft measurements of the tracer concentration [86].

The input meteorological data generally includes a vertical motion field mostly in pressure units. These data files are used by the trajectory and dispersion calculations but in case of absence, the model has a choice to replace it with an internally calculated velocity profile. This approach starts with the surface η selection to carry the parcel on this surface, then the velocity w_η is computed by following equation [87].

$$w_\eta = \left(-\frac{\partial \eta}{\partial t} - u \frac{\partial \eta}{\partial x} - v \frac{\partial \eta}{\partial y} \right) / \left(\frac{\partial \eta}{\partial y} \right) \quad (4.4)$$

The terrain under the trajectory may intersect with trajectories. If this is the case, the computational approach in the HYSPLIT4 is that it continues along the ground surface until something else causes it to depart from the ground surface, either vertical motion field or isobaric calculations [88]. This phenomenon is illustrated in Figure 4.1.

It is possible to make multiple trajectories in time by defining restart time interval and duration. For example, if the restart time interval is 1 hour and duration is 4 hours, it means that every 1 hour new release begins at the end of the previous trajectories up to 4 hours [89]. Another option to visualize the flow pattern for a particular domain is to create a matrix configuration [90].

NOAA HYSPLIT MODEL
Forward trajectory starting at 0000 UTC 01 Sep 83
CDC1 Meteorological Data

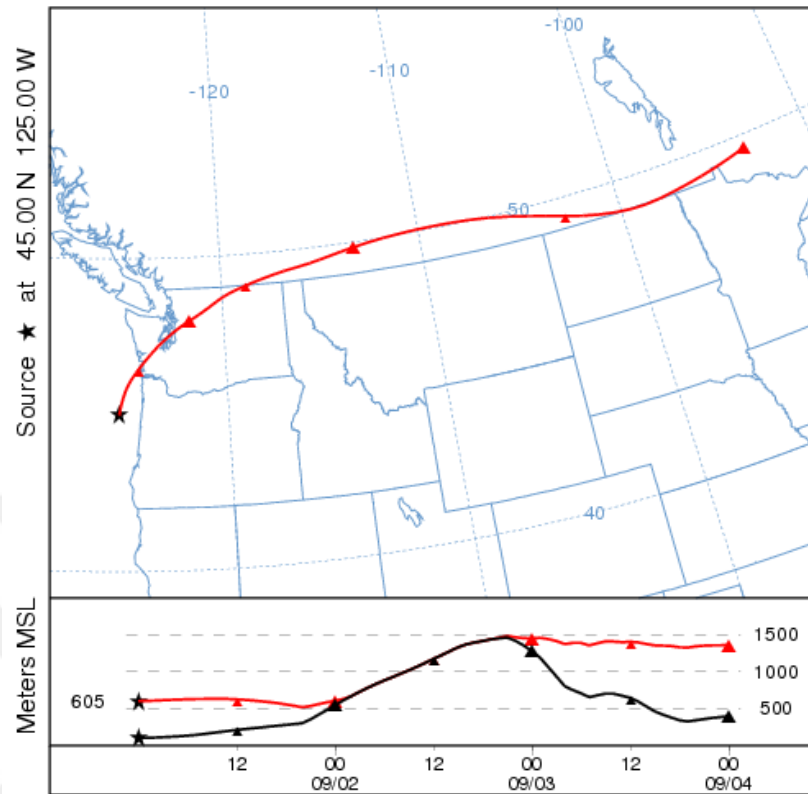


Figure 4.1 : The trajectory intersection with mountain [91].

4.3 The Air Concentration Calculation

In this section, the air concentration calculation is explained in detail. The main difference between air concentration calculation and a trajectory calculation is that the trajectory shows the path following the mean wind as prescribed by the input meteorological data whereas an air concentration calculation follows hundreds or thousands of particles essentially trajectory paths are computed for each one of those and look at the dispersal of particle density to calculate air concentration. Another important difference between air concentration calculation and single-particle trajectory calculation is that in the air concentration calculation, the turbulent component is added to the particle trajectory motion.

To ensure that the air concentration model is working correctly, a run with default variables was performed. After the run, the same result was obtained with the tutorial as illustrated in Figure 4.2 [92].

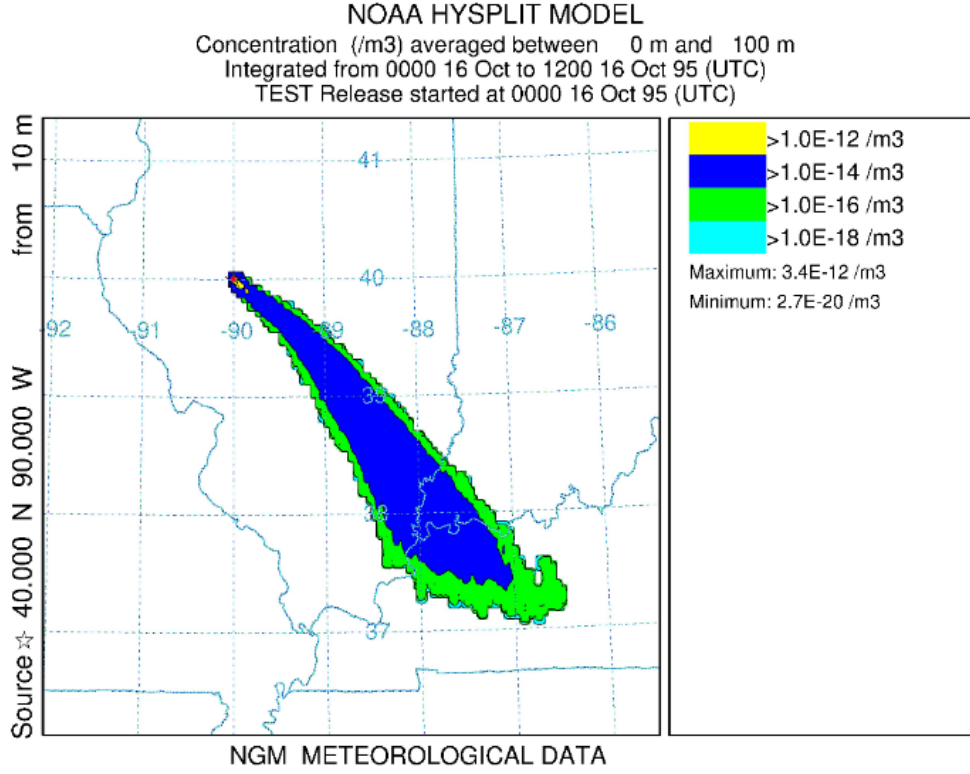


Figure 4.2 : Test model for air concentration calculation [94].

The 3D particle calculation consists of two main steps. The first result from advection motion utilizes the mean wind velocity from meteorological data file [93]. The mean position is adopted by the turbulent wind as shown in Equation 4.5.

$$P_{final}(t + \Delta t) = P_{mean}(t + \Delta t) + U'(t + \Delta t)\Delta t \quad (4.5)$$

where P_{final} is adjusted position, P_{mean} the position comes from advection and the horizontal turbulent velocity component $U'(t + \Delta t)$ at the final time that is derived from previous turbulent velocity component $U'(t)$, R is auto-correlation coefficient that relies on the time step, the Lagrangian time scale T_{Li} , and U'' is a computer-generated random component of velocity [93]. Thus, the turbulent velocity component is computed as

$$U'(t + \Delta t) = R(\Delta t)U'(t) + U''(1 - R(\Delta t)^2)^{0.5} \quad (4.6)$$

$$R(\Delta t) = \exp(-\Delta t / T_{Li}) \quad (4.7)$$

The Gaussian random component U'' originated from computer produced random number λ and the standard deviation of the velocity σ_u which is a statistical value calculated from meteorological data file content (stability, wind speed, etc.) [93].

$$\begin{aligned} U'' &= \sigma_u \lambda \\ \tan \sigma_\theta &= \sigma_u / U \end{aligned} \quad (4.8)$$

The standard deviation of the velocity component σ_u is also used to estimate particle dispersion and to compute the horizontal puff growth rate [93].

$$d\sigma_h / dt = \sigma_u \quad (4.9)$$

The air concentrations are evaluated by summing each 3D particle mass (m) at each time step that particle placed in a grid cell and dividing the summation by the grid cell volume where x , y , and z indicates the grid cell dimensions [93].

$$\Delta c = m(\Delta x \Delta y \Delta z)^{-1} \quad (4.10)$$

where c is the concentration whose unit depends on calculation such as kg/cm^3 , Bq/cm^3 etc.

The 3D particle calculation significantly depends on the number of particles released to obtain a realistic result. There is another approach in HYSPLIT4 to calculate air concentration. This approach includes modeling the centroid position of the particles by a single trajectory and modeling how the standard distribution of the particle positions within that centroid changes in time. This phenomenon is called the puff which is a single number to represent particle distribution concerning the centroid. If the particle release per cycle changes from 1 to 100 or more, the 100 puff will be released at the same time and the same location that they are mixed to different levels. This is the unique feature of HYSPLIT4. While the dispersion is modeled by the puff horizontally, vertical mixing treated as a particle model. Then, vertical puff should be divided into sub-puffs because of boundary layer wind shear. The three-dimensional puff model is a legacy from the old HYSPLIT version [95]. The puff distribution is really easy and faster than the 3D particle model in terms of justification.

4.4 Radioactive Pollutant and Dose Calculation

How the HYSPLIT4 execute the radioactive pollutant calculations is presented in this section. To understand the background of radioactive pollutant calculation, a basic examination is discussed first. A more realistic examination is described later.

In the basic examination, it is assumed that released radioactive particles decay and deposit. The air concentration and deposition will then be converted into dose. In HYSPLIT4, the source is described in units of Bq and the dose is described in units of rem although the SI unit of dose is Sievert (Sv). The decay of radioactive pollutants is considered similarly to transformation and deposition. Although the particle mass m increases with deposition, the deposited amount will decline in each time step due to the nature of the radioactive decay.

$$m_2 = m_1 \exp(-\beta_{rad} \Delta t) \quad (4.11)$$

where the decay constant β_{rad} is defined as

$$\beta_{rad} = \ln 2 / T_{1/2} \quad (4.12)$$

where $T_{1/2}$ is the half-life of the relevant radioactive isotope. While the decay process starts at the time of the particle release, actually the decay process begins as soon as radioactive particles are created. For example, when a nuclear accident takes place, the time of release to the atmosphere may not coincide with the time fission stopped. This is a significant issue for isotopes that have a shorter half-life [96].

To determine how the radioactive dose related to health effects, there is an available publication and toolbox of the United States Nuclear Regulatory Commission (NRC) [97]. The U.S. Environmental Protection Agency (USEPA) provides dose conversion factors to convert air concentration to dose [98].

The dose is the impact of the decay products on human tissue and varies according to radionuclide decay mode (alpha, beta, gamma) and energy, the mode of interaction (ingestion, inhalation, or exposure), and tissue type. For example, Cesium-137 has $3.4 \times 10^{-11} (rem/hr)/(Bq/m^3)$ for the airborne and $1.1 \times 10^{-12} (rem/hr)/(Bq/m^2)$ for the deposited materials [98]. Besides, some radionuclides have a long-half life like Cesium-137. One year after deposition, it decays so small amount that the

groundshine annually can be calculated by multiplying the dose conversion factor by 8760 hours. If the same simulation is performed with different meteorological data fields with different resolutions, calculation time will be different since the finer resolution meteorological data file contains more data to process. This also affects the air concentration results.

The grid resolution does not only affect a dispersion but also is directly linked with the deposition processes. The other thing to take into account is precipitation especially for the wet deposition which may be quite powerful as a removal mechanism for particles compared to gas. When the meteorological grid cells contain precipitation, if there is a particle within these grid cells, it will suffer some kind of removal. As the concentration grid cell gets smaller, for instance, half a degree grids compared to the one degree have 5 more grid cells, raining will likely to occur in one of these grid cells instead of all of them. As a result, fewer particles would be affected and perhaps the overall concentration downwind would be less when using a finer resolution [99]. Medium grid size is not a concern for the long-range simulations because of macro-scale meteorological data but there are a few parameters such as release location, the amount of release, and release time.

After the completion of an HYSPLIT4 run, there will be two options for post-processing (con2rem post-processing program) [100]. This post-processing program calculates the total dose by adding dose from each isotope which is calculated by multiplying the source term, the half-life of radionuclide, and dose conversion factor for each species [101].

4.5 Quantification of the Source Term

The source term in atmospheric dispersion calculation is used to characterize and quantify radioactive materials to be released to the environment. Before the characterization and quantification, the radioisotope inventory of the reactor has to be determined. The source term is then evaluated depending on the radionuclides being noble gases, halogens, etc. The radionuclide inventories in power reactors are grouped by U.S. NRC Regulatory Guide [102] the way seen in Table 4.1 and radionuclides in each group was listed in Table G.1 of Appendix G. The fractions in Table 4.1 are determined to be used in case of Design Basis Accident (DBA).

Table 4.1 : Release fraction of core inventory for power reactors [102].

Group	Release Fraction From	
	BWR	PWR
Noble Gases	1.0	1.0
Halogens	0.3	0.4
Alkali Metals	0.25	0.3
Tellurium Metals	0.05	0.05
Ba, Sr	0.02	0.02
Noble Metals	0.0025	0.0025
Cerium Group	0.0005	0.0005
Lanthanides	0.0002	0.0002

After the accident at unit 4 of the Chernobyl nuclear power plant, the estimated release of principal radionuclides and corresponding fraction were listed in Table 4.2 [104].

Table 4.2: The estimated release of principle radionuclides during the Chernobyl accident [104].

Radionuclide	Half-Life	Release Fraction %	Activity Released Bq 10 ¹⁸	Form of Radionuclides
Kr-85	10.72 hr	100	0.033	Inert Gas
Xe-133	5.25 day	100	1.7	Inert Gas
I-131	8.05 day	50	1.3	Volatile element
Te-132	3.26 day	35	0.32	Volatile element
Cs-137	30 year	30	0.29	Volatile element
Cs-134	2.06 year	25	0.19	Volatile element
Sr-89	50.5 day	10	2.0	Intermediately volatile
Sr-90	29.12 year	10	0.2	Intermediately volatile
Zr-95	64 day	8	4.4	Refractory element
Ru-103	39.3 day	8	4.1	Intermediately volatile
Ru-106	368 day	8	2.1	Intermediately volatile
Ba-140	12.7 day	15	2.9	Intermediately volatile
Ce-144	284 day	8	3.2	Refractory element
Pu-238	87.74 year	8	0.001	Refractory element
Pu-239	24390 year	8	0.0008	Refractory element
Pu-240	6537 year	8	0.001	Refractory element
Pu-241	14.4 year	8	0.17	Refractory element

In the safety analysis report of the ITU TRIGA Mark II research reactor, it is reported that the release fraction of fission products from the TRIGA fuel element measured experimentally by General Atomics as 1.5×10^{-5} [103]. In addition, it is assumed that 100 % of the noble gases and 50 % of halogens are released to the

environment. The source term is calculated for a fuel element having the highest power generation (2.6 % of the 250 kW full power) in the reactor that is operational for 4-years at full power.

In this study, on the contrary to SAR and as a hypothetical accident scenario, a release from all 69 fuel elements was considered by using real burnup value of the ITU TRIGA Mark II research reactor calculated by using the logbook. The other difference from the SAR is that beside halogens and noble gases some important radionuclides taking into account the Chernobyl and Fukushima Daiichi nuclear accidents were also considered.

To evaluate the radioisotope inventory in the ITU TRIGA Mark II research reactor, a Monte Carlo code MCNP version 6.2 was used for depletion calculation. It was assumed that the reactor was in continuous operation for 55 days at full power. The duration of the burnup was determined according to the total energy produced in the reactor since 1979 plus some additional margin to be more conservative. It should be noted here that the actual reactor operation is intermittent and it is impossible to simulate the burnup following real operational data in the log-book of the reactor. For burnup calculations, a generic MCNP input of the reactor generated by Dr. Senem Şentürk Lüle was modified. After the depletion calculation, the source term was determined with the same release fraction. The details of the source term used in this study is given in Section 5.3.

4.6 Specification of the Wind Direction by Clustering Release Particles

The trajectories of particles that are close to each other can be merged to form a cluster. The cluster analysis may be used to determine the wind direction in the long or short term. It will be used to make a comparison with other meteorological data to define wind direction in the long term for the reactor site. Since the wind direction relates to the particle cluster, each cluster shows the probability of particle flow pattern.

For example, the continuous release from Istanbul Ataturk Airport was explored by utilizing one-month meteorological data of April 2019. Every 6 hours the release took place periodically. At the end of a month, close trajectories were merged for every 12 hours. The clustering process resulted in 4 clusters because of the total

spatial variance criterion (TSV (%) < 20 or 30) as shown in Figure 4.3. As the wind mostly blew to the west, the particles moved mostly to the west of Istanbul in April 2019.

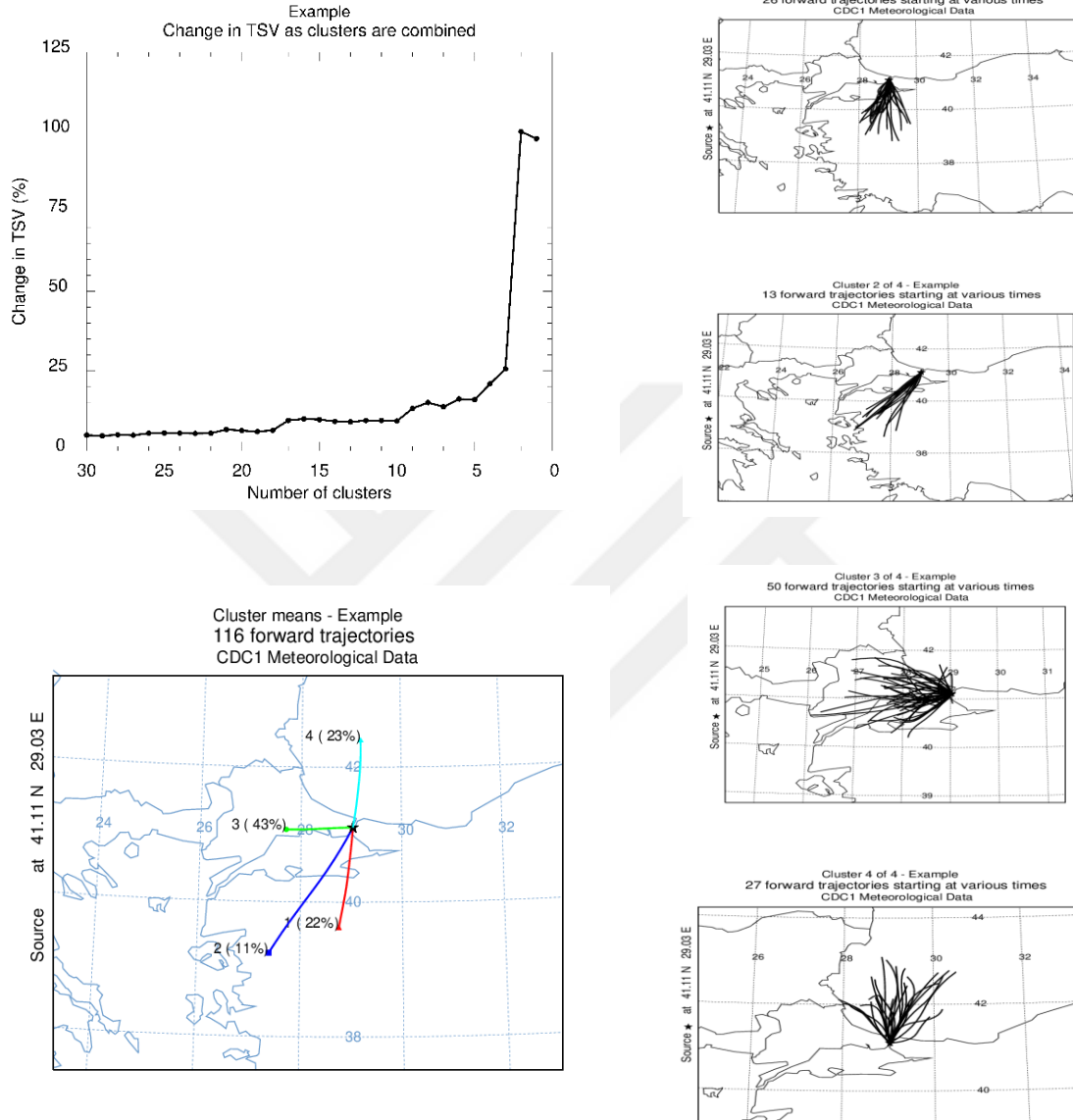


Figure 4.3 : Schematic representation of the clustering selection process.

4.7 Dilution Model

The dilution affects the transportation of radionuclides from the ground surface to down-gradient well in confined aquifers. In confined aquifers, the degree of vertical mixing can be distinguished into three regions: vertical mixed region ($\phi < 3.3$), intermediate region ($3.3 < \phi < 12$), and unmixed region ($\phi > 12$). ϕ is characterization factor that could be defined as follows [105], [106].

$$\phi = \frac{b^2}{\alpha_z x} \quad (4.13)$$

where b is aquifer thickness, α_z is vertical dispersivity, and x distance of down-gradient of release. Therefore, three different regions have three different dilutions and they are described in Equation 4.14, 4.15, and 4.16 for vertically mixed, intermediate, and unmixed regions, respectively.

$$D_{Lmixed} = R_d 4\pi n_e \frac{\sqrt{\alpha_x \alpha_y} bx}{V_T} \exp(\lambda t) \quad (4.14)$$

$$D_{Lintermediate} = R_d 4\pi n_e \frac{\sqrt{\alpha_x \alpha_y} bx}{V_T F(\phi)} \exp(\lambda t) \quad (4.15)$$

$$D_{Lunmixed} = R_d (4\pi x)^{3/2} n_e \frac{\sqrt{\alpha_x \alpha_y \alpha_z}}{2V_T} \exp(\lambda t) \quad (4.16)$$

where D_L is dilution, R_d is retardation coefficient, n_e is effective porosity, α_x, α_y are dispersivities in the specified direction, V_T is source volume, x is the distance down-gradient, b is the thickness of aquifer, λ is decay constant, $F(\phi)$ is correction function, and t is travel time determined by Equation 4.17 [107].

$$t = \frac{x}{U} R_d \quad (4.17)$$

where U is pore velocity and R_d is given in Equation 4.18.

$$U = \frac{-K(\Delta h / \Delta x)}{n_e} \text{ and } R_d = 1 + \frac{\rho_b}{n_e} K_d \quad (4.18)$$

where K is mean hydraulic conductivity, $(\Delta h / \Delta x)$ is the hydraulic gradient in the flow direction, ρ_b is bulk density, and K_d is distribution coefficient [108].

Because of surface-water/surface-water interface, the dilution is evaluated for concentration activity in the surface water (e.g., river, lake) as in Equation 4.19.

$$D_L = \frac{2R_d Q \sqrt{\pi \alpha_x x}}{UV_T} \exp(\lambda t) \quad (4.19)$$

where Q is the flow rate of surface water.

4.8 Foliar and Root Uptake Mechanism for Food

The radionuclides can be removed from radioactive cloud to surface vegetation and soils by deposition. After deposition, they may transfer to plants or lost from the plants by weathering, leaching, and abrasion. Radionuclides settling and loss processes can be explained simply with a single-compartment model as illustrated in Figure 4.4 [109].

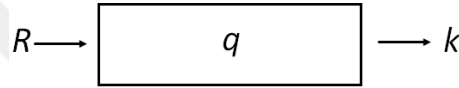


Figure 4.4 : Single compartment model.

In the model, R is the inflow rate of tracer, q is the tracer amount in the compartment, and k is outflow or loss rate of the tracer. If the model is mathematically set up, the time rate of change of tracer is

$$\frac{dq}{dt} = R - kt \quad (4.20)$$

When the integration is performed from 0 to t with $q = q(0)$ at time $t=0$, $q(t)$ is denoted by

$$q(t) = \frac{R}{k} (1 - e^{-kt}) + q(0)e^{-kt} \quad (4.21)$$

R can be evaluated by multiplication of deposition velocity V_d and average air concentration X (e.g., Ci m^{-3}).

$$R = XV_d \quad (4.22)$$

It is suitable to determine the loss rate k in terms of effective loss rate k_{eff} by adding weathering loss rate k_w to the decay constant k_p . If there is no tracer in compartment

initially meaning $q(0) = 0$ at $t=0$ and Equation 4.21 reaches equilibrium, $q = R/k$, then q can be redefined as in Equation 4.23.

$$q = \frac{XV_d}{(k_w + k_p)} \quad (4.23)$$

The activity concentration on the plant means activity amount in the dry biomass of plant (Bq kg^{-1}). Then, if q (Bq m^{-2}) is divided by dry mass of plant, average equilibrium activity concentration in the plant can be found as

$$C_{avg} = \frac{XV_d}{M(k_w + k_p)} \quad (4.24)$$

Equivalent time dependent activity concentration is obtained by substituting C_{avg} in place of q in Equation 4.20.

$$C_{avg}(t) = \frac{XV_d}{M(k_w + k_p)} \left(1 - e^{-(k_w + k_p)t}\right) + C_{avg}(0)e^{-(k_w + k_p)t} \quad (4.25)$$

The root uptake can be specified utilizing the transfer factor F_v even though it depends on several parameters (e.g., type of radionuclides, plant soil, and so on).

The dimensionless transfer factor that is interpreted as the ratio between the dry weight activity concentration in the plant and the dry weight activity concentration in the soil layer is given in Equation 4.26.

$$F_v = \frac{\text{Dry weight concentration in the plants}}{\text{Dry weight concentration in the specified soil layer}} \left(\frac{\text{Bq kg}^{-1}}{\text{Bq kg}^{-1}} \right) \quad (4.26)$$

The dry weight concentration is generally used for all plants but the fresh weight can also be used if appropriate fresh to dry weight conversion factor is available in the literature. The recommended F_v values are tabulated in [110].



5. RESULTS AND DISCUSSIONS

5.1 Simulation of I-131 Release Based on ITU TRIGA Mark II Safety Analysis Report

In this section, the results of I-131 release in ITU TRIGA Mark II Safety Analysis Report (SAR) were compared with the simulation results of HYSPLIT4 code that uses the same parameters to verify the methodology used in the thesis.

According to the scenario described in SAR, the highest power generating fuel element (2.6 % of the full power) fails after reactor operates at full power for 4 years. With release fraction of 1.5×10^{-5} from the fuel, 50 % of I-131 produced is released to the environment. Therefore, I-131 activity in the air is 1.16×10^{-3} Ci. The details of all the assumptions regarding the source term were discussed in Section 4.5.

In addition, in SAR, the average wind speed which is measured for 20 years at 10 m elevation is 4.7 m/s in the dominant wind direction of NE, air stability condition is a highly stable weather condition that is Pasquill-F. Since the I-131 activity in the air is 1.16×10^{-3} Ci and the discharging of air developed within half hours, the radioactivity discharge rate Q'' is 6.44×10^{-7} Ci.s⁻¹.

In the SAR, the activity concentration of I-131 is calculated as 7.00×10^{-12} Ci.m⁻³ at 4000 m away from the chimney by using the Gaussian dispersion equation given in Equation 3.8.

The simulation had been carried out with the same data described above with HYSPLIT4 code. When the source term is added to the Gaussian dispersion model, time dependency drops and discharge duration lost its importance for the analytical solution. On the other hand, for computational simulation, the discharge time is essential. Since approximately 15 minutes later pollutant reaches the location 4000 m away from the chimney, 15-minute samples were taken throughout the simulations. As the source term discharged after the half-hour, the second sample was taken 30 minutes later to make a comparison with the calculated value in SAR.

The simulation results showed that the maximum activity concentration is 5.9×10^{-12} Ci.m⁻³ at location 4000 m away from the chimney (in grid cell that enclosed the center of ITU Ayazağa Campus) as shown in Figure 5.1(a). It was found that the simulated activity concentration 4000 m away from the chimney is quite similar to the calculated result in the SAR.

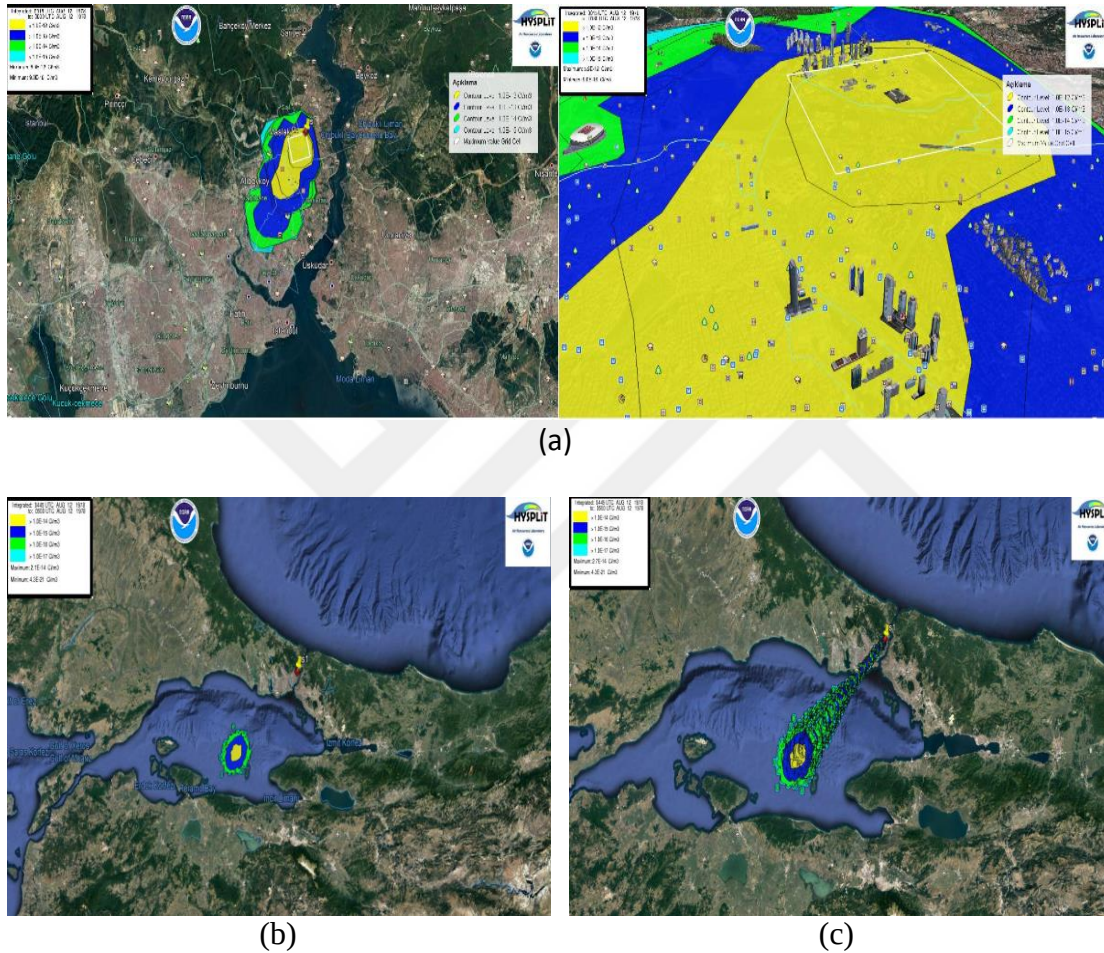


Figure 5.1 : Concentration and location of I-131 after release simulation based on SAR. After (a) 30 m, (b) after 5 h, (c) the overlapping throughout 5 h.

Although, the route of the radioactive I-131 cloud is demonstrated in Figure 5.1(a) and (b), it is more clear in Figure 5.2. After 5 hours, the cloud is over the Marmara Sea. The maximum concentration in it is rather low (2.7×10^{-14} Ci.m⁻³).

It should be noted here that although the simulation result agrees quite well with the analytical solution in SAR, the 3D particle model result is more realistic because radioactive particles may leave the computational grid cell domain which is not considered by analytical solution performed in SAR.

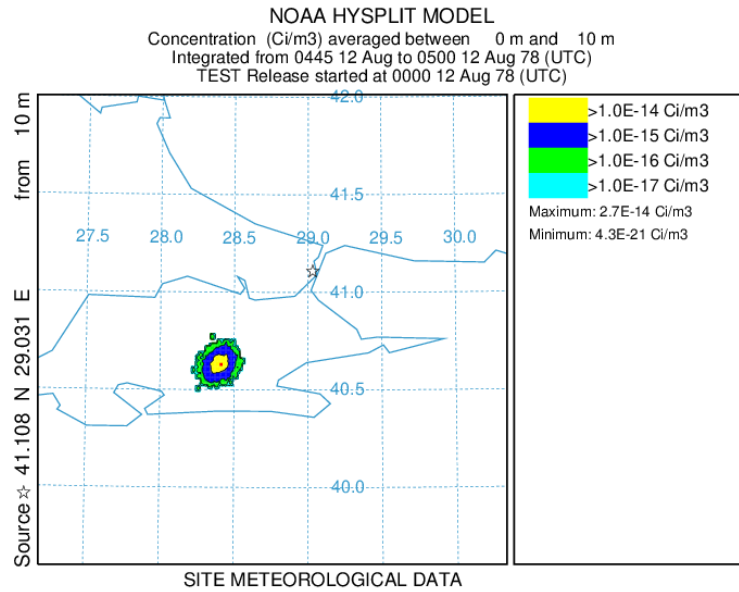


Figure 5.2 : The activity concentration and location of I-131 at the end of 5 h simulation.

5.2 The Determination of Specifications of Wind at Reactor Site

The meteorological data information taken from Istanbul/Ataturk automated surface observing system (ASOS) was used to examine long-term records of wind speed and direction. The records of the last 10 years from 31 December 2010 to 01 March 2020 are illustrated in Figure 5.3 as a wind rose.

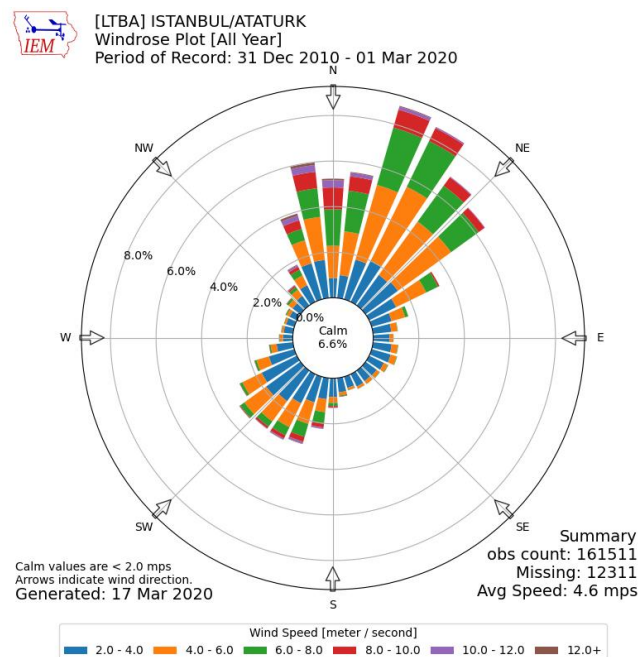


Figure 5.3 : Customized wind rose plot for the last ten years for Ataturk Airport.

Figure 5.3 shows that the wind at the station blows from the northeast most of the time. In fact, the 4 spokes around the northeast direction (NE, NNE, ENE) comprise 31% of all wind directions. This is the sum of the frequencies of each of these directions ($9+8.5+7+6.5=31\%$). The wind rose also provides details of speed from different directions. The wind blows approximately 2% of the time at speeds between 2.0 m/s and 4.0 m/s. Also, in 10 years, the wind blows with 4.6 m/s speed averagely through between NNE and NE (50-70) direction. The frequency percentage data table is given in Figure C.1 of Appendix C.

As mentioned in the particle clustering section (4.5), clustering is an alternative to describe the wind direction by using a reanalysis of global meteorological data. In this analysis, data from 01 January 2011 to 29 February 2020 was used to specify particle trajectories that are released 10 m above the ground at the location (41.107975, 29.031184 - latitude and longitude, Figure 5.4) of the reactor building.

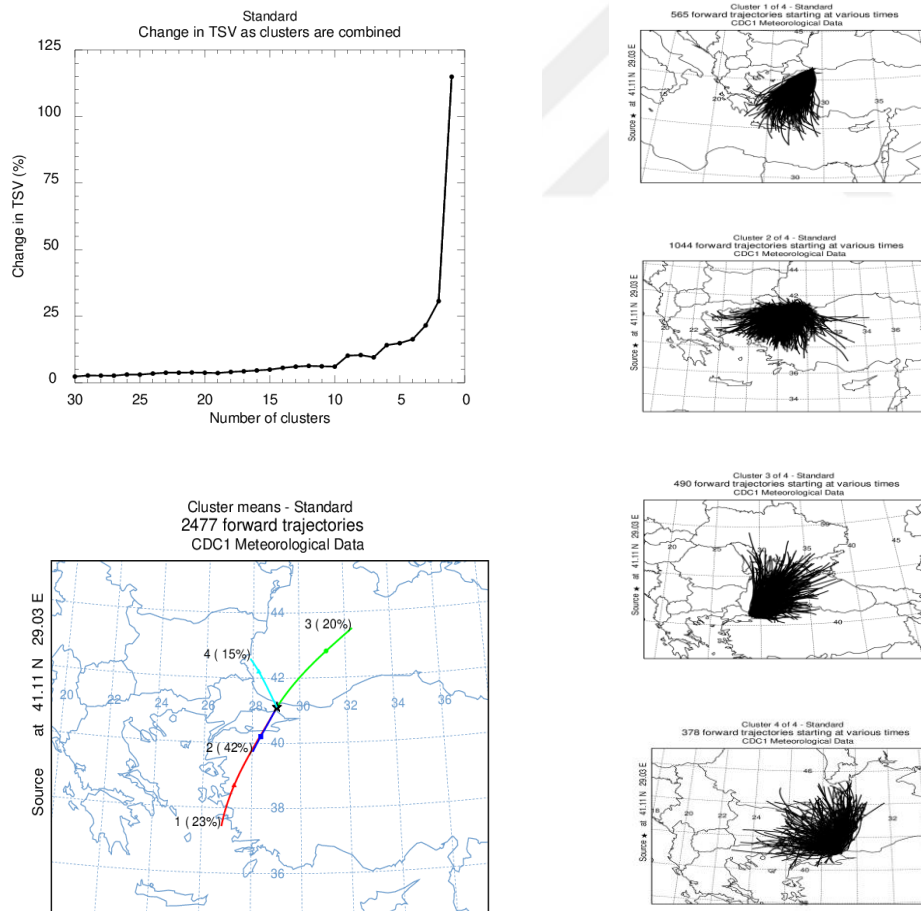


Figure 5.4: Determination of the wind direction by using global reanalysis meteorological data.

The number of clusters was selected as a 4 due to the TSV criterion (20% or 30%). These clusters are displayed in Figure 5.4.

The wind direction directly relates to the particle cluster percentage. Summation of the cluster one and two (65%) shows that the wind blows mostly NNE direction, while more than half of the rest (20 %) blows SW direction.

The wind direction mainly refers to the same direction although the data source completely differs for both measurement and cluster analysis.

Additionally, the year 2019 cluster analysis has been carried out to find the most critical case for long-range simulation in case of accident would happen and results are listed in Table 5.1. In order to understand tabulated data clearly, monthly and overall 2019 data were plotted and graphics are added in Appendix C. According to results, April can be regarded as the most critical month because trajectories mostly move over Istanbul, while they do not move long-range compared to others.

Table 5.1 : The wind direction distribution frequency by months in 2019.

Wind Direction	Monthly frequency (%)											
	01	02	03	04	05	06	07	08	09	10	11	12
000-020	0	0	0	43	33	0	0	0	0	35	53	0
010-030	0	0	0	0	0	0	0	0	0	0	0	13
020-040	0	31	0	0	0	0	0	13	0	33	0	0
030-050	0	0	33	0	0	0	49	0	41	14	0	21
040-060	45	24	18	11	0	18	0	40	0	0	0	0
050-070	0	24	0	0	0	0	40	48	26	0	0	0
060-080	0	0	0	0	0	47	0	0	0	0	0	0
070-090	0	0	0	22	0	35	0	0	0	0	0	0
090-110	0	0	0	0	0	0	11	0	0	0	0	0
120-140	0	0	0	0	8	0	0	0	0	0	0	0
150-170	0	0	0	0	0	0	0	0	0	0	0	16
210-230	0	21	0	0	0	0	0	0	0	0	0	0
220-240	0	0	30	0	48	0	0	0	0	0	0	0
230-250	42	0	0	0	0	0	0	0	11	0	0	0
240-260	0	0	0	0	0	0	0	0	0	0	22	20
250-270	0	0	0	23	0	0	0	0	0	18	0	11
260-280	0	0	0	0	0	0	0	0	0	0	24	21
270-290	0	0	0	0	0	0	0	0	0	0	0	0
280-300	0	0	18	0	11	0	0	0	0	0	0	0
300-320	13	0	0	0	0	0	0	0	0	0	0	0
330-350	0	0	0	0	0	0	0	0	22	0	0	0

5.3 The Source Term of ITU TRIGA Mark II Research Reactor for Hypothetical Accident Scenario

According to data in the logbook of the ITU TRIGA Mark II research reactor, it is calculated that it had been operated 51 days at 250 kW full power since the first criticality in 1979. 55 days of burned fuel inventory was computed by modifying the generic, verified ITU TRIGA MCNP input generated by Dr. Senem Şentürk Lüle with MCNP version 6.2 Monte Carlo code. These four more days are added to include a more conservative approach. Although hundreds of fission products are produced in fuel during power generation, in the case of an accident most of them do not leave the fuel material and some of them release with certain fraction as discussed in Section 4.5. As reported by U.S. EPR Commission [111] and Japan Nuclear Regulation Authority (NRA JAPAN) [112], radionuclides that are significantly important for accidental release are listed in Table 5.2 together with calculated source term activities for 55 days operation at full power at ITU TRIGA Mark II research reactor.

It should be noted here that the source term does not represent the whole core inventory after 55 days of operation. It is calculated by using the assumptions stated in Section 4.5.

Table 5.2 also includes groundshine and cloudshine effective dose coefficients that are presented in the U.S. Environmental Protection Agency Federal Guidance Report 12, U.S. EPA FGR 12 [113], and U.S. EPA FGR 13 [114]. They will be used in the later stages of this study.

5.4 Meteorological Data and Release Models

The meteorological data file was created manually for 2 days with 3-hour time interval. The wind direction and speed was defined between NE-NNE direction and 4.6 m/s, respectively. The mixing depth was determined as 1500 meters with a stable condition. The stability condition investigation will be discussed in detail in the next section. The high grid resolution carries great importance for short term release calculations. Therefore, high grid resolution was used for all calculations with 0.002-degree gap between latitude longitude.

Table 5.2: Emission inventory for 55 days burned ITU TRIGA Mark II Research Reactor fuels and their effective dose coefficient factors.

Nuclides	T _{1/2} (day)	Activity (Bq)	Effective DCFs	
			Cloudshine (rem/hr)/(Bq/m ³)	Groundshine (rem/hr)/(Bq/m ²)
U-237	6.75	4.46E+05	2.15E-09	4.79E-11
U-239	0.016	2.70E+08	7.81E-10	1.85E-11
Np-239	2.355	2.70E+08	2.77E-09	5.87E-11
Kr-85	3914.94	3.06E+06	8.64E-11	3.78E-12
Sr-89	50.57	2.91E+09	2.78E-11	8.17E-13
Sr-90	10634.12	2.49E+07	2.71E-12	1.02E-13
Y-90	2.67	3.15E+07	6.84E-11	1.92E-12
Y-91	58.51	3.19E+09	9.36E-11	2.07E-12
Y-92	0.15	6.98E+09	4.68E-09	9.11E-11
Y-93	0.42	7.37E+09	1.73E-09	3.28E-11
Zr-95	63.98	3.62E+09	1.30E-08	2.60E-10
Zr-97	0.70	7.39E+09	3.25E-09	6.26E-11
Nb-95	35.15	1.53E+09	1.35E-08	2.69E-10
Nb-97	0.05	7.40E+09	1.14E-08	2.32E-10
Mo-99	2.75	7.11E+09	2.52E-09	6.41E-11
Ru-103	39.28	2.20E+09	7.52E-09	1.61E-10
Ru-105	0.185	1.14E+09	1.29E-08	2.81E-10
Ru-106	368.2	4.65E+07	0.00E+00	0.00E+00
Rh-105	1.473	1.13E+09	1.34E-09	2.74E-11
Ag-111	7.45	2.01E+07	4.64E-10	9.61E-12
Sn-123	129.2	3.49E+05	1.45E-10	3.01E-12
Sn-125	9.64	1.09E+07	5.69E-09	1.08E-10
Sb-125	1007.4	1.39E+06	7.27E-09	1.53E-10
Te-132	3.25	5.00E+09	3.36E-09	7.63E-11
I-131	8.04	3.33E+09	6.08E-09	1.31E-10
I-135	0.28	7.31E+09	2.71E-08	5.29E-10
Xe-133	5.25	7.79E+09	4.82E-10	1.43E-11
Xe-135	0.38	5.75E+09	4.00E-09	9.00E-11
Cs-134	754.211	1.10E+05	2.55E-08	5.33E-10
Cs-136	13.1	6.68E+06	3.58E-08	7.31E-10
Cs-137	10960	2.50E+07	3.34E-11	1.08E-12
Ba-140	12.74	6.87E+09	2.91E-09	6.84E-11
La-140	1.68	6.82E+09	4.00E-08	7.78E-10
Ce-141	32.50	4.67E+09	1.23E-09	2.66E-11
Ce-143	33.04	6.92E+09	4.64E-09	1.00E-10
Ce-144	284.30	8.01E+08	3.07E-10	7.31E-12
Pr-143	13.57	6.46E+09	6.98E-11	7.42E-12
Nd-147	10.98	2.53E+09	2.06E-09	5.04E-11
Pm-147	958.07	7.37E+07	2.49E-13	1.23E-14
Pm-148	5.368	1.02E+06	1.04E-08	1.97E-10
Pm-149	2.21	1.26E+09	1.95E-10	4.07E-12
Pm-151	1.18	4.89E+08	5.44E-09	1.13E-10
Sm-151	32868	5.20E+05	1.30E-14	1.81E-15
Sm-153	1.94	1.87E+08	8.21E-10	2.24E-11
Eu-154	3213.76	9.02E+02	2.21E-08	4.28E-10
Eu-155	1811.39	8.08E+05	8.96E-10	2.12E-11
Eu-156	15.19	1.75E+07	2.43E-08	4.43E-10

The emission time was designated as half hour which means that all determined inventory (the source term) will be released in half-hour.

Three different dispersion models are available in HYSPLIT4: 3D and particle-vertical, Gaussian-horizontal and particle-vertical (Gh-Pv), and Top-Hat-horizontal and particle-vertical (THh-Pv). The simulations using all these three models were performed for six hours with the same meteorological input data for Cs-137 radioisotope to observe their differences and to decide which one to select for later stage simulations. Six hours later, the radioactive cloud reached the same location for all models but air concentration in 3D particle model is 2.0 and 2.2 times higher than Gh-Pv and THh-Pv models, respectively, (Figure 5.5). In order to perform the assessment with high level of conservatism, the 3D particle model was chosen for the following simulations.

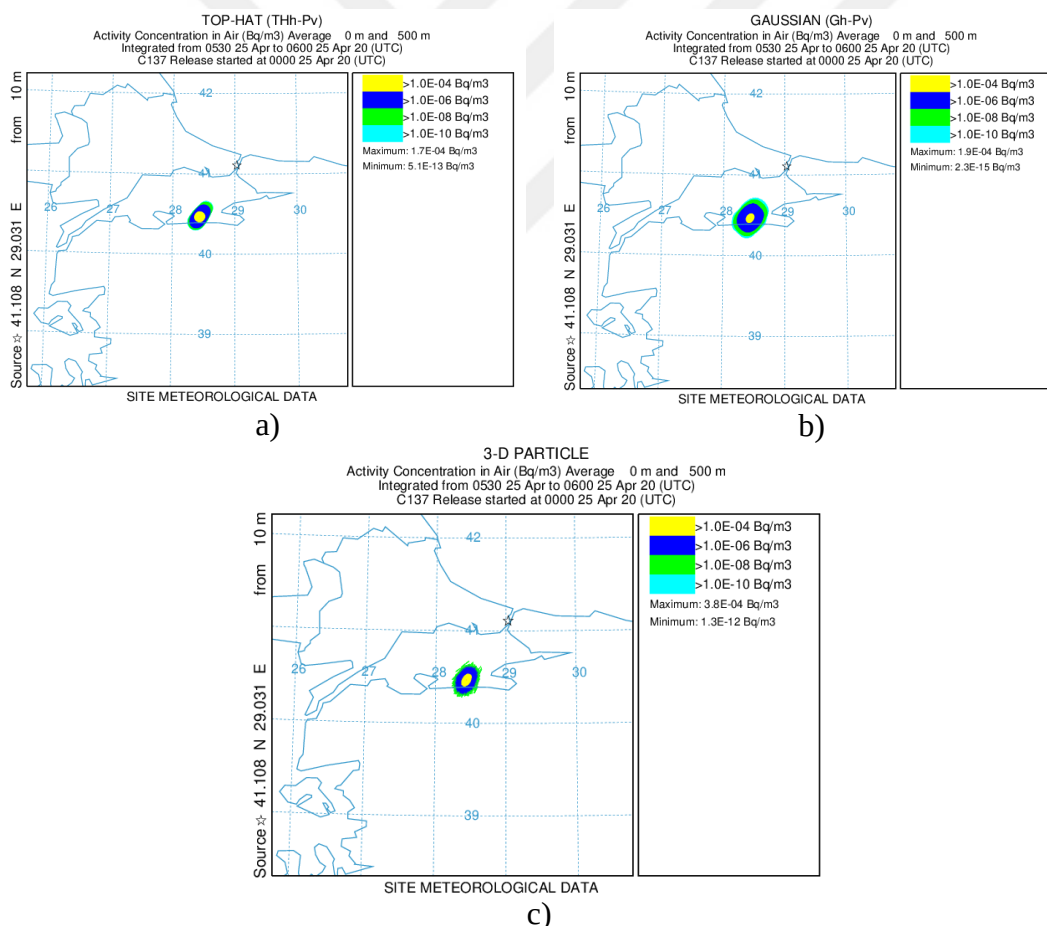


Figure 5.5 : Activity concentrations after six hours of simulation for a) Top-Hat (THh-Pv), b) Gaussian (Gh-Pv), c) 3D Particle model.

5.5 The Effect of Meteorological Data

In this section, two different meteorological data files were created in terms of the stability category to examine their effects and to select the appropriate one for the later stage calculations. The first one is stable (Pasquill-F) and the second one is unstable (Pasquill-A). The other properties remained the same and the results are compared for Cs-137 radionuclide.

During the first half-hour simulation, maximum concentration occurred in the same grid cell (41.106, 29.09) for both categories, stable and unstable. But, Figure 5.6 shows that the activity concentration in the same grid cell for stable condition (60.02 mBq/m³) is considerably greater than unstable conditions (45.78 mBq/m³). After 12 hours, the maximum averaged deposition of Cs-137 for the stable condition is approximately 1.91 times higher than unstable condition but the dissipation of particles horizontally and vertically are smaller as illustrated in Figure 5.7. Since stable condition offered more conservative results, stable (Pasquill-F) condition was preferred to describe the stability category in this study.

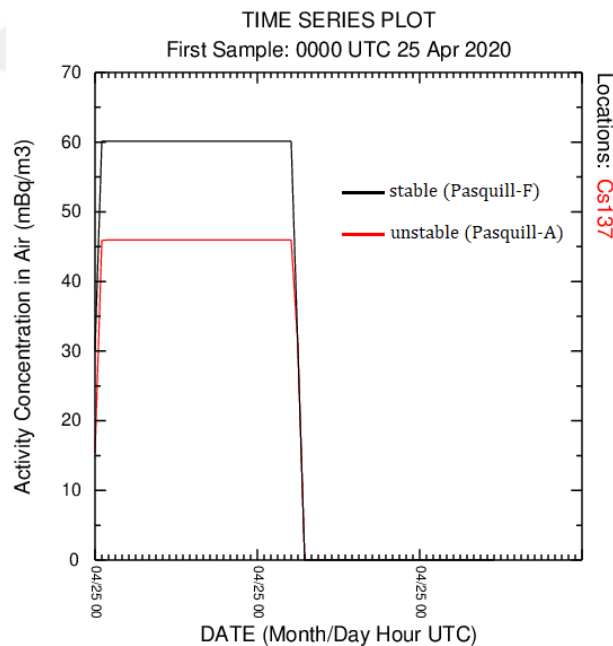
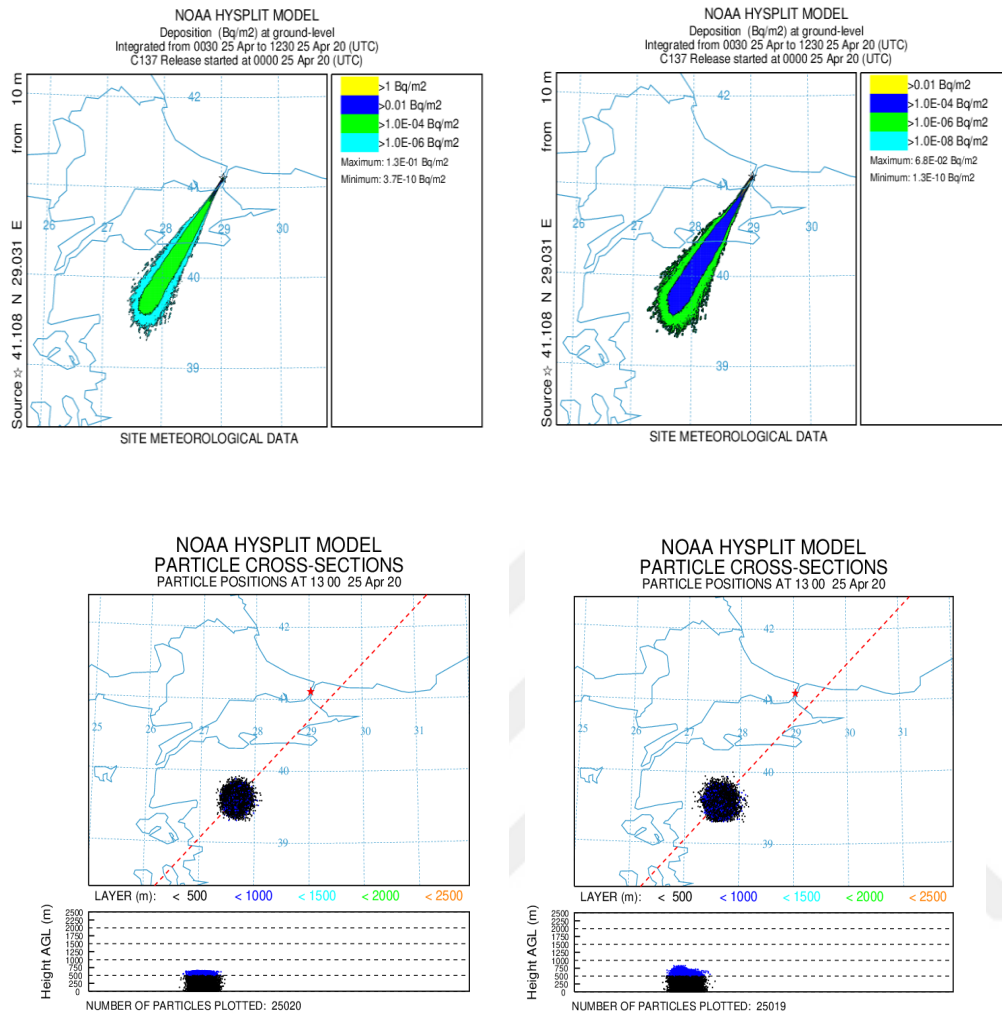


Figure 5.6: Maximum activity concentration of C-137 in the air for the stable and unstable condition.

In addition, it is observed that 13 hours later unstable particles left the meteorological grid domain; stable ones did not.



a) stable

b) unstable

Figure 5.7 : Particle movements under (a) stable and (b) unstable conditions.

5.6 External Exposure

In the light of previous analysis, a stable meteorological data file was created with NE-NNE wind direction, 4.6 m/s wind speed, 1500 m mixing depth, 3-hour interval, and stable (Pasquill-F) condition to continue the next analysis. The emission hours, the concentration grid resolution, the concentration grid height above ground level, and the average sampling interval were set as half-hour, 0.002 degree, 500 m, and half hour, respectively. The source term described in Section 5.3 was used.

During the simulations, all radionuclides in Table 5.2 were accepted as particle except noble gases (e.g. Kr-85, Xe-133, and Xe-135).

Since user-entered meteorological data do not available to set parameters for wet deposition, to compensate wet deposition, dry deposition velocity value 0.001 m/s (defined in the HYSPLIT4 code for Cs-137) was increased by 50 % which is suggested in code's tutorial [100]. As a result, the dry deposition velocity was determined as 0.0015 m/s for all particles. In addition, there is no deposition for noble gases because of their chemical characteristics.

The first average concentration sample was taken during the half-hour simulation. The maximum grid cell location was determined again as (41.106, 29.09) which is 320 m away from the reactor building along the wind direction (near the Chemical and Metallurgical Engineering Faculty building). The maximum activity concentration in air and deposition on the ground surface for each nuclide are listed in Table 5.3.

Half an hour airborne and groundshine effective dose rates were calculated by multiplying activity concentration in air and activity deposition at ground surface with effective DCFs which were provided in Table 5.2 before. The results are tabulated in Table 5.3.

Total exposure from cloudshine is 1.02 $\mu\text{rem}/0.5\text{h}$ and total exposure from groundshine is 0.35 $\mu\text{rem}/0.5\text{h}$. For the first half-hour, total exposure rate from both cloudshine and groundshine was calculated as 1.37 $\mu\text{rem}/0.5\text{h}$ in the maximum grid cell boundary and that value was used in comparing compliance with the dose criteria (0.1 rem/yr or 5.59 $\mu\text{rem}/0.5\text{h}$ for the public) of ICRP 103 [115].

One hour later maximum grid cell location was found at location (41.056, 28.983; Şişli) while 1.5 hours later the radioactive cloud reached maximum concentration at the location (41.004, 28.935; Fatih), and finally, at the end of the 2 hours, it left the historical peninsula and new maximum concentration grid cell was located (40.964, 28.897; Marmara Sea) over the Marmara Sea as illustrated in Figure 5.8. These locations were circled by taking the released point which is the reactor site at the ITU Ayazağa Campus as the center of the circle.

Figure 5.8 displays the movement of the pollutant starting from the first location to exiting the historical peninsula as described above.

Table 5.3 : Activity concentration and effective dose rate values for the first maximum concentration grid cell.

Nuclides	Activity Concentration in Air (Bq/m ³)	Airborne Dose (rem/0.5h)	Activity Deposition at Ground (Bq/ m ²)	Ground Shine Dose (rem/0.5h)
U-237	1.04E-03	1.12E-12	1.88E-02	4.50E-13
U-239	6.05E-01	2.36E-10	7.33E+00	6.78E-11
Np-239	6.32E-01	8.75E-10	1.14E+01	3.33E-10
Kr-85	7.18E-03	3.10E-13	0.00E+00	0.00E+00
Sr-89	6.81E+00	9.47E-11	1.23E+02	5.01E-11
Sr-90	5.83E-02	7.90E-14	1.05E+00	5.36E-14
Y-90	7.37E-02	2.52E-12	1.33E+00	1.27E-12
Y-91	7.46E+00	3.49E-10	1.34E+02	1.39E-10
Y-92	1.63E+01	3.80E-08	2.80E+02	1.27E-08
Y-93	1.72E+01	1.49E-08	3.06E+02	5.01E-09
Zr-95	8.46E+00	5.50E-08	1.53E+02	1.98E-08
Zr-97	1.73E+01	2.81E-08	3.08E+02	9.65E-09
Nb-95	3.58E+00	2.42E-08	6.45E+01	8.68E-09
Nb-97	1.71E+01	9.74E-08	2.69E+02	3.12E-08
Mo-99	1.66E+01	2.10E-08	2.99E+02	9.59E-09
Ru-103	5.15E+00	1.93E-08	9.27E+01	7.46E-09
Ru-105	2.66E+00	1.72E-08	4.62E+01	6.49E-09
Ru-106	1.09E-01	0.00E+00	1.97E+00	0.00E+00
Rh-105	2.65E+00	1.78E-09	4.75E+01	6.51E-10
Ag-111	4.71E-02	1.09E-11	8.47E-01	4.07E-12
Sn-123	8.17E-04	5.92E-14	1.47E-02	2.21E-14
Sn-125	2.55E-02	7.24E-11	4.58E-01	2.48E-11
Sb-125	3.25E-03	1.18E-11	5.85E-02	4.48E-12
Te-132	1.17E+01	1.97E-08	2.11E+02	8.03E-09
I-131	7.82E+00	2.38E-08	1.41E+02	9.22E-09
I-135	1.71E+01	2.31E-07	3.00E+02	7.94E-08
Xe-133	1.83E+01	4.41E-09	0.00E+00	0.00E+00
Xe-135	1.35E+01	2.69E-08	0.00E+00	0.00E+00
Cs-134	2.56E-04	3.27E-12	4.62E-03	1.23E-12
Cs-136	1.56E-02	2.80E-10	2.81E-01	1.03E-10
Cs-137	6.02E-02	9.79E-13	1.06E+00	5.71E-13
Ba-140	1.61E+01	2.34E-08	2.89E+02	9.90E-09
La-140	1.60E+01	3.19E-07	2.86E+02	1.11E-07
Ce-141	1.09E+01	6.72E-09	1.97E+02	2.62E-09
Ce-143	1.62E+01	3.76E-08	2.92E+02	1.46E-08
Ce-144	1.88E+00	2.88E-10	3.39E+01	1.24E-10
Pr-143	1.51E+01	5.28E-10	2.72E+02	1.01E-09
Nd-147	5.92E+00	6.09E-09	1.07E+02	2.69E-09
Pm-147	1.72E-01	2.15E-14	3.11E+00	1.91E-14
Pm-148	2.39E-03	1.24E-11	4.30E-02	4.23E-12
Pm-149	2.95E+00	2.88E-10	5.30E+01	1.08E-10
Pm-151	1.14E+00	3.11E-09	2.05E+01	1.16E-09
Sm-151	1.22E-03	7.92E-18	2.20E-02	1.99E-17
Sm-153	4.37E-01	1.79E-10	7.85E+00	8.79E-11
Eu-154	2.11E-06	2.33E-14	3.80E-05	8.13E-15
Eu-155	1.90E-03	8.50E-13	3.42E-02	3.62E-13
Eu-156	4.11E-02	4.99E-10	7.40E-01	1.64E-10
Total		1.02E-06		3.53E-07

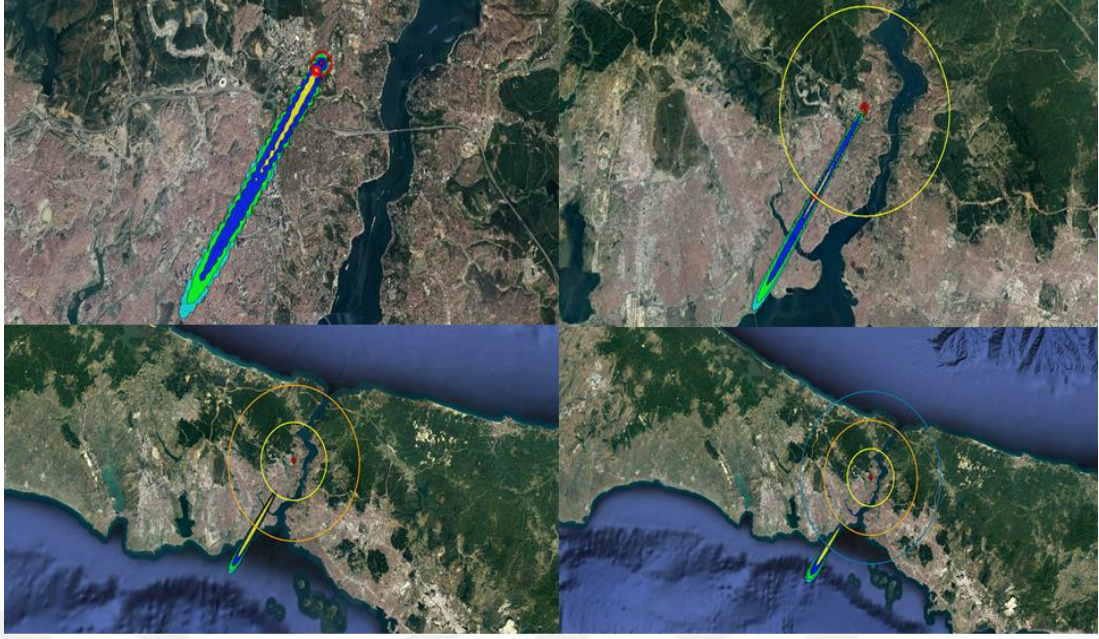


Figure 5.8 : Movement of the radioactive cloud over Istanbul.

The distance of maximum concentration grid cells from the reactor building for residential areas and their population are tabulated in Table 5.4 with effective dose rates for ground and airborne.

Table 5.4 : The effective dose rates, settling places, and populations of maximum concentration grid cells.

Residential Area	Population	Compass Direction of Wind	Distance from Reactor Building (m)	Duration (h)	Dose (rem)	
					Ground	Airborne
ITU	50000	NE-NNE	320	0.0-0.5	3.53E-07	1.02E-06
Ayazağa Campus				Annually	2.06E-04	
Şişli	280000	NE-NNE	7320	0.5-1.0	1.65E-07	5.14E-07
				Annually	1.00E-04	
Fatih	443500	NE-NNE	14661	1.0-1.5	6.07E-08	2.07E-07
				Annually	3.83E-05	
Marmara Sea	n/a	NE-NNE	21964	1.5-2.0	1.62E-08	6.09E-08
				Annually	1.05E-05	

During one year, the activity of radionuclides on the ground surface would undergo nuclear transformation. The number of transformations was estimated for each radionuclide using the following equation or integration of chain reaction for progenies of radionuclides if they have importance [113].

$$\int_0^T A(t)dt = A(0) \frac{[1 - e^{-\lambda T}]}{\lambda} \left(\frac{Bq - s}{m^2} \right) \quad (5.1)$$

$A(t)$, $A(0)$, and λ indicates activity (disintegration per unit time) of radionuclide at time t , the initial activity of radionuclide, and decay constant, respectively. The annual effective dose after one-year exposure was calculated by multiplying the number of the transformation of radionuclides during one year with groundshine effective DCFs of radionuclides that were summarized in Table 5.2 and adding half-hour airborne dose rate.

In conclusion, Table 5.4 shows that after one year, individuals located at ITU Ayazağa Campus would be maximally exposed to 0.206 mrem which does not exceed 0.1 rem/year (ICRP 103) limit.

5.7 Mortality and Morbidity Due to Inhalation and Ingestion of Tap Water and Food

In order to evaluate the health effects of radionuclide intake, mortality and morbidity risk coefficient were evaluated by using Dose and Risk Calculation (DCAL) software and U.S. EPA FGR 13 [114].

5.7.1 Inhalation calculations

Half-hour's average inhalation intake was calculated by utilizing average daily usage of environmental media for the population. The average combined inhalation intake rate, which of course depends on the gender, was taken as $18 \text{ m}^3 \cdot \text{d}^{-1}$ from Table E.1 in Appendix E. For instance, for I-131, the activity concentration of I-131 is 7.82 Bq/m^3 as seen in Table 5.3. The half-hour average inhalation activity for I-131 is calculated with methodology seen in Equation 5.2.

The same calculation for other radionuclides were performed and results are listed in Table 5.5 with the mortality and morbidity risk coefficients for inhalation and tap water intake.

$$7.82 \frac{\text{Bq}}{\text{m}^3} \cdot 18 \frac{\text{m}^3}{\text{d}} \frac{1\text{d}}{8.64 \times 10^4 \text{ s}} \cdot 1800 \text{ s} = 2.93 \text{ Bq} \quad (5.2)$$

Table 5.5 : Inhalation and tap water ingestion risk coefficients and intake quantities.

Nuclides	Half an hour average inhalation intake (Bq)	Lifetime intake from tap water (Bq)	Risk coefficient for inhalation		Risk coefficient for tap water intake	
			Mortality (Bq ⁻¹)	Morbidity (Bq ⁻¹)	Mortality (Bq ⁻¹)	Morbidity (Bq ⁻¹)
U-237	3.92E-04	0.00E+00	1.50E-10	1.74E-10	7.31E-11	1.32E-10
U-239	2.27E-01	0.00E+00	1.33E-12	1.54E-12	1.40E-12	2.00E-12
Np-239	2.37E-01	0.00E+00	8.75E-11	1.08E-10	7.70E-11	1.39E-10
Sr-89	2.55E+00	6.43E-03	5.52E-10	6.32E-10	2.10E-10	3.47E-10
Sr-90	2.19E-02	1.91E+01	2.65E-09	2.84E-09	1.34E-09	1.51E-09
Y-90	2.77E-02	0.00E+00	5.77E-11	9.65E-11	2.70E-10	4.88E-10
Y-91	2.80E+00	3.02E-05	1.98E-10	2.44E-10	2.39E-10	4.33E-10
Y-92	6.10E+00	0.00E+00	7.66E-12	1.26E-11	3.92E-11	6.69E-11
Y-93	6.46E+00	0.00E+00	2.07E-11	3.56E-11	1.09E-10	1.94E-10
Zr-95	3.17E+00	6.69E-09	3.92E-10	4.47E-10	7.09E-11	1.24E-10
Zr-97	6.48E+00	0.00E+00	8.76E-11	1.30E-10	1.89E-10	3.38E-10
Nb-95	1.34E+00	6.99E-17	1.26E-10	1.47E-10	3.81E-11	6.63E-11
Nb-97	6.41E+00	0.00E+00	2.39E-12	2.88E-12	3.60E-12	5.29E-12
Mo-99	6.24E+00	0.00E+00	8.75E-11	1.16E-10	3.12E-11	4.33E-11
Ru-103	1.93E+00	0.00E+00	2.12E-10	2.41E-10	5.88E-11	1.04E-10
Ru-105	9.97E-01	0.00E+00	1.30E-11	1.75E-11	2.10E-11	3.64E-11
Ru-106	4.09E-02	4.64E-05	2.42E-09	2.77E-09	6.45E-10	1.14E-09
Rh-105	9.94E-01	0.00E+00	7.18E-12	1.24E-11	3.52E-11	6.33E-11
Ag-111	1.77E-02	0.00E+00	1.45E-10	1.80E-10	1.24E-10	2.22E-10
Sn-123	3.06E-04	0.00E+00	1.01E-10	1.58E-10	2.10E-10	3.78E-10
Sn-125	9.55E-03	0.00E+00	9.11E-11	1.51E-10	3.01E-10	5.43E-10
Sb-125	1.22E-03	5.86E-02	3.99E-10	4.49E-10	7.27E-11	1.18E-10
Te-132	4.39E+00	0.00E+00	1.74E-10	2.52E-10	1.94E-10	4.60E-10
I-131	2.93E+00	1.68E-08	5.55E-11	5.27E-10	1.31E-10	1.23E-09
I-135	6.40E+00	0.00E+00	5.56E-12	3.63E-11	1.39E-11	8.24E-11
Cs-134	9.61E-05	3.15E-05	3.05E-10	4.45E-10	7.91E-10	1.14E-09
Cs-136	5.86E-03	0.00E+00	6.39E-11	9.44E-11	1.60E-10	2.34E-10
Cs-137	2.20E-02	2.31E+00	2.19E-10	3.21E-10	5.66E-10	8.22E-10
Ba-140	6.03E+00	5.55E-13	4.61E-10	5.48E-10	2.30E-10	4.03E-10
La-140	5.98E+00	0.00E+00	3.67E-11	5.83E-11	1.67E-10	2.69E-10
Ce-141	4.10E+00	0.00E+00	2.76E-10	3.07E-10	6.93E-11	1.25E-10
Ce-143	6.08E+00	0.00E+00	7.50E-11	1.01E-10	1.07E-10	1.92E-10
Ce-144	7.05E-01	0.00E+00	2.65E-09	2.96E-09	5.27E-10	9.52E-10
Pr-143	5.67E+00	0.00E+00	3.86E-11	5.48E-11	1.18E-10	2.14E-10
Nd-147	2.22E+00	0.00E+00	3.76E-11	5.24E-11	1.04E-10	1.88E-10
Pm-147	6.47E-02	0.00E+00	2.28E-10	2.46E-10	2.55E-11	4.57E-11
Pm-148	8.95E-04	0.00E+00	6.50E-11	9.92E-11	2.58E-10	4.65E-10
Pm-149	1.11E+00	0.00E+00	1.92E-11	3.15E-11	9.95E-11	1.80E-10
Pm-151	4.28E-01	0.00E+00	1.31E-11	2.16E-11	6.78E-11	1.22E-10
Sm-151	4.57E-04	2.62E-05	2.31E-10	2.48E-10	8.46E-12	1.50E-11
Sm-153	1.64E-01	0.00E+00	1.42E-11	2.32E-11	7.25E-11	1.31E-10
Eu-154	7.90E-07	0.00E+00	4.69E-09	5.71E-09	1.59E-10	2.79E-10
Eu-155	7.11E-04	0.00E+00	4.48E-10	5.15E-10	2.88E-11	5.13E-11
Eu-156	1.54E-02	0.00E+00	9.98E-11	1.40E-10	1.91E-10	3.42E-10

Mortality and morbidity values were found by multiplying the activities with the risk coefficient of radionuclides. Radionuclide specific mortality and morbidity values due to inhalation are displayed in Figure 5.9. It shows that the risk for the lanthanide group and some of the radionuclides in the metal group (e.g. Sr-89, Y-91, Zr-95, Zr-97, Ba-140) are relatively high besides I-131, I-132, and Te-132.

5.7.2 Tap water intake calculations

To determine tap water intake consequences, firstly, it was assumed that all deposited radionuclides washed out with rainfall and leaked into a shallow well that would be located 3 m directly down-gradient from the overflow. Groundwater would lie in a homogeneous soil layer of 1 m thickness under the water table condition. The average bulk density of soil was taken as 1.3 g.cm^{-3} [116], the average effective porosity n_e as 0.21, the mean average hydraulic conductivity K as $3.31 \times 10^{-4} \text{ cm.s}^{-1}$, and gradient of soil as 0.01 [106]. By using these information, the pore velocity was calculated from Equation 4.18. The distribution coefficients K_d in mL.g^{-1} for radionuclides are listed in Table E.2 (Appendix E). Then, retardation coefficient R_d and travel time t for radionuclides were determined from Equation 4.17 and 4.18. The characterization factor ϕ was calculated from Equation 4.13 to show the effect of aquifer for specified region. The dispersivities of soil α_x , α_y , and α_z were 0.5 m, 0.128 m, 0.128 m, respectively [117]. The average height of the rainfall flow was defined as 0.15 m to find the volume of flow and then according to the characterization factor, the dilutions of radionuclides were found by applying Equation 4.14.

Maximum precipitation measured by Turkish State Meteorological Service at the Kireçburnu region (close to the ITU Ayazağa Campus) in 2017 is 128.9 kg.m^{-2} [118]. The activity concentration of radionuclides in the rain flow was estimated by dividing the deposition amount at the ground surface with the precipitation and converting it from kilogram to liters. Eventually, the quantity of each radionuclide reaching well shallow was estimated by dividing the concentration of radionuclides in the rain flow to dilution of radionuclides. The water in the well was accepted as potable water. In addition, the deposition site is 300 m up-gradient from the ITU lake with a representative flow of $1 \text{ m}^3.\text{s}^{-1}$ [119]. The radionuclide concentration in the lake was found with Equation 4.19.

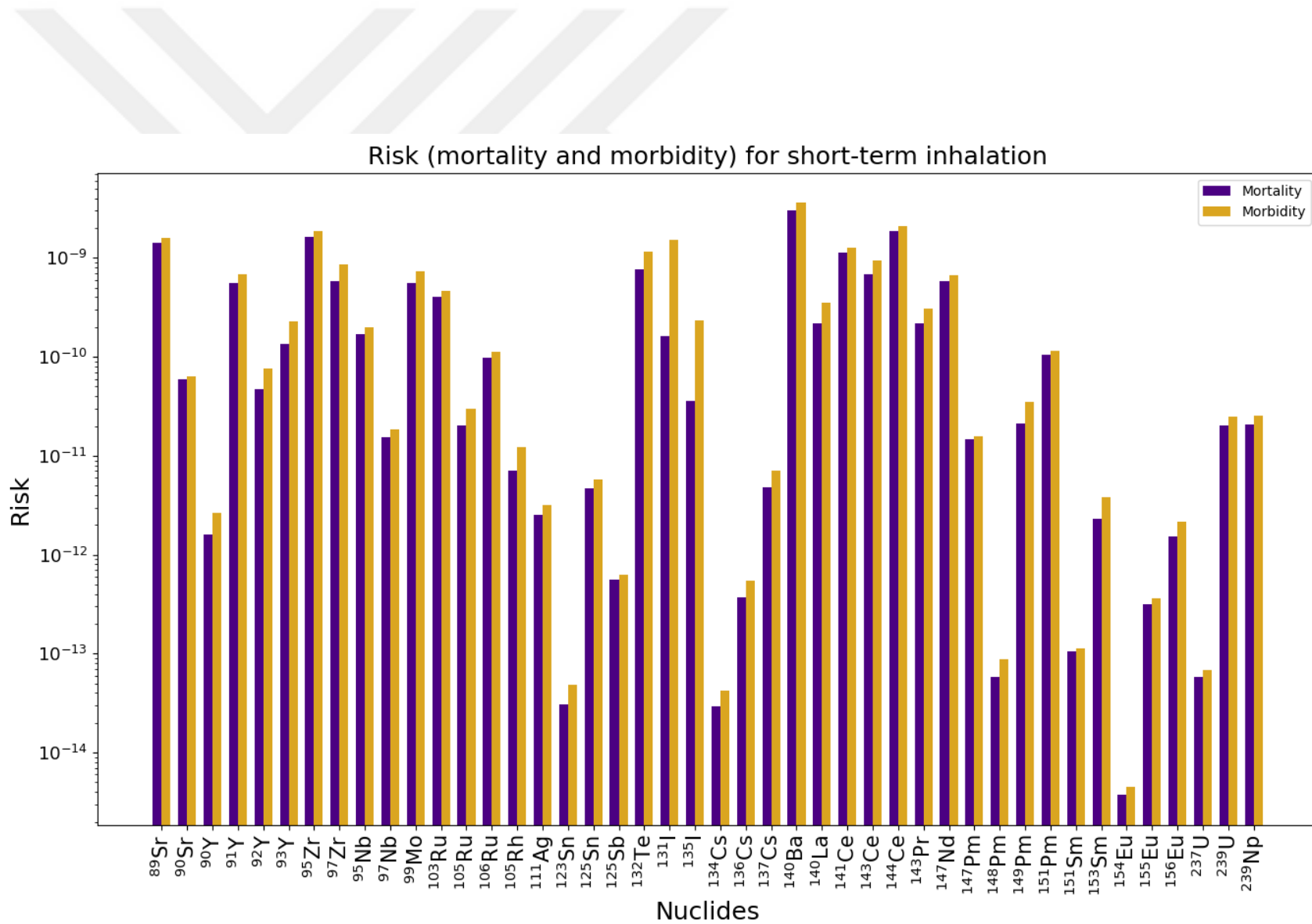


Figure 5.9 : Mortality and morbidity risk values for inhalation.

It was given in Table E.1 that the average daily intake rate R of tap water is $1.07 \text{ m}^3 \cdot \text{L}^{-1}$ and the average life expectancy is 27448 d (75.2 y) [114].

In order to find the ingestion of activity from tap water for the lifetime, multiplication of initial activity concentration in the tap water with daily intake rate throughout a lifetime is not correct because radionuclide activities in the tap water deplete with time even if all of them have already been below the limit defined by CAC (10 Bq/L [120])-some of them were displayed in Figure 5.10 and Figure 5.11.

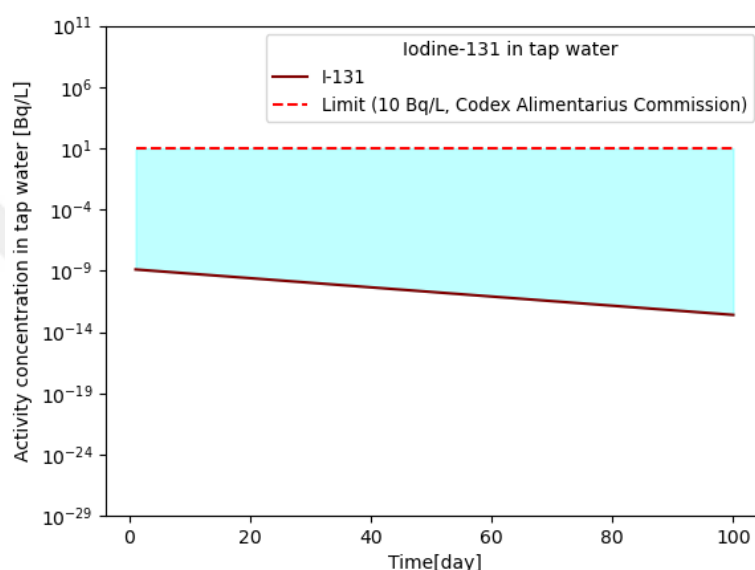


Figure 5.10 : I-131 activity concentration change in tap water over time.

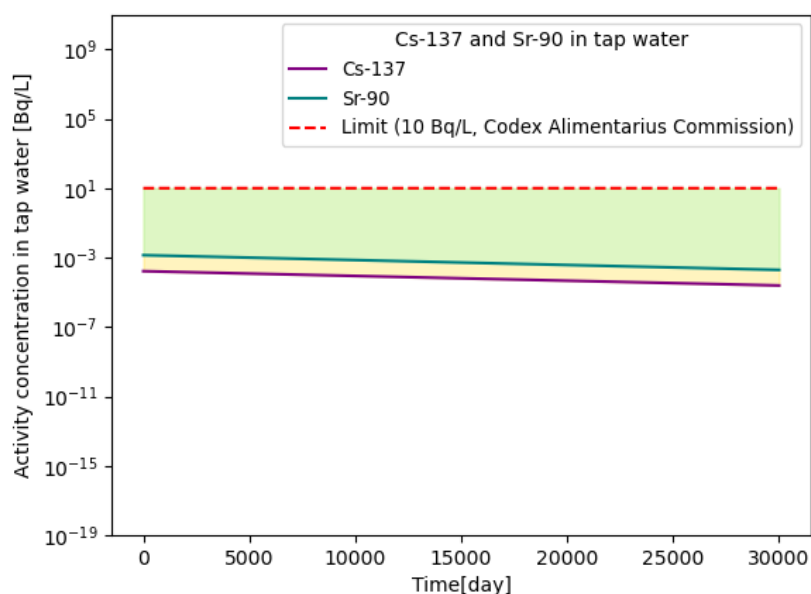


Figure 5.11 : Cs-137 and Sr-90 activity concentration change in tap water over time.

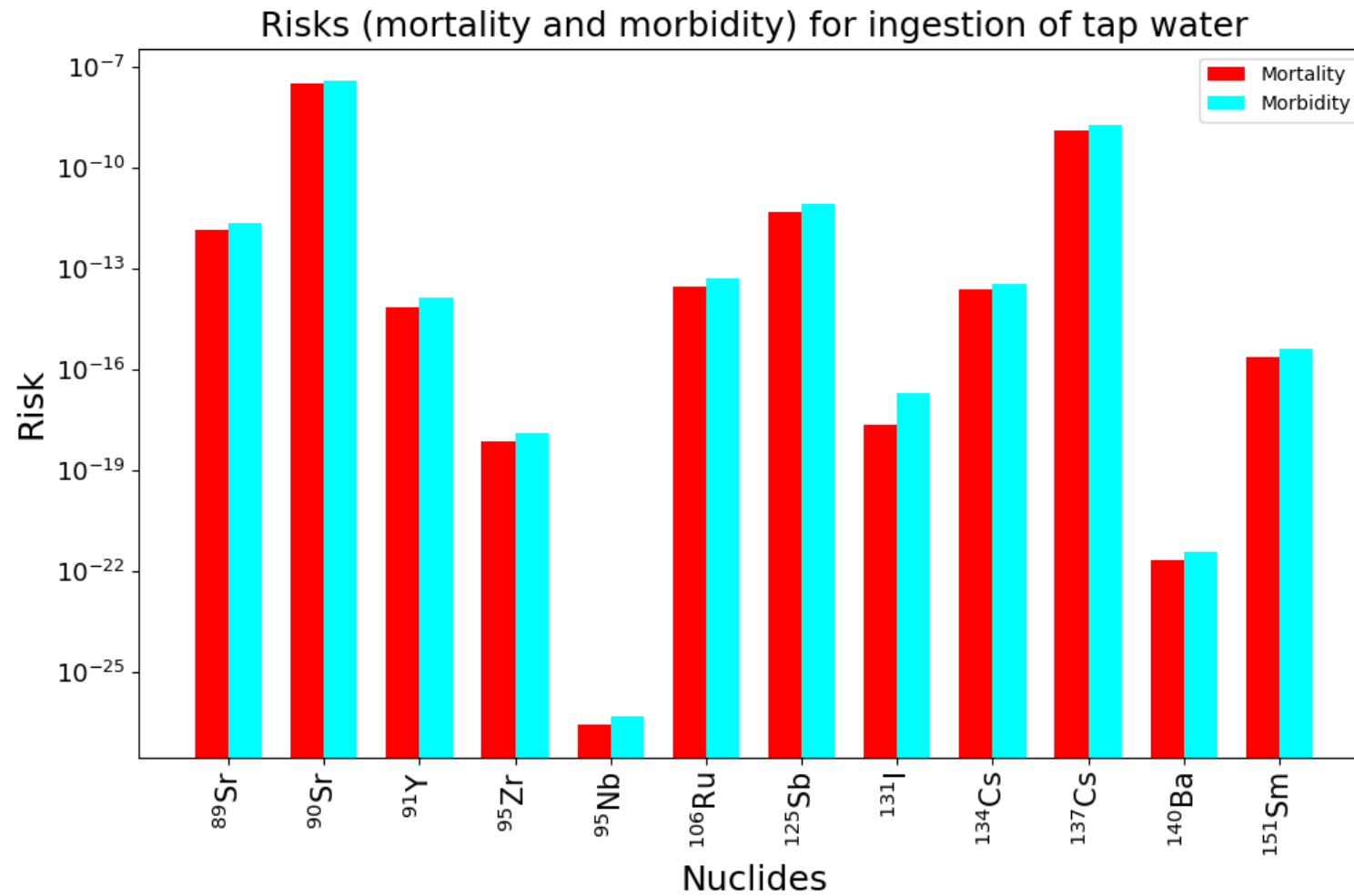


Figure 5.12: Mortality and morbidity risk coefficient for the ingestion of tap water.

Figure 5.10 and Figure 5.11 show concentration transformation in the tap water for I-131, Sr-90 and Cs137, respectively. Although Sr-90 has the highest concentration among them, it is still below the limit. Nuclear transformation is occurring slowly for radionuclides with a long half-life (Sr-90 and Cs-137) in contrast to short ones (I-131) throughout average life expectancy. Moreover, a few of them (displayed in Table F.1) decays to progenies that have a relatively short half-life and cause extra exposure to organs in the body.

Equation 5.2 provides the method to calculate mortality and morbidity risk for all conditions due to the ingestion of tap water after the determination of concentration in potable water.

$$Risk = \sum_{i=1}^{27448} (\alpha_{p,i} R C_p + (\alpha_{p,i} R) f_{p \rightarrow d} C_d + \dots) \quad (5.2)$$

where, $\alpha_{p,i}$ is activity concentration in tap water at i^{th} day, R is daily intake rate of tap water, $f_{p \rightarrow d}$ is fraction yield of daughter nuclide, and C_p and C_d are the risk coefficients of parent and daughter radionuclides, respectively.

In conclusion, when all mortality and morbidity risk values were calculated, some radionuclides displayed in Figure 5.12 were found to have relative significance regarding the effects of decay rates, dilution, and decay products for the ingestion of tap water; however, they are rather low considering the survival of the population.

5.7.3 Ingestion of food calculations

The contamination of food is a result of foliar and root uptake of radionuclides in the agricultural ecosystem. The foliar uptake of radionuclides was evaluated according to Equation 4.25. After a half-hour, corresponding concentration on vegetation (Bq/kg) was evaluated with 14 days weathering half-life ($k_w = \ln 2/14$) as suggested in IAEA TECDOC [121] despite depending on many factors, 5.4 m/days (equal to 0.0015 m/s) deposition velocity, and 0.3 kg biomass of leafy vegetable per m^2 for foliar uptake. Figure 5.13 shows the accumulation change of some radionuclides on vegetation with time. If pollutant stays some location several days instead of leaving it after half-hour, the buildup would reach equilibrium. In that case, the equilibrium value depends on both input rate R and loss rate k while reaching equilibrium but mainly depends on values of k . Therefore, radionuclides with a shorter half-life than

weathering half-life (14 days as mentioned) like I-131 (8.04 days) would reach the equilibrium quickly as displayed in Figure 5.13.

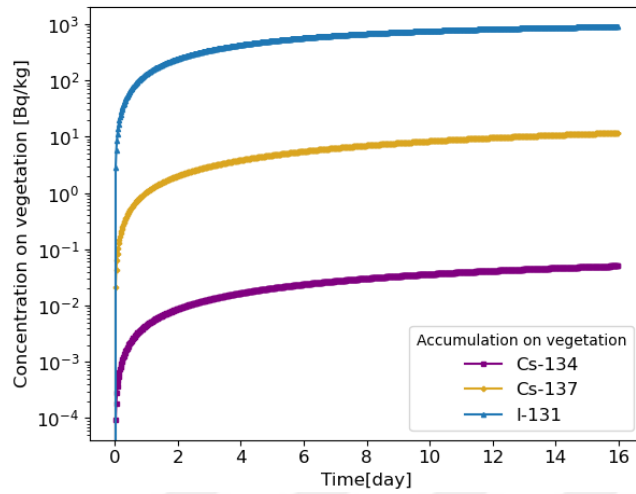


Figure 5.13 : The accumulation of Cs-134, Cs-137, and I-131 on vegetation.

The root uptake of radionuclides was evaluated considering the transfer factor F_v of radionuclides, for general consumed leafy vegetables that are based on plant and soil type [122], and their values are presented in Table 5.6. The activity density (Bq/m^2) on the soil was converted into activity concentration (Bq/m^3) by multiplying area with a depth of the soil 0.15 m since it is the average for the standardized zone for the root of plants [122]. Then, this number was divided by average soil density 1300 kg/m^3 [116] to find activity in soil ($\text{Bq/kg-dry mass soil}$). Finally, that was multiplied by the transfer factor to obtain transferred activity in food ($\text{Bq/kg-dry mass food}$) for root uptake.

After estimating total (both root and foliar uptake) concentration in the plant, the decay process was conducted for both uptake ways. The loss of radionuclides from leaf surface considered originating from weathering and physical decay whereas loss in the plants, only decay. In addition, weathering loss canceled out after one year since vegetable life in the soil is estimated approximately as one year due to harvesting. To be on the conservative side, it was also assumed that people kept consuming these contaminated vegetables throughout their life after harvesting. Therefore, for average lifetime intake of vegetables, the risk was calculated in the same way as described in Equation 5.2 but the daily intake rate of food was taken as 1.2 kg.d^{-1} according to Table E.1. The corresponding results were presented in Figure 5.14.

Table 5.6 : Root uptake fraction factors from soil to plant and risk coefficient for the ingestion of food.

Nuclides	Plant group	Soil group	Fraction factor	Risk coefficient for ingestion of food	
				Mortality (Bq-1)	Morbidity (Bq-1)
U-237	Leafy vegetables	n/a	6.80E-01	1.07E-10	1.93E-10
U-239	Leafy vegetables	n/a	6.80E-01	1.98E-12	2.86E-12
Np-239	Leafy vegetables	All	2.70E-02	1.13E-10	2.03E-10
Sr-89	Leafy vegetables	All	7.60E-01	2.97E-10	4.96E-10
Sr-90	Leafy vegetables	All	7.60E-01	1.62E-09	1.86E-09
Y-90	Leafy vegetables	All	4.00E-03	3.96E-10	7.16E-10
Y-91	Leafy vegetables	All	4.00E-03	3.51E-10	6.36E-10
Y-92	Leafy vegetables	All	4.00E-03	5.70E-11	9.77E-11
Y-93	Leafy vegetables	All	4.00E-03	1.60E-10	2.85E-10
Zr-95	Leafy vegetables	All	4.00E-03	1.01E-10	1.78E-10
Zr-97	Leafy vegetables	All	4.00E-03	2.76E-10	4.95E-10
Nb-95	Leafy vegetables	All	1.70E-02	5.41E-11	9.45E-11
Nb-97	Leafy vegetables	All	1.70E-02	5.08E-12	7.53E-12
Mo-99	Leafy vegetables	All	5.10E-01	4.06E-11	5.71E-11
Ru-103	Leafy vegetables	All	9.00E-02	8.48E-11	1.50E-10
Ru-105	Leafy vegetables	All	9.00E-02	3.05E-11	5.30E-11
Ru-106	Leafy vegetables	All	9.00E-02	9.35E-10	1.65E-09
Rh-105	n/a	All	9.00E-01	5.16E-11	9.27E-11
Ag-111	Leafy vegetables	All	1.80E-04	1.81E-10	3.26E-10
Sn-123	Leafy vegetables	All	9.40E-05	3.07E-10	5.53E-10
Sn-125	Leafy vegetables	All	9.40E-05	4.41E-10	7.96E-10
Sb-125	Leafy vegetables	All	9.40E-05	1.01E-10	1.66E-10
Te-132	Leafy vegetables	All	3.00E-01	2.78E-10	6.60E-10
I-131	Leafy vegetables	n/a	3.00E-02	1.85E-10	1.75E-09
I-135	Leafy vegetables	n/a	3.00E-02	1.90E-11	1.17E-10
Cs-134	Leafy vegetables	All	6.00E-02	9.57E-10	1.39E-09
Cs-136	Leafy vegetables	All	6.00E-02	2.05E-10	3.04E-10
Cs-137	Leafy vegetables	All	6.00E-02	6.88E-10	1.01E-09
Ba-140	Leafy vegetables	All	5.00E-03	3.34E-10	5.86E-10
La-140	Leafy vegetables	All	5.70E-03	2.41E-10	4.30E-10
Ce-141	Leafy vegetables	All	6.00E-03	1.02E-10	1.83E-10
Ce-143	Leafy vegetables	All	6.00E-03	1.56E-10	2.81E-10
Ce-144	Leafy vegetables	All	6.00E-03	7.73E-10	1.40E-09
Pr-143	Leafy vegetables	All	2.00E-02	1.73E-10	3.14E-10
Nd-147	n/a	All	2.00E-02	1.53E-10	2.76E-10
Pm-147	Cereals	All	1.40E-02	3.72E-11	6.70E-11
Pm-148	Cereals	All	1.40E-02	3.77E-10	6.80E-10
Pm-149	Cereals	All	1.40E-02	1.46E-10	2.64E-10
Pm-151	Cereals	All	1.40E-02	9.90E-11	1.78E-10
Sm-151	Leafy vegetables	All	6.00E-03	1.23E-11	2.18E-11
Sm-153	Leafy vegetables	All	6.00E-03	1.06E-10	1.92E-10
Eu-154	Leafy vegetables	All	6.00E-03	2.29E-10	4.03E-10
Eu-155	Leafy vegetables	All	6.00E-03	4.19E-11	7.48E-11
Eu-156	Leafy vegetables	All	6.00E-03	2.77E-10	4.79E-11

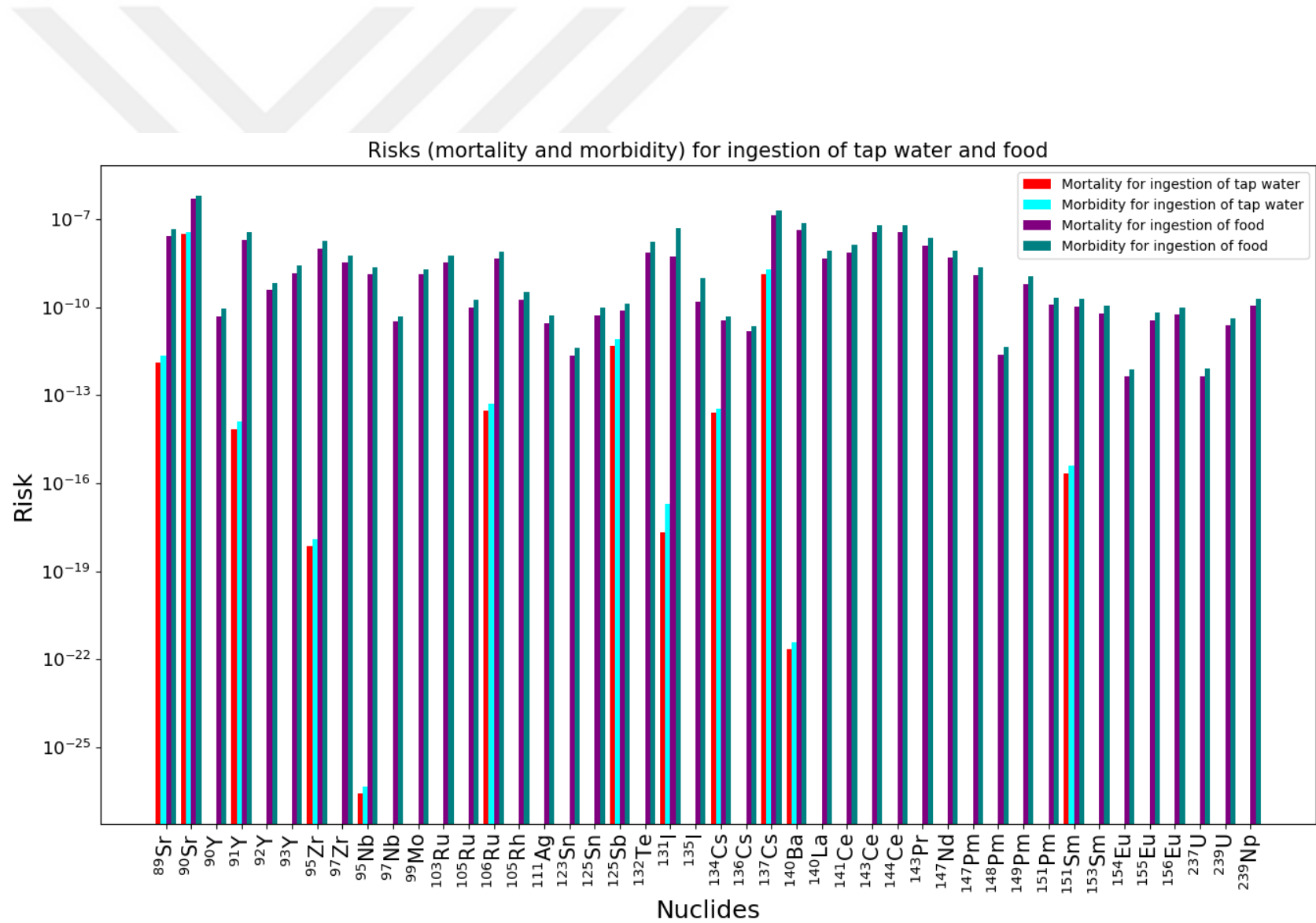


Figure 5.14: Mortality and morbidity risk coefficient for the ingestion of tap water and food.

Figure 5.14 shows the risk following the ingestion of contaminated tap water and food in two groups; mortality and morbidity. The risk for the ingestion of food is substantially higher than the ingestion of tap water. Many radionuclides have no risk for the ingestion of tap water while all of them carry the risk for the ingestion of food. The risk levels for both ingestion paths were found relatively close for some radionuclides such as Sr-90, Sb-125, and Cs-137. However, for some others such as Y-91, Zr-95, Nb-95, I-131, and Ba-140, these risk levels are not close to each other. The risk for ingestion of contaminated tap water and food is quite low considering the survival of the population and cancer mortality rates [114].

CAC limit differs for activity in food (100 Bq/kg). Figure 5.15 shows that in a few days, I-131 activity in food suddenly fell down to negligible values in the logarithmic scale by means of effective loss rate (weathering loss and physical decay) even though initial activity was already below the limit.

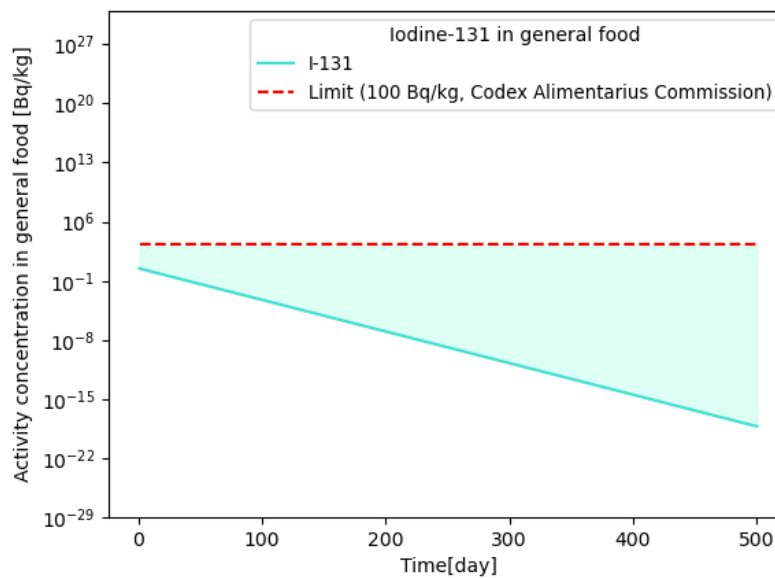


Figure 5.15 : I-131 activity change in general food over time.

Sr-90 and Cs-137 activity concentration change in food is displayed in Figure 5.16. It shows that Sr-90 and Cs-137 concentration in food are well below the CAC limits (100 Bq/kg for Sr-90 and 1000 Bq/kg for Cs-137) in addition to the limit of NRA JAPAN (10 Bq/kg) for Cs-137. Even more, it is obvious for Sr-90 and Cs-137 that at the end of the one year, decrease in concentrations decelerate since weathering loss cancels out.

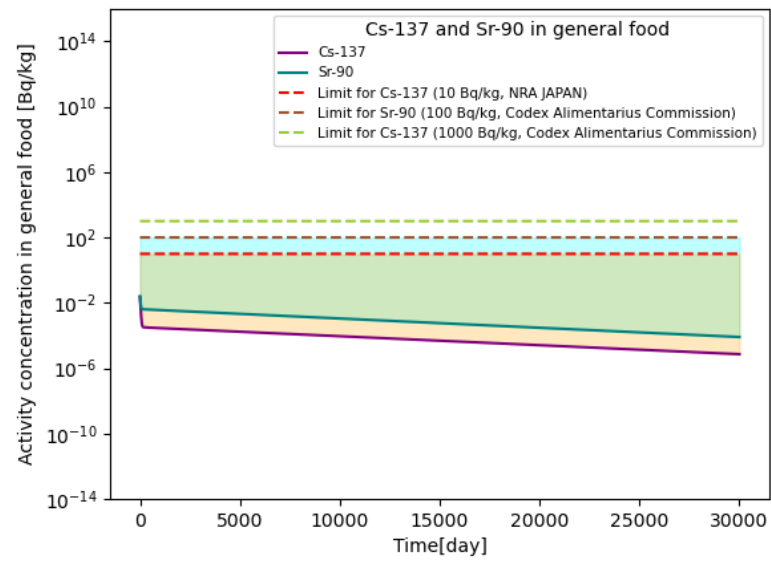


Figure 5.16 : Cs-137 and Sr-90 activity change in general food over time.



6. CONCLUSIONS AND RECOMMENDATIONS

In this thesis, the particle dispersion model was used to calculate activity concentrations and density distributions of radionuclides as well as their health effects in case of a hypothetical accident at ITU TRIGA Mark II research reactor.

In the hypothetical accident, it was assumed that the reactor operated continuously at full power (250 kW) for 55 days and all 69 fuel elements failed at the end of this cycle. The actual reactor inventory at the end of 2019 was simulated as realistically as possible. In safety analysis report of ITU TRIGA Mark II research reactor, the reactor was operated for 4 years and only the highest power generating fuel element producing 2.6% of the power was failed. In addition, only noble gases and halogens leaked from the fuel with a rate of 1.5×10^{-5} . In this study, radionuclides that are considered in NRC Regulatory Guide 2000 [102], IAEA Report of Chernobyl [104], EPR Commission final safety analysis report (FSAR) [111] and Japan Nuclear Regulation Authority (NRA JAPAN) [112] beside relatively short half-life radionuclides such as Ce-141, Ce-142, Ce-143, Eu-154, Eu-155, and Eu-156 which are not taken into consideration in these reports were analyzed with the same leakage rate mentioned above. Therefore, the source term in this study included several radionuclides with regard to design basis accidents and design extension conditions providing a conservative approach.

At the first phase of the study, the average wind direction estimation for the reactor site was performed. The result of the analysis showed that the average wind direction altered from NE direction to NE-NNE over time when compared with the ITU TRIGA Mark II safety analysis report in 1979. On the contrary, the average wind speed approximately stayed the same since the value is 4.7 m/s in SAR and 4.6 m/s in this study. These outcomes were supported by measured meteorological data information from Istanbul/Ataturk ASOS and processed global reanalysis meteorological data. This step is vital for all calculations coming afterwards.

At the second phase, the source term for this study was calculated since it is one of the main requirements of dispersion calculations. In order to determine the source term, the core radionuclide inventory must be known. The generic, validated and verified, MCNP6.2 input of the reactor generated by Dr. Senem Şentürk Lüle was modified for burnup calculations with the parameters mentioned above. Then, the source term was calculated from the resulting core inventory.

At the third phase, dispersion calculations were performed with HYSPLIT4 code. The studies in the literature show the evidence of possible linkage between dispersion models, grid resolution, and accuracy. Since Gaussian horizontal-particle vertical (Gh-Pv) and Top-Hat-horizontal particle-vertical (THh-Pv) models are distribution models that are using the normal distribution to determine puff radius in terms of standard deviation (3σ and 1.5σ , respectively) and maximum grid cell concentration in terms of mean value, 3D particle model pollutant range became considerably longer. The simulation results indicated that activity concentration in the grid cell from 3D particle model is 2.0 and 2.2 times greater than Gh-Pv and THh-Pv models, respectively. It is clear that the accuracy of results strongly depends on grid resolution especially for short-term simulations rather than stability condition. In addition, simulations showed that under unstable condition particles tend to spend more time before leaving the grid cell in certain time intervals compared to a stable condition if grid resolution is low. With high grid resolution (0.002 degree), half-hour average activity concentration for the stable condition is 31.5% higher than unstable condition concentrations. As a result, the 3D particle model and stable condition were selected for the upcoming calculations to be more conservative.

The fourth phase covers the calculation of external exposure rate associated with dispersed radioactive pollutants in the air and deposited activity density on the ground surface. The exposure limit for the public (0.1 rem/year) has been defined in ICRP 103 [115]. Therefore, the aim of this part is to find whether the public limit is exceeded or not for the hypothetical accident considered in this study. It was observed that non-settled noble gas radionuclides Kr-85, Xe-133, and Xe-135 contributed to exposure for a given period of time whereas deposited ones' contribution was long-lasting. Total cloudshine and groundshine exposure of half-hour resulted in maximum 1.37 μ rem at ITU Ayazağa Campus (near the Chemical

and Metallurgical Engineering Faculty building) which is below the limit for the public (0.1 rem/yr or 5.59 μ rem/0.5h). Similarly, the highest calculated exposure annually, 0.206 mrem, was at the same location due to nuclear transformation of deposited radionuclides which is also below public limit.

The results of this thesis not only clarify external exposure of released radionuclides but also show the health effects of radionuclides on the human body in case of inhalation and ingestion. The fifth phase was focused on this topic. In half-hour inhalation, risky radionuclides can be the ones that have a relatively short half-life in addition to their high activity concentration in air and high-risk coefficients (e.g. Sr-89, Y-91, Zr-95, Zr-97, Mo-99, Te-132, I-131/132, Ba-140, La-140, Ce-141, Ce-143, and Ce-144). The findings showed that Ba-140 is at the top of the list with 3.00E-09 mortality and 3.65E-09 morbidity risks owing to its decay progeny and high-risk coefficient. Nevertheless, risks are quite low concerning the survival rates of population.

The existence of radionuclides in tap water is dangerous for human life if their concentration is above the allowed limits [123]. In this investigation, it was found that lifetime ingestion of some radionuclides such as Sr-89, Sr-90, Y-91, Ru-106, Sb-125, I-131, Cs-134, and Cs-137 from contaminated tap water could carry a risk since they had relatively low retardation by soil, short travel times to reach well, low dilution, high concentration in pollutant, progenies, and high-risk coefficient, even though some of them have a relatively short half-life e.g. Sr-89, Y-91, Ru-106, I-131, Sb-125, and Cs-134. For other radionuclides, there was no considerable risk. It was found that even the initial concentrations of short half-life I-131 and long half-life Sr-90 and Cs-137 in contaminated tap water are below the Codex Alimentarius Commission (CAC) limits. In addition, it was estimated that Sr-90 with 29.12 years half-life has the highest risk among the other radionuclides with 3.07E-08 mortality and 3.81E-08 morbidity in case of ingestion of contaminated tap water throughout the lifetime. Additionally, the concentration of Sr-90, I-131, and Cs-137 in the ITU pound due to the hypothetical accident were found as 1.69E-12, 1.57E-18, and 2.01E-13 Bq L⁻¹, respectively. Risks are rather low considering the survival rates.

The last analysis performed was on the ingestion of contaminated food. Although uptake and loss rate mechanisms of foliar and root uptake differ, they directly depend on chemical characteristics of radionuclides, weather conditions, soil (determined

all), and plant types. The results showed that radionuclides were intercepted by leaves of vegetables before settling to the ground surface. The accumulation of the radionuclides on the vegetable surfaces continues until air pollutant moves out of the air parcel while the weathering loss from the leaf of vegetables could still cause the soil contamination even after pollutant leaves the area. Since the mobility of radionuclides in soil influenced by several factors, the concentration of density of the radionuclides in the plant due to root uptake is less than foliar uptake. When radionuclides transported in the groundwater, because of dilution, they mostly lose their significance for the ingestion of tap water compared with the ingestion of food. According to simulations, although many plants were affected from contamination, the calculated concentration in plants is well below the limits especially for Sr-90 ($2.56\text{E-}02$ Bq/kg), I-131 ($2.16\text{E-}02$ Bq/kg), and Cs-137 ($2.24\text{E-}02$ Bq/kg)—CAC limit for Sr-90 and I-131 is 100 Bq/kg, CAC and NRA JAPAN limits for Cs-137 are 1000 Bq/kg and 10 Bq/kg, respectively. Even though Sr-90 maintains its importance in terms of mortality ($5.03\text{E-}07$) and morbidity ($6.43\text{E-}07$) among the other radionuclides, risks are rather low considering the survival rates.

In general, results showed that different models and atmospheric conditions play an important role in the dispersion; in the aftermath of dispersion, intake ways appear to take a key role in human health.

Although this study provided valuable information about the dispersion calculation and corresponding health effects, there were some limitations. The analysis of the hypothetical accident scenario was conducted by user-entered meteorological data that do not have specific humidity information therefore wet deposition analysis could not be performed. Instead of wet deposition, the dry deposition velocity increased to compensate it. Another limitation is that in order to estimate the source term, it was assumed that the research reactor was in continuous operation at 250 kW at for 55 days that provides the same kWh energy. In reality, reactor operation is intermittent. On the other hand, it was assumed that the diluted radionuclide concentration in the well was utilized as tap water without any loss. Additionally, the uptake scenario of radionuclides from soil to plant was designed as foliar and root uptake but secondary mechanisms such as water splashing did not take into account. Overestimations and lack of information in the literature regarding the ingestion of

food caused the utilization of elemental analogs to determine uptake fractions of radionuclides (e.g., Ce for lanthanide group).

The first comprehensive study on the hypothetical accident scenario for ITU TRIGA Mark II research reactor provided information about the movement of the radioactive pollutant over Istanbul and resulting mortality and morbidity risk for the population in long term.

In conclusion, the results of this thesis which adopts conservative methodology showed that even for a very conservative hypothetical accident scenario at ITU TRIGA Mark II research reactor, the dose levels and risks are below international limits.

Future studies should focus on overcoming the above mentioned shortcomings.



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APPENDICES

APPENDIX A: The stability categories, σ_y and σ_z parameters had been determined as a function of distance from the source.

APPENDIX B: Wind rose percent frequency data for ISTANBUL/ATATURK (LTBA) airport.

APPENDIX C: Results of wind direction analysis of 2019 by clustering method.

APPENDIX D: Particle movement under stable unstable air conditions.

APPENDIX E: Distribution coefficient K_d for selected radionuclides and gender specific and combined daily usage of environmental media.

APPENDIX F: Radionuclides and their progenies U.S. EPA FGR 13.

APPENDIX G: Radionuclides composition for design basis analysis.



APPENDIX A: The stability categories, σ_y , and σ_z parameters had been determined as a function of distance from the source.

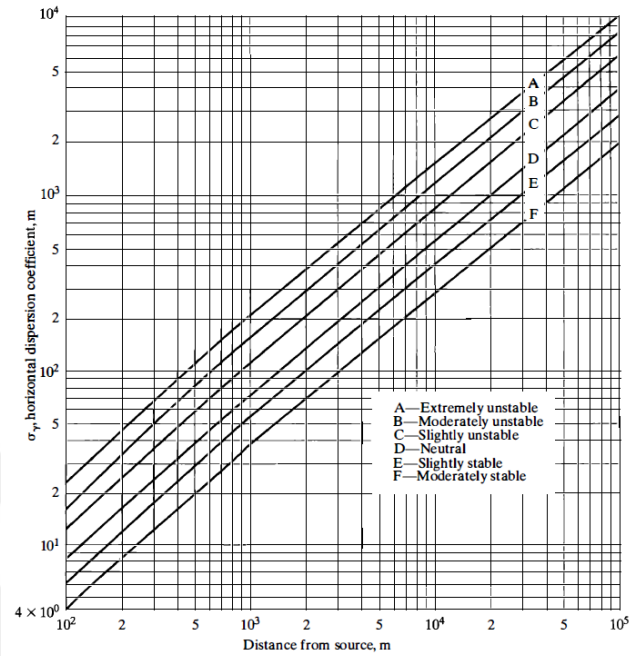


Figure A.1 : Horizontal dispersion coefficient σ_y as a function of distance from source for the various Pasquill conditions [124].

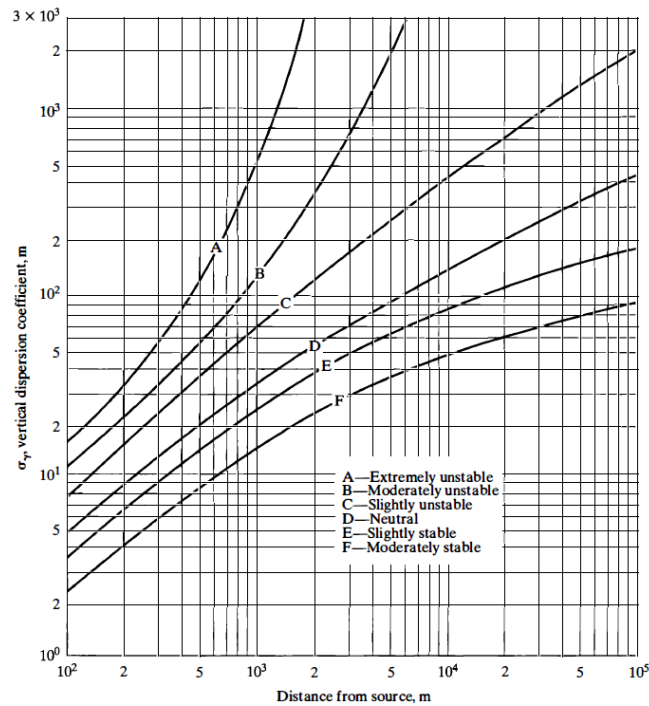


Figure A.2 : Vertical dispersion coefficient σ_z as a function of distance from source for the various Pasquill conditions [124].



APPENDIX B: Windrose Data Table (Percent Frequency) for ISTANBUL /
ATATURK (LTBA).

Table B.1 : Windrose Data Table (Percent Frequency).

Direction	The calm of wind speeds (%)					
	2.0-4.0 (m/sec)	4.0-6.0 (m/sec)	6.0-8.0 (m/sec)	8.0-10.0 (m/sec)	10.0-12.0 (m/sec)	12+ (m/sec)
000-010	0.869	1.413	1.599	0.959	0.318	0.070
000-020	1.007	1.932	1.793	0.635	0.158	0.036
010-030	1.814	3.412	2.619	0.819	0.135	0.036
020-040	1.993	3.624	2.235	0.627	0.056	0.004
030-050	1.658	2.895	1.942	0.460	0.034	0.000
040-060	1.756	2.885	1.495	0.320	0.023	0.000
050-070	1.320	1.466	0.585	0.064	0.003	0.000
060-080	0.910	0.619	0.140	0.005	0.000	0.000
070-090	0.806	0.269	0.017	0.001	0.000	0.000
080-100	0.712	0.172	0.007	0.000	0.000	0.000
090-110	0.822	0.269	0.022	0.001	0.000	0.000
100-120	0.867	0.271	0.023	0.005	0.000	0.000
110-130	0.723	0.182	0.029	0.005	0.001	0.000
120-140	0.607	0.149	0.025	0.001	0.000	0.000
130-150	0.578	0.149	0.011	0.001	0.000	0.000
140-160	0.604	0.109	0.011	0.001	0.001	0.000
150-170	0.509	0.084	0.021	0.009	0.001	0.000
160-180	0.631	0.138	0.045	0.019	0.002	0.000
170-190	0.826	0.257	0.135	0.064	0.019	0.003
180-200	0.932	0.574	0.513	0.162	0.060	0.011
190-210	1.172	0.982	0.594	0.226	0.084	0.021
200-220	1.423	1.166	0.397	0.155	0.054	0.011
210-230	1.660	1.102	0.282	0.095	0.024	0.003
220-240	1.860	1.182	0.229	0.033	0.013	0.004
230-250	1.716	0.944	0.119	0.019	0.005	0.000
240-260	1.162	0.566	0.089	0.013	0.003	0.000
250-270	0.721	0.263	0.063	0.013	0.000	0.000
260-280	0.426	0.145	0.026	0.006	0.002	0.001
270-290	0.409	0.090	0.020	0.004	0.002	0.001
280-300	0.374	0.080	0.022	0.002	0.001	0.000
290-310	0.353	0.142	0.049	0.012	0.001	0.000
300-320	0.425	0.221	0.097	0.025	0.004	0.002
310-330	0.524	0.332	0.148	0.070	0.031	0.005
320-340	0.813	0.475	0.280	0.146	0.076	0.027
330-350	1.642	1.052	0.518	0.396	0.209	0.096
340-360	1.678	1.900	1.264	0.727	0.298	0.112



APPENDIX C: Results of the wind direction analysis for 2019 by clustering trajectories.

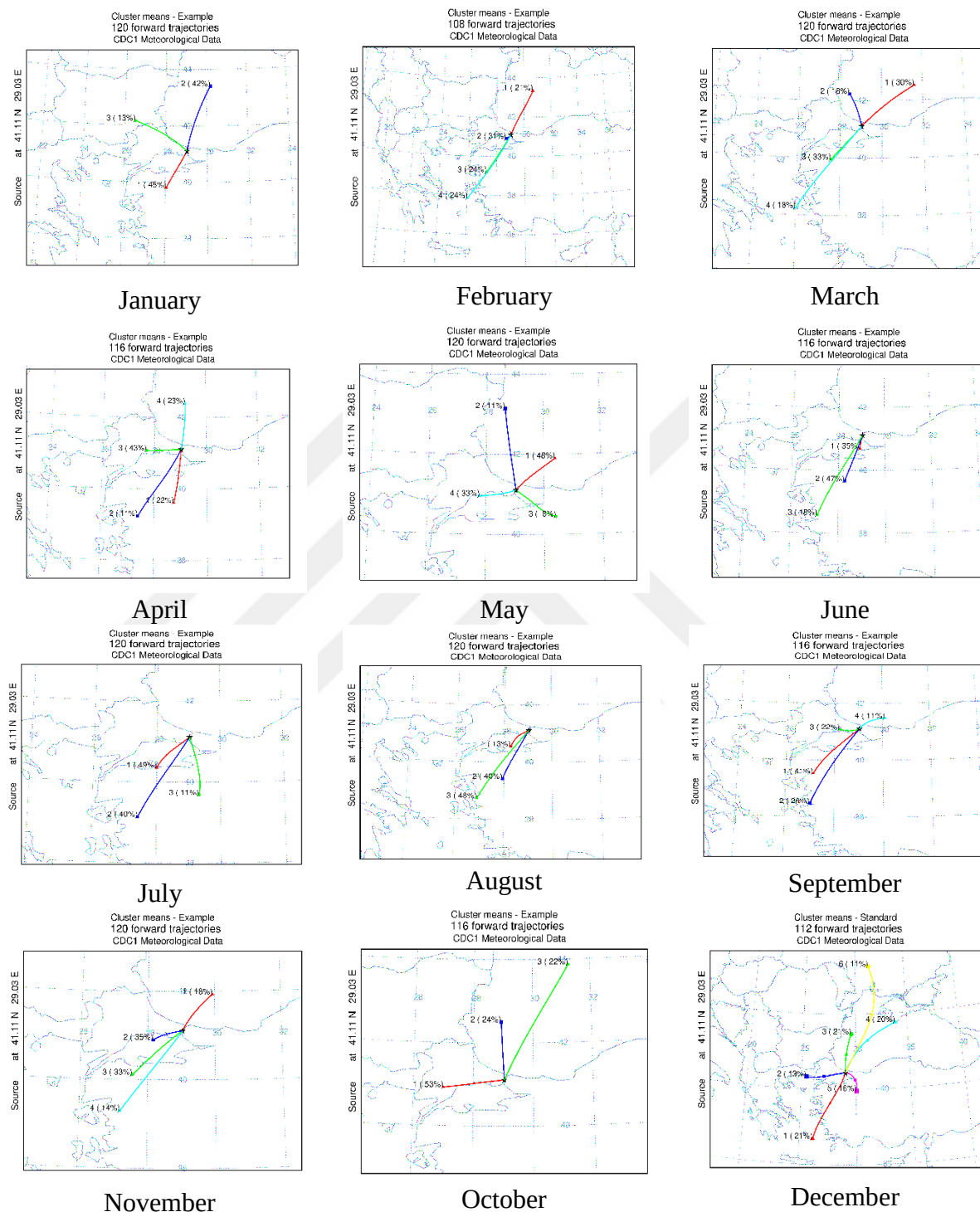


Figure C.1 : Results of wind direction analysis of 2019 by clustering trajectories.



APPENDIX D: Particle movement under stable unstable air conditions.

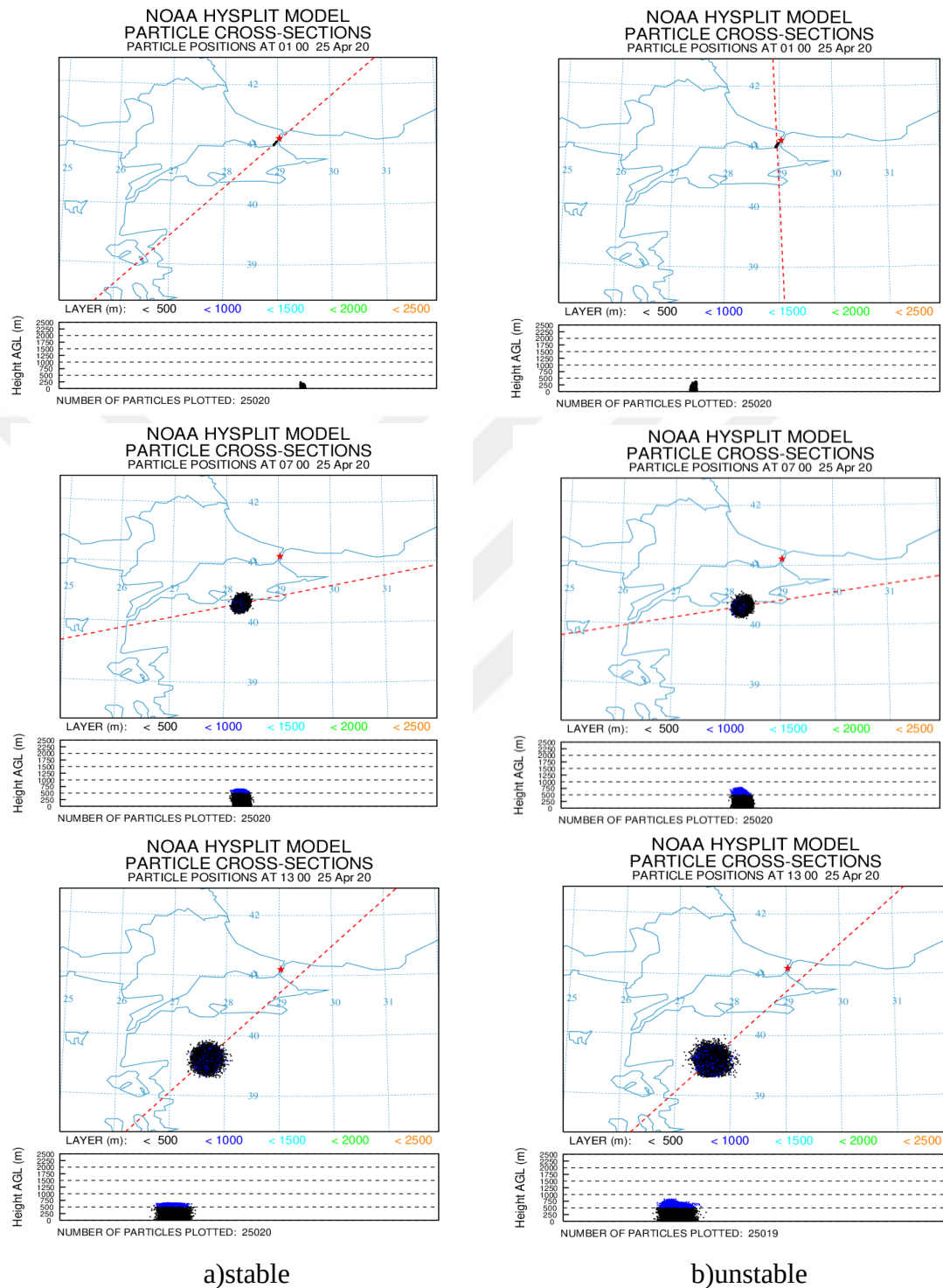


Figure D.1 : Particle movement under stable unstable air conditions.



APPENDIX E: Gender-specific and combined daily usage of environmental media and distribution coefficient K_d for selected radionuclides.

Table E.1 : Average daily usage of environmental media by the two hypothetical populations [114].

Medium	Males		Females		Combined	
	Stationary	Current	Stationary	Current	Stationary	Current
Air (m ³)	19.2	19.8	16.5	16.3	17.8	18.0
Tap Water (L)	1.29	1.25	0.93	0.90	1.11	1.07
Diet (kcal)	2418	2450	1695	1717	2048	2075

Table E.2 : Distribution coefficient, K_d , for selected radionuclides [122].

Nuclides	Soil group	Distribution Coefficient (L kg⁻¹)
U-237	All	7.10E-01
U-239	All	7.10E-01
Np-239	All	1.30E+00
Sr-89	All	4.00E-01
Sr-90	All	4.00E-01
Y-90	All	1.00E+00
Y-91	All	1.00E+00
Y-92	All	1.00E+00
Y-93	All	1.00E+00
Zr-95	All	2.00E+00
Zr-97	All	2.00E+00
Nb-95	All	2.00E+00
Nb-97	All	2.00E+00
Mo-99	All	7.00E+00
Ru-103	All	5.00E+00
Ru-105	All	5.00E+00
Ru-106	All	5.00E+00
Rh-105	All	6.00E-01
Ag-111	All	3.60E+01
Sn-123	All	1.30E+02
Sn-125	All	1.30E+02
Sb-125	All	6.00E-01
Te-132	All	1.80E+02
I-131	All	1.00E-02
I-135	All	1.00E-02
Cs-134	All	4.30E+00
Cs-136	All	4.30E+00
Cs-137	All	4.30E+00
Ba-140	All	4.00E-01
La-140	All	5.30E+03
Ce-141	All	1.20E+02
Ce-143	All	1.20E+02
Ce-144	All	1.20E+02
Pr-143	All	1.20E+02
Nd-147	All	1.20E+02
Pm-147	All	4.50E+02
Pm-148	All	4.50E+02
Pm-149	All	4.50E+02
Pm-151	All	4.50E+02
Sm-151	All	2.40E+02
Sm-153	All	2.40E+02
Eu-154	All	2.40E+02
Eu-155	All	2.40E+02
Eu-156	All	2.40E+02

APPENDIX F: Radionuclides and their progenies U.S. EPA FGR 13 [114].

Table F.1 : Radioactive decay products and fraction yield [114].

Nuclide	Decay Mode	Decay Product	Fraction
U-239	B-	Np-239	1.00E+00
Sr-90	B-	Y-90	1.00E+00
Zr-95	B-	Nb-95	9.93E-01
Zr-97	B-/IT	Nb-97m→Nb-97	9.47E-01/1.00E+00
Mo-99	B-/IT	Tc-99m→Tc-99	8.76E-01/1.00E+00
Ru-103	B-/IT	Rh-103m→Rh103m	9.97E-01/1.00E+00
Ru-105	B-	Rh-105	1.00E+00
Sn-125	B-	Sb-125	1.00E+00
Sb-125	B-/IT	Te-125m→Te-125	2.28E-01/1.00E+00
Te-132	B-	I-132	1.00E+00
Ba-140	B-	La-140	1.00E+00
Ce-143	B-	Pr-143	1.00E+00
Ce-144	B-	Pr-144	9.82E-01
Nd-147	B-	Pm-147	1.00E+00
Pm-151	B-	Sm-151	1.00E+00



APPENDIX G: Radionuclide grouping for design basis analysis [102].

Table G.1 : Elements in each radionuclides group.

Group	Elements
Noble Gases	Xe, Kr
Halogens	I, Br
Alkali Metals	Cs, Rb
Tellurium Group	Te, Sb, Se, Ba, Sr
Noble Metals	Ru, Rh, Pd, Mo, Tc, Co
Lanthanides	La, Zr, Nd, Eu, Nb, Pm, Pr, Sm, Y, Cm, Am
Cerium	Ce, Pu, Np



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